Nuclear Medicine and Radiologic Imaging in Sports Injuries

Andor W.J.M. Glaudemans
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Foreword

As President of the International Federation of Sports Medicine (FIMS), I am honoured to write a foreword to this interesting and important initiative: "Nuclear Medicine and Radiologic Imaging in Sports Injuries", edited by Andor Glaudemans (coordinating editor), Rudi Dierckx, Jan Gielen and Hans Zwerver. Personally, I have known Jan Gielen now for many years. He is a current member of the FIMS Scientific Commission.

The textbook is current and concise, and is essential to provide the background information for sports medicine physicians required to practice with confidence in emergency and chronic situations. This volume gives insight in the actual importance of the assessment of injuries with the support of radiologic and nuclear medicine imaging techniques. The chapters written by experts in the field give an overview of actual radiological modalities (computed radiography, CT, ultrasound and MRI) and nuclear medicine imaging techniques (including PET-CT and SPECT-CT) for specific indications, pointing out the specific merits of both. The scope is comprehensive with focus on orthopaedic sports lesions.

The medical society is aware that sports medicine is an integrated multidisciplinary field embracing relevant areas of clinical medicine (sports traumatology, medicine of sports, and sports psychiatry), appropriate allied scientific disciplines (including physiology, psychology, and biomechanics), radiology and nuclear medicine in its natural ally. Sports medicine physicians are increasingly aware that the responsibilities of sports medicine involve not only competitive sports but also recreational sports, and consequently, to this respect, I am proud to recognise over the past years that sports medicine has grown in reliability thanks to its efforts in disseminating the principles of the health aspects of all people engaged in sport and physical activity. In this context, the sport medicine physicians' work has to be dedicated to the protection of the athletes' health, including planning of the medical aspects of sport events and medical treatment, in order to allow them to safely compete in national and international sports events.

Already since the beginning, FIMS promotes the publication of educational books and initiatives enforcing continuous professional development, and this textbook really deserves a special attention.

To my colleague and friend Jan Gielen and to my colleagues Andor Glaudemans, Rudi Dierckx and Hans Zwerver go my sincere congratulations.

Lausanne, Switzerland F. Pigozzi, MD, FIMS President

Preface

A physically active lifestyle is widely promoted since it has numerous positive effects on healthy aging. With this focus on an active lifestyle for everyone, patients and athletes, in all ages, beginners and experts and at a recreational and a professional level, more sports- and exercise-related injuries may be expected. To keep these exercisers "on the move," on the one hand early diagnosis and early therapy decision making are key issues in sports medicine, while on the other hand diagnostic imaging is of increasing importance in successful diagnosis and management of sports injuries, both in recreational and elite athletes.

Sports medicine, as a specialty, has gained much importance in the recent years. Sports and exercise medicine involves the medical care of injury and illness in sports and has a large-scale application in improving the health of the general public and patients with chronic disease, for example, through advice on exercises. However, sports and also "Exercise as a Medicine" may also result in unfavorable side effects on the musculoskeletal system. Optimal management of these injuries requires careful clinical examination, accurate diagnosis, and experience and knowledge of sport-specific movement patterns. The sports medicine specialist treats a wide range of patients from elite sportspersons over recreational people to those who recover from illness and injury. The invaluable importance of this expert area is now increasingly recognized. As an example in 2014, sports and exercise medicine became a new specialty within the Dutch medical community.

Nuclear medicine and radiology are both expanding medical fields, which are potentially able to satisfy the demands of the sports medicine physician by offering precise diagnosis, insights into pathophysiology, monitoring of rehabilitation, and imaging of treatment outcome. Radiologic imaging techniques, such as X-ray, CT, and MRI, already for years play an important role in sports medicine with, for example, growing possibilities in MRI sequences. The development of hybrid imaging systems with better spatial resolution also have led to an increasing use of nuclear medicine techniques. SPECT/CT, PET/CT, and PET/MRI are important developments bringing anatomy and physiology together.

Although there have been some textbooks on imaging sports injuries, the number of these books is limited and mainly focus on radiological techniques. To the best of our knowledge, this is the first comprehensive textbook that combines the perspectives of sports medicine, radiology, and nuclear medicine in one volume. The editors are working in the field of nuclear medicine (Andor Glaudemans and Rudi Dierckx), radiology (Jan Gielen), and sports medicine (Hans Zwerver). In order to obtain a high-quality multi-author textbook, they invited international specialists in all three fields.

The basic chapters describe each specialty, their characteristics, strengths, and weaknesses and provide an overview of all possibilities these specialties may offer. The topographic sections of injuries of the head and face, spine, chest, shoulder, elbow and forearm, wrist and ankle, pelvic region, knee, lower leg, ankle and foot, all exist of three chapters: the first describing the sport-specific injuries, the second describing the radiological perspective with many illustrations, and the third describing the nuclear medicine perspective also with illustrations. After this topographic section, the chapters focus on specific characteristics in adolescents, women, dancers, and musicians. A chapter on equine sports injuries, also to be considered a special athlete, is meant to broaden the scope, as is the case in a special chapter dedicated to the heart as a special muscle in athletes and to the effect of anabolic-androgenic steroids on the heart muscle. The last seven chapters describe the expert views in specific sports (tennis, soccer, cycling, running, and boxing) and the experiences with injuries in Olympic and Paralympic athletes.

We realize that this approach resulted in overlap, albeit from different perspectives. We think this was unavoidable because much integration of the knowledge in radiology, nuclear medicine, and sports medicine is still at its beginning. With this regard, we hope this textbook will prove not only to be useful for those involved in patient care, but also may provide a platform for further common research.

We are happy that our book is produced by one of the premier publishers in the field. This guarantees a high quality of reproduction and allows for the inclusion of many color figures, which is essential in the fields of radiology and nuclear medicine. We would like to thank Dr. Sylvana Freyberg from Springer Verlag for her help and support during the development of this book.

We were also intrigued by the enthusiastic response from contributors from all over the world who made this endeavor successful. Although deadlines sometimes had to be postponed because of the many tasks and roles in the medical field we all play, we appreciated the efforts and enthusiasm of all the authors involved. Hence, our sincere thanks for their contributions. The result to us looks a fine compilation of present evidence, knowledge, and expertise. We hope the interested reader may build on this.

Combining the knowledge of all three specialties involved will hopefully enhance interdisciplinary communication for better patient care and joint research. We sincerely hope that this textbook will become a useful and stimulating reference for sports medicine specialists, radiologists, nuclear medicine specialists, and all professionals working in the field, at the benefit of athletes and patients involved.

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Research Fields

- Imaging of infectious and inflammatory diseases (amyloidosis, fungal infections, vasculitis, endocarditis, patients with bacteremia, vascular graft infections, tuberculosis, atherosclerosis, diabetic foot infections, prosthetic joint infections, osteomyelitis, infections in children)
- Hormonal receptor imaging: estrogen receptor (FES-PET) and androgen receptor (FDHT-PET)
- Imaging of oncological diseases
- Imaging of sports injuries
- Radioisotope therapeutic strategies

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Author of more than 500 peer-reviewed publications in international journals, editor of 9 textbooks

Research Fields

Broad interest in nuclear medicine, focus on neuroscience and oncology
- SPECT/conventional nuclear medicine
- PET: research and clinical applications
- Development of novel radiotracers
- Rodent models of human disease
- Medical physics
- Quality, ethics, and economics

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Research Fields

- Radiological imaging and sports medicine
- Gait lab studies in sports and art performers
- Developing skeleton and height prediction
- Imaging and imaging-guided interventions in MSK and sports
- Imaging and imaging-guided interventions of bone and soft tissue tumors

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Research Fields

Broad interest in sports and exercise medicine, focus on musculoskeletal injuries
- Tendinopathy
- Overuse injuries in sports
- Exercise-related injuries in chronic disease
- Exercise and healthy aging

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Part I

Basics

Sports Medicine and Imaging

1

Johannes (Hans) Zwerver

Contents

Abstract

Sports and exercise medicine deals with the medical care of the exercising individual. Strong evidence shows that physical *in*activity increases the risk of many adverse health conditions, including major noncommunicable diseases such as coronary heart disease, type 2 diabetes, and breast and colon cancers and shortens life expectancy. Therefore, exercise is increasingly prescribed by physicians and promoted through government-based health campaigns to prevent the morbidity and mortality caused by inactivity. A side effect is an increasing number of sports- and exercise-related injuries. For optimal management of these conditions, often imaging is necessary to establish a precise diagnosis from the start and to plan the best treatment and rehabilitation strategy.

Dealing with elite athletes, often under time pressure for the next game or an upcoming tournament, poses specific challenges to the medical personnel involved. Good communication between the sports medicine physician and imaging specialist, exchange of relevant information and adequate knowledge of musculoskeletal imaging, and some feeling for what is going on in the athlete are important factors for optimal management.

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1.1 Introduction

Sports medicine, or even better sports and exercise medicine, is a rather new specialty that deals with the medical care of the exercising individual. Sports medicine not only involves the delivery of medical care to elite and nonelite athletes, but it also includes prescribing exercise to inactive people at risk for or patients who already suffer from chronic disease (http://www.fsem.co.uk/media/4165/sport_and_exercise_medicine_a_fresh_approach.pdf, Matheson et al. 2011).

1.2 Exercise Is Medicine

Strong evidence shows that physical inactivity increases the risk of many adverse health conditions, including major noncommunicable diseases such as coronary heart disease, type 2 diabetes, and breast and colon cancers and shortens life expectancy (Lee et al. 2012). Physical inactivity is the fourth leading cause of death worldwide (Kohl et al. 2012). It has been estimated that physical inactivity causes 6 % of the burden of disease from coronary heart disease, 7 % of type 2 diabetes, 10 % of breast cancer, and 10 % of colon cancer. Inactivity causes 9 % of premature mortality or more than 5.3 million of the 57 million deaths that occurred worldwide in 2008. If inactivity were decreased by 25 %, more than 1.3 million deaths could be averted every year (Lee et al. 2012). Based on these alarming statistics, many countries have started effective campaigns to stimulate people of all ages to achieve a more physically active lifestyle and to participate in sports (Heath et al. 2012).

Sports physicians and other health care workers also have an important role in prescribing exercise to inactive people and chronic patients in order to prevent the increasing morbidity and mortality associated with inactivity (Matheson et al. 2011, 2013; Sallis 2009).

The American College of Sports Medicine (ACSM) recommends – in order to promote and maintain health – that all healthy adults aged 18–65 years need moderate-intensity aerobic (endurance) physical activity for a minimum of 30 min on 5 days each week or vigorous-intensity aerobic physical activity for a minimum of 20 min on 3 days each week (Haskell et al. 2007). Combinations of moderate- and vigorous-intensity activity can be performed to meet this recommendation. Moderate-intensity aerobic activity, which is generally equivalent to a brisk walk and noticeably accelerates the heart rate, can be accumulated toward the 30-min minimum by performing bouts each lasting 10 or more minutes. Vigorous-intensity activity is exemplified by jogging and causes rapid breathing and a substantial increase in heart rate. In addition, every adult should perform activities that maintain or increase muscular strength and endurance a minimum of 2 days each week. Because of the dose-response relation between physical activity and health, persons who wish to further improve their personal fitness, reduce their risk for chronic diseases and disabilities, or prevent unhealthy weight gain may benefit by exceeding the minimum recommended amounts of physical activity.

Increased physical activity and sports participation inevitably lead to a higher number of specific sports- and exercise-related illnesses and musculoskeletal injuries (Hootman et al. 2002; Shephard 2003). Because of these injuries, novice "athletes" might disappointedly drop out their just started exercise program, and more experienced exercisers might have to reduce their active lifestyle drastically. In this way no health benefits can be expected. Establishing a precise diagnosis from the start and initiating a good treatment rehabilitation program leading to complete recovery are very important for all of them, especially since the greatest risk factor to get an injury is a previous injury. Imaging can play an important role in the effective conservative and surgical management of injuries. It is also helpful to give the athlete visual information that an injury is present (e.g., a stress fracture) and convince him/her that (relative) rest is absolutely necessary.

1.3 Imaging in Sports and Exercise Medicine

As in any other branch of medicine, an appropriate diagnosis can only be established after a thorough history and careful physical examination. Often additional functional tests have to be performed by the injured athlete to obtain valuable information on their movement patterns, strength, and coordination. Both intrinsic and extrinsic sports-related factors (Table 1.1), which might have contributed to the injury, should be taken into account when diagnosing a sports injury and especially in formulating an effective individually tailored treatment and rehabilitation program.

Either on the sideline or in the clinic, an important decision the sports medicine physician has to make is whether an injury needs imaging or not. Obviously this is a subjective decision based on clinical experience and diagnostic examination skills. Due to technological advances like the availability of office and/or even sideline-based ultrasound (US), dedicated magnetic resonance imaging (MRI), and hybrid diagnostic imaging combining 3-dimensional reconstruction computer tomography (CT) and nuclear medicine-based imaging techniques, the clinician now has to choose from a variety of diagnostic options. An extensive description of these imaging modalities is beyond the scope of this chapter but can be found in Chaps. 2 and 3. With these newer imaging techniques, clinical judgment when to order specific testing procedures and how to interpret normal and abnormal findings becomes

Table 1.1 Injury factors

Intrinsic factors	Extrinsic factors
Age	Training program
Sex	Sports technique
Body size and composition	Level of competition
Genetics	Equipment
Current health status	Environmental conditions
Malalignment	Psychological factors
Strength and flexibility	Nutrition
Previous injury	Drugs

even more important. According to Coris et al. (2009), some basic ground rules, which follow "good medical practice," can be set (Coris et al. 2009):

1. Imaging should be undertaken only if it is likely to influence patient management.
2. The dose of ionizing radiation to the patient should be considered.
3. Requesting appropriate imaging method requires an understanding of the pathologic process.
4. Plain X-ray should be the first imaging technique, but in more superficial tendon and muscle injuries, ultrasound (US) may be more appropriate.
5. The cost of the examination to the patient and the community should also be considered.

In order to choose the most appropriate diagnostic procedures, good communication between the sports medicine physician and the imaging specialist is very important. The sports medicine physician should provide the radiologist or nuclear imaging specialist with relevant clinical findings but also with sports-specific information and its impact on the musculoskeletal system. Only in this way, the correct imaging technique can be chosen. Ideally the imaging specialist should have a keen interest in sports and the musculoskeletal system. Even more important, especially when dealing with elite athletes, is an understanding of what is going on and what is at stake in/for the athlete. He/she should be aware of the fact that in a competitive athlete even a minor abnormality, without clinical significance in a nonathlete patient, may hamper the training program or readiness to play.

Besides its role in diagnosis and decision-making, imaging techniques can also help to perform certain therapeutic procedures. For example, ultrasound can be used to guide intra-articular and intralesional therapeutic injections. It has been demonstrated that this increases the accuracy of needle placement and improves clinical outcome compared to non-guided procedures (Raza et al. 2003; Sibbitt et al. 2009).

1.4 Imaging in Elite Sports Medicine

In the "curious" and often demanding world of elite sports, the role of sports medicine and imaging seems to be quite different. Although "good medical practice" has to be followed, and the health of the athlete has the highest priority, the focus is on performance enhancement, competition, and return to play as quickly as possible. Therefore sports medicine physicians often request additional and costly imaging more easily, as they often need a more rapid and accurate diagnosis to guide management. Imaging techniques are also readily used to monitor ongoing pathology and to facilitate return-to-play decisions (McCurdie 2012). Support from sports-minded radiology and nuclear medicine imaging specialists is very helpful in these situations.

One should also realize that imaging results might have an impact on the confidence and performance of the athlete. For example, a minor abnormality on an MRI scan without clinical consequences might disturb the psychological state of the athlete if revealed just before the game. On the other hand, a negative scan can help to boost the athlete's confidence to a great performance. There exists a risk for over-imaging because repeated imaging is asked for to find out whether the injury is improving. One should also realize however that there is not always a clear relationship between symptoms and imaging findings, and this should be clearly explained to the athlete.

An unwanted development but sometimes reality in high-performance sports is that athletes themselves (or the coaching staff or managers) demand a particular scan. As a matter of "first seeing than believing," they can only be convinced to train or compete after a scan has been made. Obviously this approach should be discouraged by ways of building up a good relationship with the athlete and staff and by providing them with relevant and understandable information.

In elite sports settings, imaging is also used for screening and pre-participation assessments (McCurdie 2012). Presigning medical assessments are common in professional sports, and imaging techniques are increasingly used to document damage and sequelae from previous injuries or long-term athletic involvement. This information, which not always reflects clinical condition and readiness to play, may, rightly or wrongly, be used to negotiate the terms of a contract.

Conclusion

Physical activity is important in both prevention and treatment of many common diseases. However, sports injuries can pose serious problems to both the recreational exerciser and the (elite) athlete. The use of imaging can be important for the sports physician to establish an initial precise diagnosis and to set up an appropriate treatment intervention and rehabilitation program. Good interdisciplinary communication, sharing of relevant clinical and sports-related information, knowledge which imaging technique is most suitable for musculoskeletal injuries, and last but not least some feeling of what is going on in the athlete's mind will contribute to optimization of injury management in active people.

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Radiologic Imaging Techniques

2

Jan L.M.A. Gielen and P. Van Dyck

Contents

Abstract

Accurate diagnosis with the use of radiological imaging is often required if clinical findings in sports injuries are nonspecific. The preferred imaging modality is multifactorial. Often an optimal imaging pathway is not available. This chapter reviews the general imaging strategies that can be employed to diagnose and grade sports injuries. Radiographs in two orthogonal perpendicular projections

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are generally the first and often the only imaging needed for the evaluation of fractures. In case of clinical suspicion of radiographic occult fracture, MRI is the method of choice. The presence of radiopaque foreign bodies, intra-articular bone fragments, or advanced degenerative joint changes and the results after fixation can be assessed with radiographs.

Major advantages of US are its high spatial resolution for superficial structures, low cost, availability at short notice, ease of examination, short examination times, and lack of radiation exposure. Since approximately 30 % of sports injuries deal with muscle and tendon injuries, ultrasound (US) plays a major role in primary diagnosis of sports traumatology. US palpation, active and passive dynamic US study, and color-power Doppler imaging may be very helpful to the correct diagnosis. In patients with tendinosis, angiogenesis in the tendon may be correlated with clinical symptoms and discriminates early from advanced stages of tendinopathy. Furthermore, US provides image guidance for interventional procedures. For better evaluating deeply located structures, other (cross-sectional) imaging modalities may be required. Other disadvantage of ultrasound includes operator dependency.

CT imaging, by virtue of its excellent multiplanar capability and submillimeter spatial resolution, is a valuable imaging tool for the evaluation of all kinds of sports injuries. It has proved to be an effective method for documenting bone injuries particularly in complex bony structures such as the wrist and pelvis and may often show post-traumatic changes not shown by radiography. It may be helpful for the assessment of comminuted fractures, improving visualization of the fracture's extent and location, shape and position of the fracture fragments, and the condition of articular surfaces. New iterative CT reconstruction algorithms and cone beam computerized tomography (CBCT) techniques are developed to reduce radiation dose with similar or even increased image quality.

The major advantage of CT arthrography (CTA) is the assessment of the cartilage lesions continuous with the articular surface of the cartilage. Limitations of CTA include its invasiveness, possible allergic reaction, use of ionizing radiation, and poor extra-articular soft tissue contrast resolution.

Magnetic resonance imaging is the most complete radiological imaging technique with accurate evaluation of musculoskeletal soft tissue, bone, and joint structures. Its major indication in sports injury is internal derangement of joints, occult bone fractures, stress reaction and fracture of bone, and deeply located muscle and tendon tears. Acute, subacute, and active chronic lesions are demonstrated with high conspicuity due to their increased water content that produces a "light bulb effect" on fat-suppressed sequences with long repetition time (TR); this sequence has become the cornerstone of musculoskeletal imaging.

Equipment and techniques for MRI vary widely; it is generally accepted that high-field-strength magnets provide the highest quality images.

Major indications for MR arthrography (MRA) are labral lesions of the shoulder and hip joint, TFC and intrinsic ligament lesions of the wrist, and grade III osteochondral lesion of the talus.

Abbreviations

CR	Computerized radiography
CT	Computerized tomography
CTA	Computerized tomography with arthrography
DICOM	Digital imaging and communications in medicine
DWI	Diffusion-weighted MR imaging
EFOVS	Extended-field-of-view ultrasonography
e-MRI	Extremity-only small-bore MRI
FAI	Femoroacetabular impingement
FS	Fat suppression
GRE	Gradient echo
LT	Lunotriquetral (intrinsic carpal ligament)
MRA	Magnetic resonance arthrography
MRI	Magnetic resonance imaging
MTJ	Musculotendinous junction
PRP	Platelet-rich plasma injection therapy
SE	Spin echo
SL	Scapholunate (intrinsic carpal ligament)
SNR	Signal-to-noise ratio
SPACE	Sampling perfection with application-optimized contrasts using different flip-angle evolution
STIR	Short-tau inversion recovery
TE	Echo time
TR	Repetition time
TSE	Turbo spin echo

2.1 Introduction

Accurate diagnosis with the use of radiological imaging is often required if clinical findings in sports injuries are nonspecific. Even if symptoms and clinical findings in sports injuries are specific, further imaging investigations may be required for grading purposes to optimize treatment planning (Cook and Purdam 2009).

The preferred imaging modality depends on the diagnostic and grading award balanced against the clinicians' comfort and radiologists' experience with those modalities, the financial costs, and availability and invasiveness of each technique. The optimal imaging pathway is discussed in the specific chapters. Often such a pathway is not available; in these cases, imaging should be tailored to individual cases. This chapter reviews the general imaging strategies that can be employed to diagnose and grade sports injuries. The overall merits of each imaging technique, with its specific advantages and limitations, will be highlighted. The reader will find some overall practical guidelines for the evaluation of sports injuries that, in our opinion, may be useful in daily clinical practice.

2.2 Imaging Modalities

2.2.1 Plain and Computed Radiography and Arthrography

Radiographs in two orthogonal perpendicular projections are generally the first and often the only imaging needed for the evaluation of fractures. Although oblique (¾) views may be helpful, e.g., to demonstrate fractures of the radial head or for detection of bone spurs in anterior and posterior ankle impingement, they are not commonly used in daily clinical practice and have largely been replaced by cross-sectional imaging. In case of clinical suspicion of radiographic occult fracture, it is well known that in ankle distortion about 35 % of the fractures are radiographically occult (Connel et al. 1996). CT is used in complex fractures for complete visualization; MRI is the method of choice for occult fractures and post-traumatic avascular necrosis (Breitenseher 1999) (Fig. 2.1). The lack of soft tissue contrast resolution is a well-recognized limitation of plain radiography; computed radiography (CR) is characterized with improved but still incomplete soft tissue evaluation but has the advantage of its DICOM format with the ease of electronic distribution. When present, soft tissue changes can be used as indirect signs of osseous, articular, and soft tissue pathology. Displacement or blurring of periarticular and intermuscular fat planes in case of acute trauma is related to joint effusion, hemarthrosis, and muscle tear or contusion. Furthermore, the presence of radiopaque foreign bodies, intra-articular bone fragments, or advanced degenerative joint changes can be assessed with radiographs. Stress views may provide indirect evidence of ligament injury. However, recent studies have questioned the value of stress radiographs. For example, in chronic ankle pain, it has been shown that there is significant overlap between stable and unstable ankles, according to the guidelines of the American College of Radiology (ACR 2012). Radiographs are mandatory to confirm the results after internal or external fixation with reduction of dislocations and alignment of displaced fracture fragments, for monitoring the fracture healing with callus formation or detection of soft tissue calcification after severe muscle or ligament trauma (e.g., myositis ossificans and Pellegrini-Stieda disease), and to detect cracks of osteosynthetic material. When complications of the healing process occur, such as loosening, infection, or avascular necrosis, the role of plain radiography may be limited due to its low sensitivity in the early stages, and other techniques, such as scintigraphic imaging and/or MRI, may be useful. For decades, conventional arthrography (after sterile preparation and injection of intra-articular contrast medium) was used for investigating intra-articular pathology. This imaging modality has now largely been replaced by cross-sectional imaging techniques and is only performed as part of CT or MR arthrography.

2.2.2 Ultrasound

Major advantages of US are its high spatial resolution for superficial structures, low cost, availability at short notice, ease of examination, short examination times, and lack of radiation exposure. Since approximately 30 % of sports injuries deal with

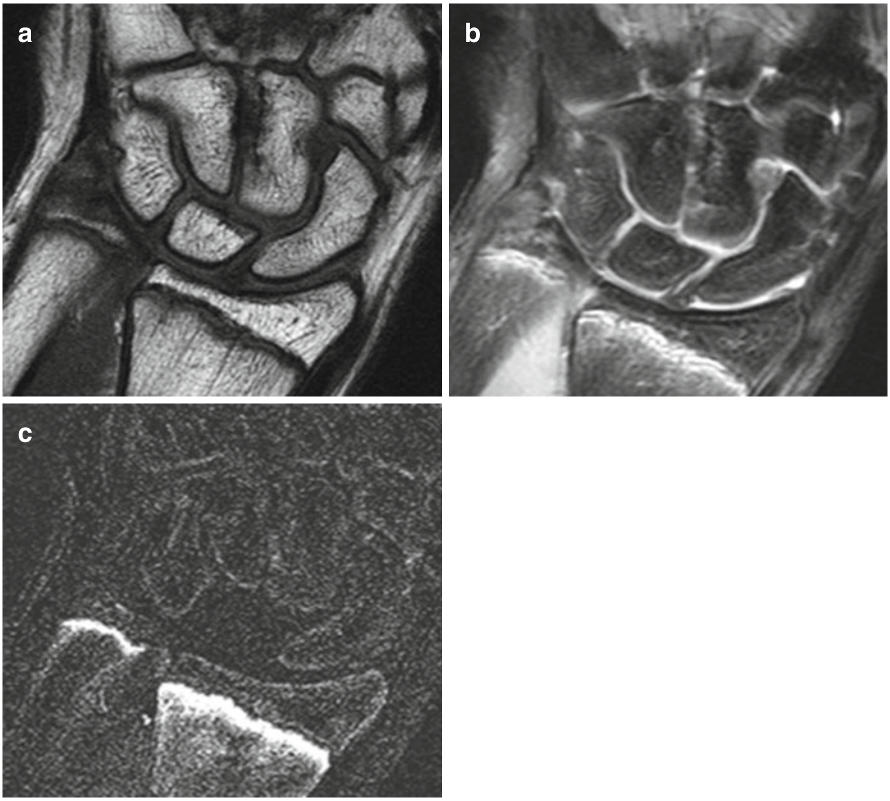

Fig. 2.1 MRI of avascular necrosis of the lunate. Child, 13 years old, with centrally located chronic pain at the dorsal aspect of the wrist. High-level tennis player. No obvious acute trauma. (**a**) Coronal SE T1-WI prior to intravenous gadolinium injection, (**b**) coronal TSE intermediate TE WI, (**c**) Coronal digital subtraction image of T1-WI after and before intravenous gadolinium administration. Normal fat signal on T1-WI (**a**), homogeneous suppression of signal on water-sensitive intermediate TE series, and absence of bone marrow edema at all the carpal bones (**b**). Normal shape of the carpal bones and absence of gadolinium enhancement at the entire lunate (**c**). This case demonstrates the importance of IV gadolinium administration in diagnosis of AVN to prove the lack of vascular perfusion in the absence of other signs of AVN as there are crescent line, demarcation line, and collapse

muscle and tendon injuries, ultrasound (US) plays a major role in sports traumatology, helping the clinician to decide whether the athlete should or should not return to training and competition (Peterson and Renstrom 1986). Due to the excellence of spatial resolution and definition of muscle structure, US keeps its leading edge when dealing with muscle strain and contusion, both in the initial phase for recognition of a lesion, but also for follow-up of lesions and search for healing problems such as fibrosis, muscle cysts, hernias, or myositis ossificans. High-frequency (13 MHz or higher) linear-array probes are used to perform musculoskeletal US examinations; only the deeper-located muscles and tendons are documented at a

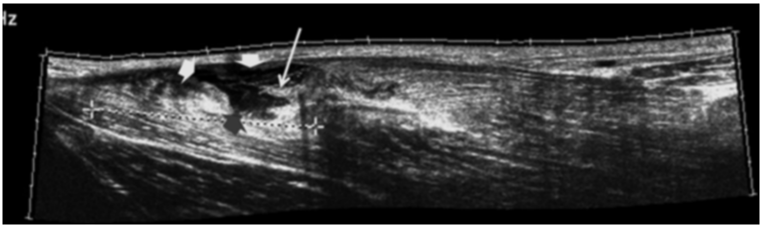

Fig. 2.2 Ultrasound of an adductor longus muscle tear. Longitudinal EFOVS of the proximal half of the right adductor longus in an adult soccer player after sudden snap during ball kicking. Examination performed 2 days after the injury. The EFOVS covers a length of 21 cm including the proximal MTJ and muscle belly of the adductor longus. Disruption of fiber discontinuity with distally retracted tendon (*arrow*) surrounded by a hyporeflective serosanguinous fluid collection with irregular margins (*arrowheads*). The hyporeflective fluid collection accentuates the structural anomaly of the muscle improving lesion conspicuity

lower resolution leading to less sensitivity, e.g., hamstrings muscles and the deep flexor compartment of the lower leg in well-trained sports people with increased muscle mass. The highest accuracy of ultrasound is calculated 24–72 h after the muscle injury; this is related to the easy ultrasound detection of fully developed serosanguinous fluid collections (Fig. 2.2). Because of this drawback, ultrasound evaluation on the sports field is not indicated. Transverse and longitudinal evaluation is mandatory. Lesion detection is most accurate by transverse screening of the involved muscle compartments from origin to insertion. US palpation is a very valuable tool, trying to find the point of maximal tenderness during the examination by a gentle but firm compression of the probe on the skin (Peetrons 2002). Active and passive dynamic US study may be very helpful to the correct diagnosis, e.g., to search for muscle hernia (during muscle contraction), to discriminate grade II (partial) and grade III (complete) muscle or tendon tears, or to evaluate the anterior and lateral snapping hip syndrome (during hip flexion and lateral rotation). To avoid artifacts or pitfalls, comparison with the contralateral side may be necessary. The addition of color-power Doppler imaging to US has allowed for the noninvasive study of blood flow and vascularization within anatomic structures and angiogenesis in lesions (Fig. 2.3). The highest accuracy is reached in the evaluation of angiogenesis in superficial and relaxed structures with gentle probe manipulation. In patients with tendinosis, angiogenesis in the tendon may be correlated with clinical symptoms [Weinberg et al. 1998; Zanetti et al. 2003] and discriminates early (reactive) from advanced (dysrepair or degenerative) stages of tendinopathy (Cook and Purdam 2009). Furthermore, US provides image guidance for interventional procedures such as drainage of fluid collections and cysts (Peetrons 2002), percutaneous tenotomy, and platelet-rich plasma (PRP) injection in chronic tendinopathy. US-guided sclerosis of neovascularity in painful chronic tendinosis has been described as an effective treatment with significant reduction of pain during activity by Öhberg and Alfredson; their accuracy however is until now not reproduced by other centers; in a large RCT only moderate results were obtained with few of the patients cured; the majority still had reduced function and substantial pain after 24

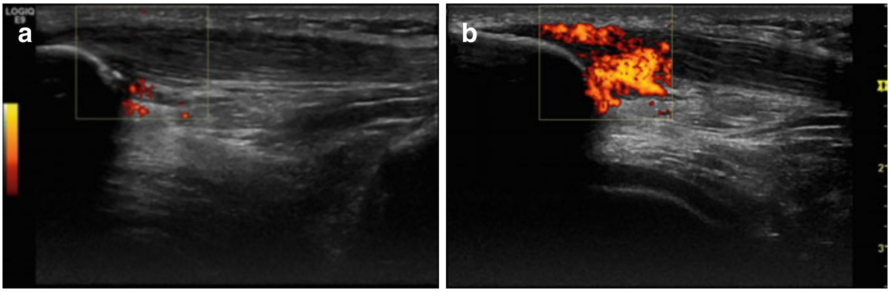

Fig. 2.3 Ultrasound of patellar tendinosis (jumper's knee), advanced stage with angiogenesis. Sagittal US examination in 17-year-old female volleyball player with chronic pain at right the patellar apex. (**a**) Image with stretched quadriceps muscle, (**b**) image with relaxed quadriceps muscle and with gentle probe manipulation. Demonstration of thickening of the patellar tendon at its origin without obvious major structural anomalies and regular lining on the image with stretched quadriceps muscle. (**a**) Demonstrates no angiogenesis and (**b**) demonstrates major angiogenesis at the thickened area of the tendon and at the anterior cranial part of Kager's fat plane

months of follow-up (Öhberg and Alfrendson 2002; Hoksrud et al. 2012). The trade-off for high-frequency, linear, musculoskeletal transducers is their limited depth of penetration and the small, static scan field. This is a disadvantage if the structure to be visualized is large (e.g., large intramuscular hematoma) or deeply located (e.g., hip joint). Extended-field-of-view sonography (EFOVS) overcomes the disadvantage of a small static field by generating a panoramic image. With this technique, during longitudinal probe translation over the skin of the patient, sequential registration of images along a broad examination region and their subsequent combination into an image of larger dimension and format is obtained (Weng et al. 1997). EFOVS does not add much in diagnosis but is, however, easily interpretable by the novice and improves cross-specialty communication. For better evaluating deeply located structures, such as the hip joint, hamstrings, and deep posterior lower leg compartment in an obese or well-trained patient, other (cross-sectional) imaging modalities are often required. Other disadvantages of ultrasound include operator dependency, selective and often incomprehensible documentation, and the inability to penetrate osseous structures. Despite the latter, ultrasound is sensitive to rule out cortical fractures of superficially located bones and is more accurate to detect rib fractures compared to radiographs (Evans and Harris 2012).

2.2.3 Multidetector Spiral CT Scan

2.2.3.1 Technique

CT imaging, by virtue of its excellent multiplanar capability and submillimeter spatial resolution due to the development of the spiral acquisition mode and current multidetector row technology, is a valuable imaging tool for the evaluation of all kinds of sports injuries (Berland and Smith 1998). Very fast image acquisition time of large volumes with submillimeter section thickness has become the norm. It has proved to be an effective method for documenting injuries particularly in complex bony structures such as the wrist and pelvis and may often show post-traumatic changes not shown by radiography. For most musculoskeletal studies, slice thickness is 0.75 mm, reconstructed to 1 mm images with increment of 0.5 mm. The images should be assessed using both bone and soft tissue window settings. From the three-dimensional data set, images can be reformatted in other planes (2-D technique) and be used for volume rendering (3-D technique). The 2-D reformatting of sagittal and coronal images from axial images can highlight longitudinal fracture lines and can make it easier to evaluate horizontal interfaces, such as the acetabular roof. The 3-D rendering allows different displays of the volume data. Surface rendering by thresholding, which, in contrast to volume rendering, incorporates only a portion of the data into the 3-D image, is the most widely used technique. By adding a virtual light source, a shaded surface display (SSD) can be achieved, which enhances the 3-D understanding of the image. However, it may provide an inadequate display of undisplaced and intra-articular fragments, and, in comparison to axial imaging, surface rendering does not increase the detection rate of fractures and should only be supplementary to plain films and axial CT scan in the evaluation of comminuted fractures. Volume rendering, incorporating all the data into the 3-D image, requires more computer manipulation. All reconstruction methods offer a more effective display of complex anatomic and pathologic structures. It may be helpful for the assessment of comminuted fractures, improving visualization of the fracture's extent and location, shape and position of the fracture fragments, and the condition of articular surfaces (Bohndorf et al. 2001). New iterative CT reconstruction algorithms and cone beam computerized tomography (CBCT) techniques are developed to reduce radiation dose with similar or even increased image quality (see Sect. 2.3).

2.2.3.2 CT Arthrography

Intra-articular injection of iodinated contrast material mixed with 1 ml of a 0.1 % solution of epinephrine is performed under fluoroscopic or ultrasonographic observation (Newberg et al. 1985; Jacobson et al. 2012; Berkoff et al. 2012). The volume of contrast medium injected depends on which joint is studied: shoulder, 10–15 ml; wrist, 5 ml; hip, 10 ml; knee, 20 ml; and ankle, 6–12 ml. After injection of contrast material, patients are asked to perform full-range mobilization of the joint with weight bearing and walking a few steps if a joint of the lower limb is involved. Anteroposterior, lateral, and oblique views are routinely obtained to image the entire articular cavity. Subsequently, multidetector CT is performed. The major advantage of CT arthrography (CTA) for the assessment of the cartilage is the excellent conspicuity of focal morphologic cartilage lesions continuous with the articular surface of the cartilage that results from the high spatial resolution and the high attenuation difference between the cartilage substance and the joint contrast filling the lesion (Fig. 2.4). Vande Berg et al. (2002) found, in a study with spiral CTA of cadaver knees, a better correlation for grading articular surfaces between macroscopic examination and spiral CTA than with MR imaging. Other potential advantages of spiral CTA with respect to MR imaging are the short examination time, the availability at

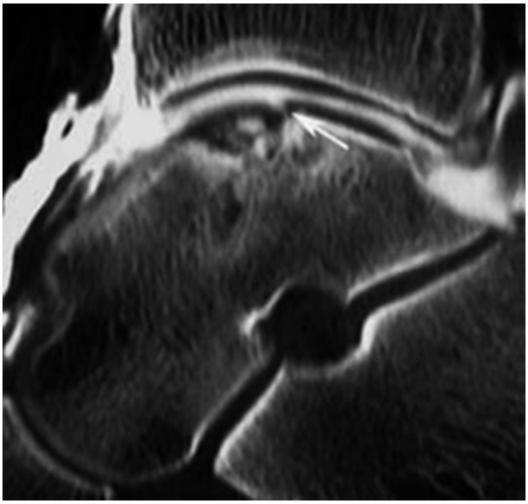

Fig. 2.4 CT arthrography of the ankle. 24-year-old soccer player with chronic ankle pain and history of repetitive ankle distortion. Radiographs demonstrate osteochondral lesion of the talus with in situ fragment (grade 3). CTA is performed to discriminate adherence of the fragment. Sagittal multiplanar reconstruction demonstrates the osteochondral defect with centrally located bone fragment; posterior to the fragment contrainfiltration is documented (*arrow*) that is not surrounding the fragment

short notice (short waiting list), and the low sensitivity for and limited degree of imaging artifacts related to the presence of microscopic metallic debris which may hinder MR imaging studies. Limitations of CTA include its invasiveness, possible allergic reaction, use of ionizing radiation, and poor extra-articular soft tissue contrast resolution. Another major limitation of CTA imaging of the cartilage is its complete insensitivity to alterations of the deep layers of the cartilage.

2.2.4 Magnetic Resonance Imaging

Magnetic resonance imaging is the most complete radiological imaging technique with accurate evaluation of musculoskeletal soft tissues, bony structures, and joints. Its major indication in sports injury is internal derangement of joints, occult bone fractures, stress reaction and fracture of the bone, and deeply located muscle and tendon tears. Acute, subacute, and active chronic lesions are demonstrated with high conspicuity due to their increased water content that produces a "light bulb effect" on fat-suppressed sequences with long repetition time (TR); this sequence has become the cornerstone of musculoskeletal imaging. This light bulb is present in similar areas with high tracer uptake in bone scintigraphy and PET imaging. Specific MRI applications in the musculoskeletal system are addressed in the specific chapters.

2.2.4.1 Technique

Equipment and techniques for MRI vary widely, and although it is generally accepted that high-field-strength magnets provide the highest quality images, there has been considerable advancement in the technology of low-field-strength systems over the past few years, greatly improving their image quality. Open-bore gantry design is available in low- and midfield MRI and has specific musculoskeletal advantages related to off-center positioning and patient comfort with less claustrophobic renouncement. Absence of claustrophobia and low cost are the major advantages of low-cost extremity small-bore design (e-MRI); this is available at low field up to 1.5 T and used for investigation of the peripheral joints only (wrist, elbow, foot and ankle, and knee). Although appropriate selection of imaging planes will depend on the location and desired coverage of the anatomical region to be examined and the pathology to be expected, a complete MR examination of musculoskeletal regions requires that images be obtained or reconstructed in the axial, coronal, and sagittal planes. Of utmost importance is to respect the anatomical orthogonal planes since, with excessive rotation of a limb, inappropriate positioning of imaging planes may result in images which are difficult to interpret. Oblique planes may also be useful, e.g., in the hip in FAI (paracoronal and parasagittal images) and wrist in LT ligament disorders (paraxial images). The number of pulse sequences and combinations ("hybrid techniques") is almost infinitive: in musculoskeletal MR, the most commonly used sequences include conventional spin echo (SE) for T1 weighting, turbo SE (TSE) sequences for intermediate or T2 weighting, and gradient echo (GRE) sequences. SE T1-WI is used for anatomic detail and as an adjunct in the evaluation of the osseous structures. TSE sequence has replaced conventional SE for T2 weighting (due to its relatively long acquisition times). However, because of image blurring, TSE sequences are not recommended for proton density imaging. Blurring can be reduced by increasing TE, decreasing the inter-echo time and echo train length (ETL), and increasing matrix. At higher field strengths (3 T), volume sequences are available with multiplanar reconstruction capacity at high resolution (0.5 mm) in all imaging planes. 3D-SPACE (sampling perfection with application-optimized contrasts using different flip-angle evolution) is recently pushing 2D TSE T2 or intermediate TE to the background (Fig. 2.5). TSE sequences are less susceptible to field inhomogeneity than SE sequences. Therefore, when metallic artifacts are present, such as in postsurgical patients, TSE sequences are preferred over SE and GRE. GRE sequences and TSE sequences with intermediate TE are used for the evaluation of articular cartilage. GRE sequences are used for dynamic contrast-enhanced imaging. They are also used in a limited number of T2 protocols (glenoid labrum, meniscus of the knee). When using short TE in T1-weighted or PD images, one should take the magic angle phenomenon into account, a source of false-positive MR findings. Furthermore, a pulse sequence is always a compromise between acquisition time, contrast, detail, or signal-to-noise ratio (SNR). SNR is highest in TSE and decreases respectively in SE and GRE sequences. Concerning the different fat-suppression (FS) techniques, in our institution, we prefer the spectral FS technique because of its better SNR and spatial resolution compared to inversion recovery fat-suppression techniques (Fleckenstein et al. 1991). Both T2-WI with (spectral) FS and STIR images are most sensitive to bone marrow and soft tissue edema or joint effusion. For good detection of fluid with preservation of anatomical detail and good differentiation between joint fluid and hyaline cartilage, we include an FS TSE intermediate-weighted sequence (TR/TE = 75/30–35 msec) in at least one imaging plane in our standard protocols. Cartilage-specific sequences

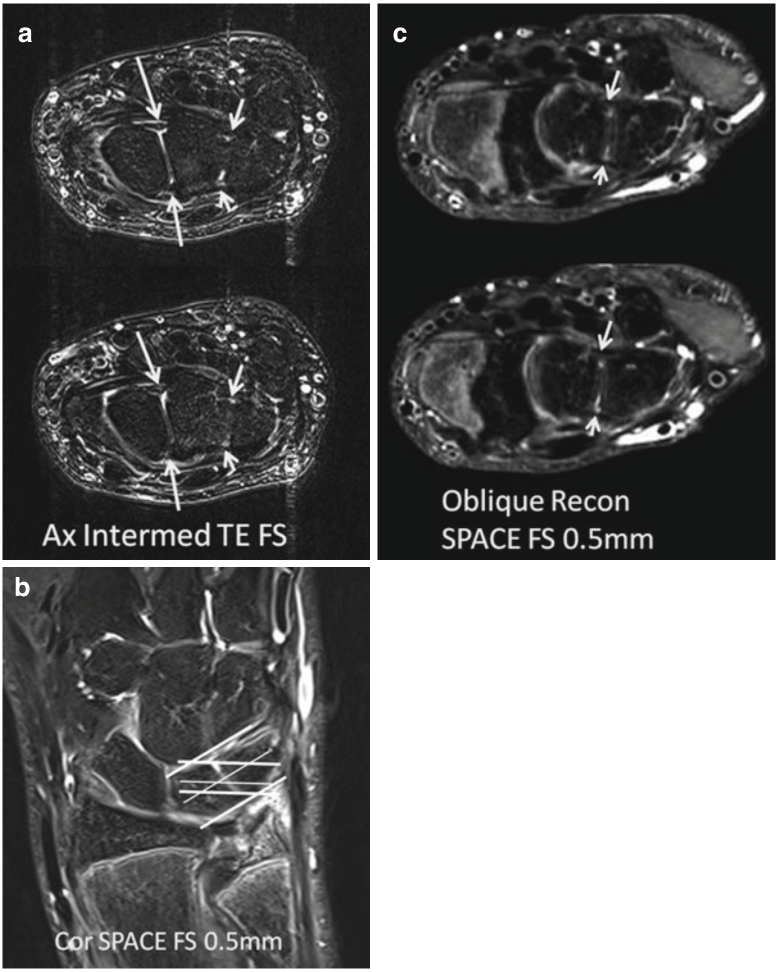

Fig. 2.5 SPACE volume sequence of the wrist in tennis player with chronic ulnar-sided wrist pain. Tennis player, male, 17 years old, with chronic ulnar-sided right wrist pain. (**a**) Axial TSE intermediate TE FS sequence of the right wrist. Easy demonstration of the intrinsic SL ligament at its dorsal and palmar components (*arrows*) but difficult demonstration of the LT ligament (*short arrows*). (**b**) Coronal volume TSE intermediary TE FS (SPACE) demonstrating the axial plane of A and the oblique axial reconstruction plane of (**c**). Easy demonstration of LT ligament (*short arrows*) (**c**). Oblique axial multiplanar reconstructions of series B perpendicular to the lunotriquetral joint space

have been developed (Disler et al. 2000; Ulbrich et al. 2013). The musculoskeletal system, especially in the extremities, is not influenced by motion, and as a consequence, motion artifacts are rare. Infolding artifacts can be avoided by selecting an appropriate imaging matrix, saturating anatomical areas outside the region of interest, and off-center imaging. Artifacts due to distortions of the local magnetic field are attributable to ferromagnetic and, to a lesser degree, nonferromagnetic orthopedic devices. The use of surface multichannel coils will improve the SNR; smaller slice thickness and larger matrices are essential for soft tissue imaging. The choice of small "field of view" (FOV) without changing the matrix size will increase the spatial resolution. Sometimes, imaging of the contralateral side may be useful, requiring a larger FOV and the use of a body coil. Contrast-enhanced MR studies lead to a prolonged examination time and high costs, and therefore, the use of intravenous contrast agents is not indicated when evaluating a sports lesion. It should be reserved for cases in which the results would influence patient care (Kransdorf and Murphey 2000). Application of intravenous gadolinium is indicated when dealing with a tumoral or pseudotumoral mass to detect neovascularization and intralesional necrosis (which is a major parameter for malignancy), in cases of inflammation or as part of indirect arthrography. For detection of subtle areas of contrast enhancement, we use subtraction images (SE T1-WI with FS after minus SE T1-WI with FS before gadolinium) (static MR imaging). After IV administration of gadolinium, STIR-type sequences should not be used, since not only fat but also enhancing tissue will be shown with a reduced signal intensity.

MR arthrography (MRA) with direct, 3 % diluted gadolinium DTPA, injection in the joint or indirect technique with intravenous administration and joint mobilization is used in specific joints and specific indications. Major indications for MRA are labral lesions of the shoulder and hip joint, TFC and intrinsic ligament lesions of the wrist, and grade III osteochondral lesion of the talus. More detailed description of the technique and indications is available in the specific topographic chapter of the book (Chaps. 17, 26, and 35).

Diffusion-weighted (DWI) MR sequences detect Brownian motion in areas with increased water content and allow mapping of the diffusion process of water in tissues. Water molecule diffusion patterns can therefore reveal microscopic details about tissue architecture, either normal or in a diseased state. In areas with restricted diffusion, increased T2 signal is present; in areas with increased water content without diffusion restriction, a low SI is detected. DWI is of practical use in sports-related brain concussion.

Recently, diffusion tensor imaging (DTI) has been used to study muscle architecture and structure. In the future, DTI may become a useful tool for monitoring subtle changes in the skeletal muscle, which may be a consequence of age, atrophy, or disease (Galban et al. 2004). Furthermore, important information about muscle biomechanics, muscle energetics, and joint function may be obtained with unique MRI contrast such as T2 mapping, spectroscopy, blood-oxygenation-level-dependent (BOLD) imaging, and molecular imaging. These new techniques hold the promise for a more complete and functional examination of the musculoskeletal system (Gold 2003). The clinical MR imaging protocol will be greatly influenced by local preferences, time constraints, and MR system available (field strength, local coil). For an in-depth discussion of the different MR imaging protocols, the reader is referred to subsequent chapters. MRI has the disadvantage of not always being well accepted by patients, of being incompatible with dynamic maneuvers, and of not always being possible in emergency conditions. Furthermore, it provides the evaluation of an entire anatomical area – bone structures included – but is only good for the study of a limited part of the skeleton. This is in contrast to scintigraphy, with which the whole skeleton can be evaluated at once. Otherwise, MRI helps to elucidate the true nature of highly nonspecific hotspots on scintigraphy. For a discussion of the value of nuclear medicine techniques used in sports lesions, we refer to the specific chapters.

2.3 Effective Radiation Dose Related to Radiography and CT Compared with Nuclear Imaging

A wide range of radiation absorbed doses is delivered to patients by various diagnostic imaging modalities that use ionizing radiation (radiography, CT, nuclear medicine). The potential for radiation-induced injuries exists. Quantitative proof of risks for radiation-induced cancer in humans can be derived from the life span study at organ cumulative doses above approximately 100 mSv, although significant effects can only be observed above 200 mSv (Little 2003; Heidenreich et al. 1997). The effective radiation dose is regarded as a good indicator for the possible biological effect of radiation; it is a measured unity to compare the stochastic risk of a nonuniform exposure of ionizing radiation with a uniform exposure to the body. Its actual SI unit of measurement is Sv (Sievert); the old unity was rem (radiation equivalent in men), 1 Sv = 100 rem (McCollough and Schueler 2000). The natural background radiation is the natural radiation; it varies by geographic location; the mean level of NBR is 2.5–3 mSv/year. BERT (background equivalent radiation time) is the unit of measurement to compare the effective radiation dose of imaging procedures with the natural background radiation of 1-year time (3 mSv). For example, one thorax radiography is equivalent to 1/52 BERT; 1 CT abdomen is equivalent to 3.3 years BERT. Digital radiography and iterative CT reconstruction or cone beam CT imply less effective radiation dose compared to conventional radiography and classic CT reconstruction, respectively. At the knee multislice computed tomography (MSCT) with iterative reconstruction effective radiation doses range between 0.27 and 0.48 mSv; for CBCT the effective radiation dose was 0.12 mSv, compared to digital radiography of the knee in lateral view of 0.018 mSv and 0.012 mSv for AP view (Koivisto et al. 2013). Table 2.1 gives an overview of typical effective radiation doses in musculoskeletal radiographs, CT, and nuclear imaging techniques (Parry et al. 1999). A series of ten PET or four PET-CT examinations on older equipment may imply a radiation dose with increased cancer risk! Radiologists and specialists in nuclear medicine should be aware of methods by which radiation dose may be minimized with regard to using the lowest possible dose to achieve a diagnosis. Medical alternatives should be taken in consideration for CT and nuclear imaging techniques such as MRI of the whole body. We have to weigh the acute risk for the patient on the one hand and on the other hand the overall low risk of radiation exposure.

Table 2.1 Typical effective radiation doses in adult diagnostic radiological imaging and nuclear medicine

Imaging modality	Body part	Effective dose mSv	BERT equivalent in weeks
Radiography	Skull	0.4–0.7	7–12
	Cervical spine	0.2–0.4	3–6
	Lumbar spine	0.5–1.5	9–26
	Limb	<0.1	<2
Digital radiography	Knee	0.012–0.018	0.07–0.1 (11–17 h BERT)
	Hand	0.001	0.02 (3 h BERT)
MSCT conventional	Head	1–2	17–35
	Pelvis	3–4	52–69
	Cervical spine	2–4	35–69
	Lumbar spine	3–5	52–87
MSCT iterative reconstruction	Knee	0.27–0.48	1.5–2.5
CBCT	Knee	0.12	0.7
Bone scintigraphy SPECT 99 m Tc-diphosphonates[a]		3	52 (1-year BERT)
PET[b]		4	69 (1.5-year BERT)
PET/CT		5.5	96 (2-year BERT)
Cancer risk threshold		100	1,733 (33-year BERT)

[a] ^{99m}Tc-diphosphonates: 0.0057 mSv/MBq. According to EANM bone scintigraphy requirements 2003 and NVNG requirements 2007, adult dose is 500 MBq and the effective dose is 2.85 mSv. With SPECT-CT additional dose of 0.5-1.0 mSv (low-dose CT)

[b] ^{18}F-FDG: 0.019 mSv/MBq. According to EANM requirements 2003 and NVNG requirements 2007, 3 MBq/kg, a person with weight 70 kg = 210 MBq, effective dose is 3.99 mSv. With low-dose CT additional dose of 1.5 mSv

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Nuclear Medicine Imaging Techniques

3

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Contents

Abstract

Nuclear medicine is a rapidly developing field which focuses on the imaging of physiological processes and the evaluation of treatment of specific diseases. It involves the use of radiopharmaceuticals for both purposes. Different radiopharmaceuticals have different kinetics and can therefore be used to image processes in the body, the function of an organ or the presence of a specific cellular target. In sports medicine, bone scintigraphy and leukocyte scintigraphy play important roles. Radiopharmaceuticals in bone scintigraphy are diphosphonate complexes

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which are absorbed onto the hydroxyapatite crystal of newly formed bone and therefore represent osteoblast activity. When combined with the radionuclide technetium-99 m (^{99m}Tc), it is very suitable for imaging. Bone scintigraphy, especially combined with additional single-photon emission computed tomography and conventional computed tomography (SPECT/CT), can, e.g. discriminate a (stress) fracture from osteoarthritis. In leukocyte scintigraphy, autologous white blood cells are labelled with ^{99m}Tc and reinjected in the patient. In case of an active infection, the leukocytes accumulate at the location within 24 h after administration. The combination of three-phase bone scintigraphy with leukocyte scintigraphy has the best test characteristics for identifying infectious processes in the peripheral skeleton. The positron emission tomography (PET) radiopharmaceutical fluor-18-labelled fluorodeoxyglucose (^{18}F-FDG) is indicated for infectious processes of the axial skeleton (osteomyelitis and spondylodiscitis). Its uptake mechanism is distinct from that of diphosphonate complexes; it represents the glycolytic activity of cells. ^{18}F sodium fluoride is another PET tracer to image the skeleton. However, at the moment it has no role in sports medicine.

3.1 Introduction

Nuclear medicine is a rapidly developing field which focuses on imaging of physiological processes and the evaluation of treatment of specific diseases. It involves the use of radiopharmaceuticals for both purposes. Different radiopharmaceuticals have different kinetics and can therefore be used to image processes within the body, the function of a specific organ or the presence of a specific cellular target (receptor, enzyme, antibody, etc.). Radiopharmaceuticals are usually administered intravenously. So, images are made from radiation which is emitted from within the patient. These characteristics form the main distinction with radiology, which mainly focuses on tissue anatomy by using external radiation sources.

This book chapter discusses the basic principles of nuclear medicine and the existing camera types. Special focus will be given to the different imaging techniques which are generally available to image sports injuries.

3.2 Principles of Nuclear Medicine

3.2.1 Basics of Nuclear Medicine

In nuclear medicine radiopharmaceuticals are used to image physiological process in the body. Radiopharmaceuticals consist of two compounds: a radioactive element (radionuclide) attached to a chemical compound or pharmaceutical (drug, antibody, etc.). A radionuclide is an unstable atom. To understand the basics of nuclear medicine, knowledge of basic physics is important.

An atom (or nuclide) consists of a nucleus and orbiting electrons. The nucleus is composed of positively charged protons and neutrons (which have no charge). The number of protons within the nucleus of an atom is called the atomic number (Z).

In an electrically neutral atom, the number of protons equals the number of electrons. Each element has a unique atomic number. So, the chemical symbol of each element is synonymous with the atomic number. The number of neutrons in a nucleus is denoted by N. The atomic mass number (A) is the summation of protons and neutrons in a nucleus: $A = Z + N$.

Nuclides with similar characteristics can be grouped into nuclear families. Isotopes are nuclides with the same number of protons (thus, atomic number Z) and therefore nuclides of the same element.

Most nuclei that are present in nature are stable. However, some are not stable and transform themselves to form stable configurations. This transformation can result in emission of either particles or energy (γ-photons) from the nuclei. This transformation, which is spontaneous and occurs at random, is called radioactive decay. So, any nuclide that is unstable is radioactive and is therefore called a radionuclide. The rate at which the atoms decay is measured in disintegrations per second or in Becquerel (Bq). One disintegration per second equals 1 Bq.

Radionuclides are abundant in nature, but can also be produced artificially. Radionuclides that are present in nature are long-living radionuclides and are not suitable for imaging. All of the radionuclides in nuclear medicine are produced by means of bombarding stable nuclei with high-energy particles in a cyclotron (Fig. 3.1), linear accelerator or nuclear reactor.

Fig. 3.1 Image of a cyclotron, a particle accelerator in which charged particles accelerate from the centre outward, along a spiral path. These particles are held within an exact course by static magnetic fields and accelerated by rapidly alternating voltage. When the particles have developed the desired kinetic energy, they hit a target. This creates secondary particles (e.g. fluorine-18), which are guided outside the cyclotron and into instruments for radiopharmaceutical production

3.2.1.1 Decay Processes

There are several types of nuclear decay processes. Two of those are important for imaging purposes in sports medicine. The first one is called 'metastable-state transitions'. A metastable state is an excited state of the nucleus that exists for a measurable lifetime. The atom in metastable state is the same as the atom in ground state, since they have the same Z and N. The only difference is the energy state. The decay of a metastable state towards the ground state occurs through de-excitation by means of γ-emission. An example is the decay of molybdenum-99 (^{99}Mo) through technetium-99 m (^{99m}Tc) towards ^{99}Tc. The prefix 'm' indicates the metastable state. ^{99m}Tc decays by emitting a γ-ray with a characteristic energy of 140 kilo-electronvolt (keV). ^{99}Mo, on its turn, is a radionuclide which is produced by neutron bombardment of a target containing uranium-235. It disintegrates by emitting an electron (β^-). ^{99}Mo is commercially available in technetium-99 m generators, which is used to extract ^{99m}Tc in an on-site setting. Every nuclear medicine department has access to such a generator.

The second type of decay important in sports medicine is 'positron decay'. In this decay process a positron is emitted, because of an excess of protons in the unstable nuclide. The decay process can be described by the conversion of a proton into a neutron, with the emission of a positron with a certain amount of kinetic energy. A positron (β^+) is a positively charged electron. A positron cannot exist at rest in nature. As soon as it loses its kinetic energy, it immediately combines with an electron and undergoes a reaction called annihilation. The masses of the two particles are completely converted into energy: two annihilation γ-ray photons, each with energy of 511 keV, which leave their production site opposite to each other (Fig. 3.2). This is the basics of positron emission tomography (PET). The most important example of a positron emitting radionuclide is fluoride-18 (^{18}F).

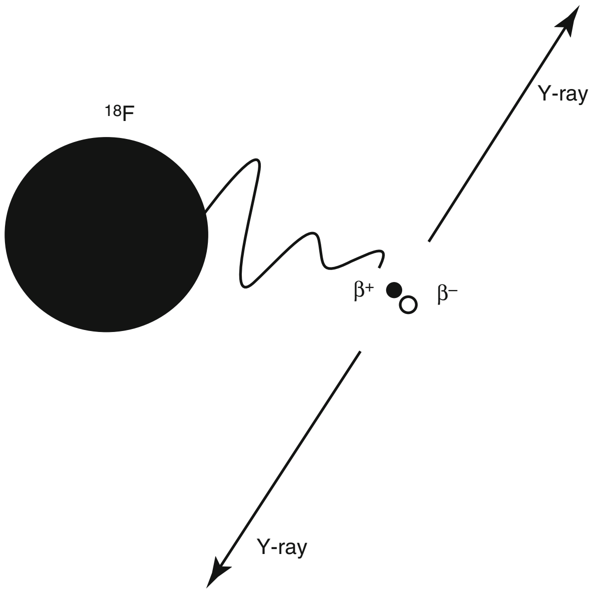

Fig. 3.2 Principle of annihilation. The radionuclide ^{18}F emits a positron (β^+), which finds an electron (β^-) at the end of its course. Both particles annihilate and two γ-rays having 511 keV of energy are produced, 180° apart

3.2.1.2 Physical Half-Life

As mentioned before, the decay of each individual radionuclide is a random and spontaneous process. However, in a large group of the same radionuclides, the decay is rather constant. In fact, each radionuclide has its uniquely defined decay constant (λ). A term which is more commonly used for defining decay is 'physical half-life' ($T_{1/2}$). This is the time required for one-half of a group of radionuclides to decay. The half-lives of the most important radionuclides in sports medicine are 6.01 h for ^{99m}Tc and 1.83 h for ^{18}F.

3.2.2 Camera Systems

Radiopharmaceuticals are usually administered intravenously. Therefore, the patient is the source of radioactivity. The cameras that are used in nuclear medicine to visualize the radiopharmaceuticals are the gamma camera and the PET camera. The detection of γ-rays emitted from the patient and transforming it into an image is the main principle of the camera systems used in nuclear medicine.

3.2.2.1 Gamma Camera

A γ-camera (or Anger scintillation cameras, named after its inventor) consists of the following components: a collimator, a scintillation crystal, a light guide, photomultiplier tubes and a positioning and energy discrimination system. The individual components are discussed in this section.

A collimator is a thick sheet of lead with multiple holes. The individual holes guide the individual γ-ray photons towards the scintillation crystal. Photons which do not travel in the right direction are absorbed in the septa between the holes. Different types of collimators are available, depending on the energy level of the emitted γ-rays from the radionuclide. For γ-ray photons of ^{99m}Tc, the parallel hole collimator is the collimator of choice. Only those photons which pass the collimator in a perpendicular course are transferred. Sometimes a pinhole collimator is used, especially for imaging small structures or organs.

After passing through the collimator holes, the γ-ray photons encounter the scintillation crystal. The individual photons are absorbed in the crystal (usually sodium iodide (NaI)) and converted into a small flash of light. As the energy of the photon increases, the flash of light becomes brighter. This flash of light is transferred through a silicon light guide to minimize the loss of intensity.

Next, the light reaches the photomultiplier tubes (PMTs). In fact, one flash of light is detected by multiple PMTs. The light interacts with photocathodes and is transformed into a photoelectron. This signal is amplified by electrodes or dynodes at increasing voltages in the PMTs, but also in external electronic preamplifiers. These signals are combined in a positioning system, which gives each signal from the individual PMTs different weights to derive the positioning information of γ-ray photons in x- and y-directions.

Finally, the energy pulse is examined (z-direction), to ensure that only photons falling within the photopeak are accepted. Usually, the same pulse as for positioning is used.

The technique as described above forms the basis of conventional planar nuclear medicine images. However, it has many limitations. Image quality is rather poor, due to low contrast, limited spatial resolution and poor statistics of detected γ-ray photons. In the last decennia, the image quality has been improved by the introduction of high-resolution collimators. At this moment, the spatial resolution of the gamma camera is around 8 mm.

3.2.2.2 Single-Photon Emission Computed Tomography (SPECT)

Image contrast of conventional planar imaging is rather low due to the presence of overlying structures that interfere with the region of interest. The effect of this superposition can be overcome by collecting images from different angles around the patient, thereby creating a 3D image. Dedicated gamma cameras have the opportunity to use this technique, called single-photon emission computed tomography (SPECT), to improve the sensitivity. This collection of images can be reconstructed into different slices and visualized in transverse, sagittal and coronal views. These tomographic images have higher contrast, because of the elimination of overlying activity.

Initially SPECT was performed with a single-head gamma camera system, rotating in a 360° orbit. This was a time-consuming method, not always well tolerated by patients. Nowadays, dedicated gamma cameras are supplied with a dual-head or (in less extant) triple-head configuration, thereby making SPECT possible in approximately 20 min.

3.2.2.3 Positron Emission Tomography (PET) Camera

Positron emission tomography (PET) is a unique imaging tool to visualize various physiological processes in the body. As mentioned in the section on decay processes (Sect. 3.2.1.1), positrons cannot exist freely. At the end of its kinetic energy (or at the end of its range), a positron meets his antimatter and annihilates into two 511 keV γ-ray photons, each in opposite directions. The detection of both photons is needed to determine the location of the annihilation in the field of interest (e.g. the thorax). Both these two photons have to be detected within a certain time window, to consider these two as one pair from the same annihilation process. A ring-shaped detector system is needed for this method of photon detection. Until recently, this time window had a predefined value. However, new developments in software lead to a correction method for the time a photon needs to travel from its origin to the detector, the so-called 'time of flight', which has advantages for spatial resolution. This, for example, makes PET systems different form SPECT systems.

A second difference from SPECT is that PET does not need the use of a collimator. Therefore, PET is able to provide images with better spatial resolution (approximately 4 mm) than planar images and SPECT (both approximately 8 mm). Third, the scintillation crystal in PET scanners consists of lutetium oxyorthosilicate (LSO) instead of NaI, which has much greater efficiency in detecting high-energy γ-rays (Melcher 2000).

Another difference between PET and SPECT is the correction for attenuation, i.e. correction for decrease in photon energy due to absorption in the body. In stand-alone PET systems, attenuation correction occurs with a transmission scan of a positron-emitting radionuclide (usually germanium-68 (^{68}Ge)) which travels along the ring system.

Originally, PET was introduced for visualization of metabolic processes in the brain. However, nowadays it is used heavily in clinical oncology (primary tumour and metastases), cardiology (myocardial perfusion) and infection detection. In sports medicine, PET can play a role in detecting metabolic activity at the site of fractures, infections, joint problems, enthesopathies and stress-related problems, secondary to sports activity.

3.2.2.4 Hybrid Systems

Developments in both soft- and hardware led to the implementation of hybrid systems, combining SPECT and PET with multi-detector computed tomography (CT). In these SPECT/CT (Fig. 3.3) and PET/CT cameras (Fig. 3.4), SPECT or PET and CT are performed in an immediate sequential setting, without changing the position of the patient. This co-registration provides physiological information, which can be perfectly correlated with anatomical information.

An additional advantage of these systems is that CT can also be used for attenuation correction. Therefore, the need of an additional ^{68}Ge source has become obsolete in these hybrid camera systems. This leads to a more exact correction (based on Hounsfield units of different anatomic structures) and scanning time reduction. Furthermore, costs are reduced (one imaging modality), and the one-stop-shop principle (one scan instead of two separate scans) reduces waiting time for the patient.

Fig. 3.3 Hybrid camera system, combining single-photon emission computed tomography with conventional computed tomography (SPECT/CT). These camera systems are at present the state of the art. They can be used for several nuclear medicine techniques. In sports medicine, they can be used for bone and leukocyte scintigraphy. The two opposing heads in the centre of the image are the gamma cameras, making this a dual-head system. The CT is incorporated in the gantry, to which the camera heads are attached (Courtesy of Siemens Medical Systems)

Fig. 3.4 Hybrid camera system, combining positron emission tomography with conventional computed tomography (PET/CT). These camera systems are at present the state of the art, as well. In sports medicine, they can be used for fluorine-18 (^{18}F)-labelled fluorodeoxyglucose PET and ^{18}F sodium fluoride PET (Image courtesy: Jan Pruim)

Very recently, hybrid camera systems in which PET is combined with magnetic resonance imaging (PET/MRI) were introduced, especially for oncologic and cardiologic indications (Drzezga et al. 2012; Nekolla et al. 2009). In these PET/MRI systems, the different modalities can be used in a simultaneous setting, instead of a sequential matter. Furthermore, the attenuation correction is different in MRI compared to CT. The value of these PET/MRI systems in sports medicine is not yet determined.

3.3 Bringing Nuclear Medicine and Sports Medicine Together

Imaging in nuclear medicine depends on both the radionuclide and the chemical or pharmaceutical compound that is used in the administered radiopharmaceutical. In fact, the non-radioactive compound directs the radionuclide to the desired target. The choice of radiopharmaceutical most suitable for the individual patient depends on the complaints of the patient, the findings on physical and laboratory examination and the question and differential diagnosis the referring clinician has. In conventional nuclear medicine and SPECT, ^{99m}Tc is the most common radionuclide used for labelling. In PET, ^{18}F is most commonly used.

This section discusses the use of different radiopharmaceuticals in nuclear medicine imaging in sports injuries. Also, the radiation dose of these different radiopharmaceuticals is discussed.

3.4 SPECT Techniques

3.4.1 Bone Scintigraphy

Bone scintigraphy is a widely available and well-established modality within nuclear medicine. It is one of the oldest techniques within this field of imaging, with a clinical experience for almost 50 years. It still remains the cornerstone of modern nuclear medicine practice. Its sensitivity is very high; however, its specificity is rather limited.

Amongst the early radionuclides were phosphorous-32, strontium-85 (^{85}Sr), ^{87m}Sr and ^{18}F. Despite the fact that ^{18}F is superior to ^{85}Sr, it is not widely available since it is produced in a cyclotron. The introduction of ^{99m}Tc made any imaging technique within nuclear medicine easier, including bone scintigraphy. In fact, the labelling of sodium triphosphate with ^{99m}Tc was the basis of bone scintigraphy as we know it today (Subramanian and McAfee 1971). Phosphates are ubiquitously present in nature and predominantly in the bone. Several chemical compounds containing phosphates have been evaluated for bone imaging, including pyrophosphate (PP), methylene diphosphonate (MDP), hydroxymethane diphosphonate (HDP, Fig. 3.5) and dicarboxypropane diphosphonate (DPD). A disadvantage of PP is the fact that it is prone to enzymatic hydrolysis. Diphosphonates are very stable and resistant to hydrolysis. DPD demonstrates the fastest blood clearance (Vorne et al. 1983); however, this advantage is not significantly different from other diphosphonates as long as scanning is performed 2–3 h after administration. HDP has the highest initial localization in the normal bone and the highest bone-to-soft-tissue ratio, compared to DPD and MDP, the latter showing the lowest localization (Godart et al. 1986). Therefore, the radiation dose to normal tissue is slightly lower in MDP than DPD and HDP. Eventually, each of the three agents has a high lesion-to-normal-bone ratio, and therefore HDP, MDP and DPD can all be used for bone scintigraphy.

To understand the mechanism of skeletal uptake of the bone-seeking radiopharmaceuticals, basic knowledge of bone anatomy and physiology is mandatory.

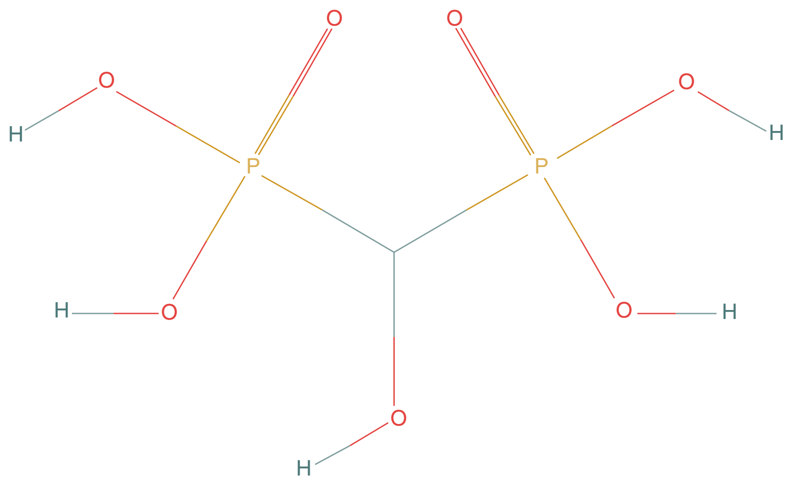

Fig. 3.5 Chemical structure of hydroxymethane diphosphonate ($P_2O_7H_5$)

3.4.1.1 Bone Anatomy

The bone is build of an outer surface (cortical bone) and an inner spongy structure (trabecular or cancellous bone). The trabeculae are oriented along lines of stress to provide maximum strength. It responds to physical stress by growing in length. Bone is surrounded by the periosteum, a fibrous sheath. Arterioles and capillaries which originate here penetrate the bone and enter the Haversian system and medullary space. In infants and children, the periosteum is thick and participates in bone formation. As bone matures, the periosteum becomes thinner and more adherent to the bone.

There are five types of bones in the human body: long, short, flat, sesamoid and irregular. Long bones are characterized by a diaphysis (consisting of the compact bone at the surface, the trabecular bone in the deeper layer containing red marrow, and a medullary cavity containing yellow marrow) and an epiphysis at both ends. Between the diaphysis and the epiphyses, the metaphysis is located. This is the location of the epiphyseal plates and thus the part of the bone that grows during childhood. At the end of its growth, it ossifies into bone. The epiphysis is covered with hyaline cartilage. The femora, tibiae, fibulae as well as the humeri, ulnae and radii are examples of long bones.

Short bones have only a thin layer of compact bone surrounding the trabecular interior. The carpalia and tarsalia are short bones. Flat bones consist of two parallel layers of compact bone with trabecular bone inside, for example, the sternum and the cranium. Sesamoid bones are embedded in tendons, like the patellae. Irregular bones do not fit the classification, as a consequence of their shape and name. Bones of the spine and pelvis are irregular bones.

3.4.1.2 Physiology of Bone Formation

The skeleton is a dynamically active organ system that undergoes continuous remodelling: it continuously repairs and strengthens itself. Bone remodelling is distinct from bone formation. Bone formation during embryonic development occurs through endochondral and intramembranous ossification. During intramembranous ossification, bone is formed directly from connective tissue. In endochondral ossification, the cartilage precedes the eventual bone. Thus, growth in length is a result of endochondral ossification of proliferating cartilage in epiphyseal plates.

Bone is a heterogeneous calcified connective tissue consisting of 65 % mineral and 35 % organic matrix. This organic matrix consists of approximately 90 % of collagen fibres. The mineral part is made up of calcium carbonate, calcium phosphates and crystalline hydroxyapatite. This part exists in a state of equilibrium with plasma, exchanging freely and rapidly between compartments. It contains 99 % of the body's calcium and has therefore a critical function in the normal calcium balance.

On a cellular level there are three major types of bone cells: osteoblasts (bone-forming cells), osteocytes (mature osteoblasts surrounded by matrix) and osteoclasts (bone-resorbing cells). Osteoblasts are primarily responsible for the synthesis of extracellular matrix: they lay down the collagen, which becomes mineralized during bone formation. In disease state the function of these osteoblasts changes. There is an uncontrolled change in mineralization activity. This change forms the basis of bone scintigraphy. ^{99m}Tc-labelled diphosphonate complexes are absorbed on calcium phosphate in the new formed hydroxyapatite matrix. Therefore, uptake on bone scintigraphy represents local osteoblast activity.

As bone expands, osteoblasts become trapped in the matrix they produce and develop into osteocytes. Therefore, osteocytes are mature osteoblasts which have lost their ability to form bone, but rather play a role in maintenance activities. Osteoclasts are giant cells that resorb bone. They also secrete lytic enzymes, which dissolve inorganic calcium salts.

In a normal situation bone metabolism and remodelling is a balanced process. The process of resorption and formation of new bone occurs on the surface of bone. Collagen fibres are organized in patterns that create holes in the matrix. These holes are the site of hydroxyapatite crystal deposition. The osteoblast is the primary cell that promotes this deposition by increasing the phosphate ion concentration. It reduces the solubility of calcium and favours crystallization.

Bone remodelling is a complex process being regulated in both local and systemic settings. Parathyroid hormone (PTH), 1,25-dihydroxycholecalciferol (vitamin D_3) and – in lesser extent – calcitonin play active roles in this process. PTH stimulates osteoclastic bone resorption and decreases osteoblast activity. Vitamin D stimulates osteoblast activity and therefore collagen synthesis, since these cells have vitamin D receptors. Calcitonin reduces bone resorption by deactivating osteoclasts.

3.4.1.3 Imaging Technique

There are several ways to perform a bone scintigraphy (Fig. 3.6). The method of choice depends on the question the referring clinician has and which diagnosis is suspected. A bone scintigraphy can be divided into three phases. The first phase is a radionuclide angiogram, or flow study, performed dynamically for 2 min directly after administration, over the part of interest. In this phase, the radiopharmaceutical is delivered to the surface of the bone. There is an increase in bone uptake in areas with high blood flow. The second phase is a soft tissue phase, or blood pool phase, also performed on the region of interest. These images are performed directly after the first phase (2–5 min after injection). The third phase (or static phase) represents the situation in which the radiopharmaceutical has been absorbed into the hydroxyapatite matrix of the bone. This incorporation process takes time. Therefore, this static image is usually performed 3 h after administration. A three-phase bone scintigraphy characterizes the vascularization of a process as well as its metabolic activity. All three phases are necessary in cases of suspected inflammation (arthritis, synovitis, sacroiliitis, osteomyelitis, etc.), recent (stress) fractures and primary neoplasms. A single late-phase image is sufficient for diagnosing degenerative changes or screening for bone metastases.

Usually a bone scan consists of either a limited study of a specific part of the skeleton, with or without a flow and blood pool image, or a total-body scan, also with or without a flow and blood pool image of a limited part of the skeleton. When performing a limited study of, e.g. the knees, it is wise to include the joints proximal and distal to the location of interest from which pain may be referred. The introduction of hybrid camera systems gave access to complimentary SPECT/CT, for exact localization of focal radiopharmaceutical accumulation and reducing the effect of overlying activity (Fig. 3.7).

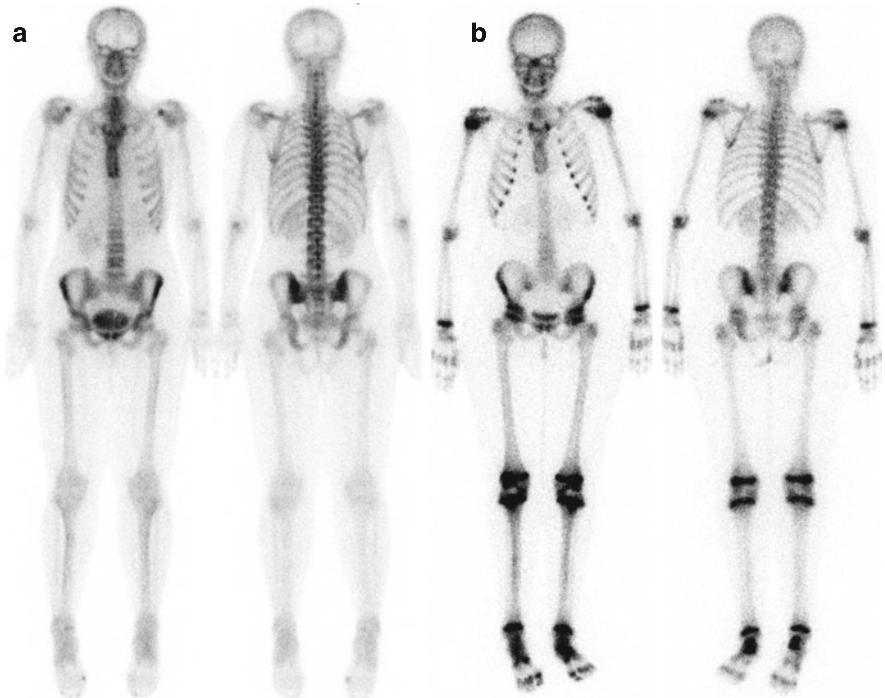

Fig. 3.6 Late static images of a normal bone scintigraphy in an adult (**a**) and in a child (**b**). Note the intense uptake in the epiphyses in **b**, indicating a growing skeleton

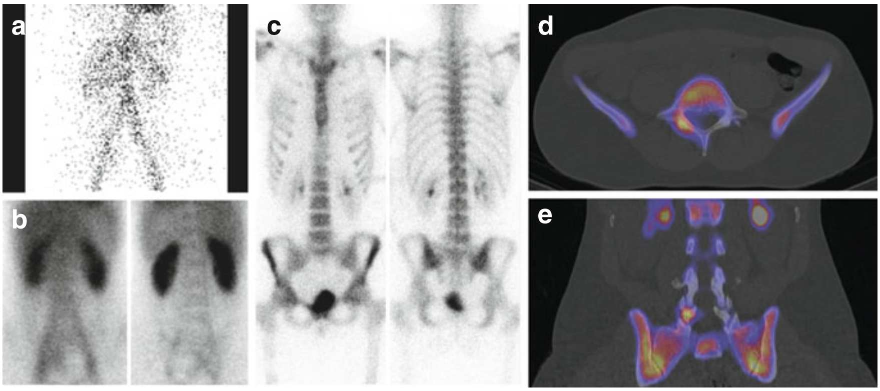

Fig. 3.7 Three-phase bone scintigraphy, using 724 MBq ^{99m}Tc-HDP, of a 23-year-old female ice skater. She suffered from lower back pain for approximately 3 months. The flow (**a**, anterior view) and blood pool images (**b**, both anterior and posterior view) as well as the late static images (**c**, both anterior and posterior view) show a normal distribution of the radiopharmaceutical. An additional SPECT/CT was made (**d**, **e**). These images show elevated uptake at the right lateral lamina of vertebral L5, near the facet joint. The CT showed no fracture, indicating a stress reaction of the bone. This example emphasizes the added value of a complimentary SPECT/CT

3.4.1.4 Indications

Bone scintigraphy can be performed for several indications. The most important indications in sports medicine include enthesopathies, medial tibial stress syndrome, stress or avulsion fractures, degenerative changes (including osteoarthritis), vitality of bone structures and inflammation. In all these indications a flow and blood pool image should be performed in combination with a late static image. Also in orthopaedic indications as loosening or infection of prostheses, as well as primary bone tumours, a three-phase bone scintigraphy is needed. Furthermore, bone scintigraphy has additional value over conventional radiological techniques in the acute phase of a fracture of the smaller bones, e.g. the scaphoid bone (Fig. 3.8).

Other indications for which only a late static image is necessary, however infrequent in sports medicine, include screening for dissemination in patients with malignancies (breast cancer, lung cancer and prostate cancer), metabolic bone diseases (primary and secondary hyperparathyroidism, osteomalacy and vitamin D deficiency) and benign diseases (Paget's disease, fibrous dysplasia and osteoid osteoma).

3.4.1.5 Radiation Dose

The average dose of activity administered for bone scintigraphy is 500 MBq (range 300–740 MBq) (Bombardieri et al. 2003). In patients under 18 years of age, the dose radioactivity is determined according to their weight (approximately 7.5 MBq/kg body weight). In babies a minimum activity of 40 MBq is necessary for images of sufficient quality. Bone is the organ which receives the highest radiation dose (0.063 mGy/MBq). The effective dose (i.e. the dose to the whole body) for patients undergoing bone scintigraphy is 0.0057 mSv/MBq, which results in 2.85 mSv for bone scintigraphy using 500 MBq ^{99m}Tc-HDP (ICRP 80 1998).

The radiation dose of a low-dose CT as a part of complimentary SPECT/CT leads to an additional 0.5–1 mSv. To compare with, the worldwide average background radiation dose for humans is about 2,4 mSv per year.

3.4.2 Leukocyte Scintigraphy

Scintigraphy using labelled autologous white blood cells (leukocyte scintigraphy) has already been developed in the 1970s and is still considered the gold standard technique for infections. This technique is highly specific, since they accumulate by active migration into inflamed tissues. However, a degree of non-specific accumulation must be taken into account, depending on the degree of vascular permeability. After injection, labelled leukocytes show rapid clearance from the lungs and blood pool, with progressive migration into the spleen, liver, bone marrow and in sites of infections where a neutrophilic infiltrate predominates. The labelled leukocytes adhere to the vascular endothelium and then migrate towards the infected area through the endothelium and basal membrane, thereby providing a specific indicator for leukocyte infiltration. Leukocyte scintigraphy can be

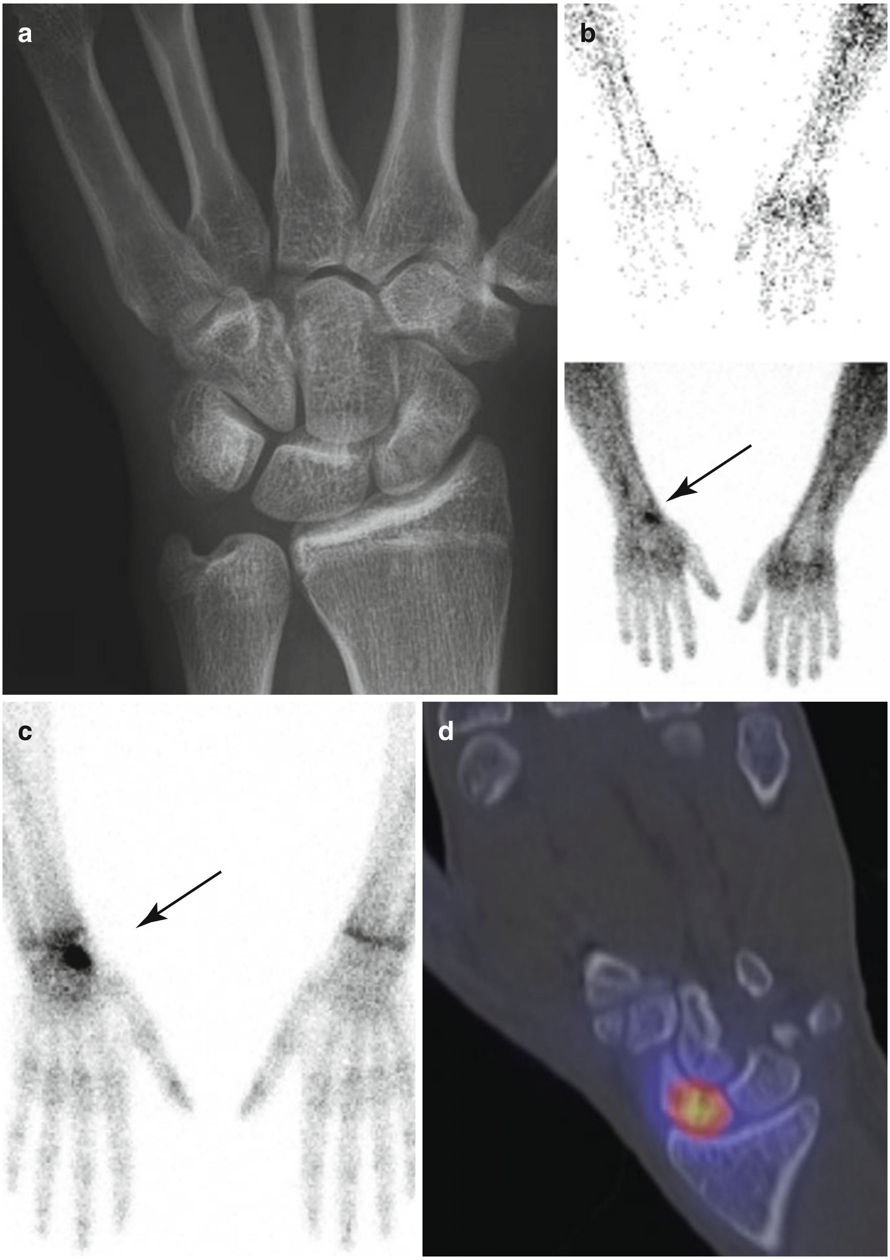

Fig. 3.8 Three-phase bone scintigraphy, using 684 MBq ^{99m}Tc-HDP, of a 16-year-old patient with a painful left wrist after a soccer trauma. A conventional X-ray image of the wrist (**a**) showed no evidence for a fracture; however, this was made in the acute setting after the trauma. The flow and blood pool images of the bone scintigraphy (**b**) show intense focal uptake at the medial side of the left wrist (*arrow*) in the blood pool phase. The difference in flow between both hands is due to intravenous administration of the tracer in the right arm. In the late phase the intense uptake in the left wrist is more evident (**c**). Additional SPECT/CT images (**d**) show that the uptake (*arrow*) is located in the scaphoid bone, indicating a fracture. In conclusion, bone scintigraphy can visualize functional changes before anatomic abnormalities are present on conventional radiology images, especially in small structures

performed with either ^{99m}Tc-exametazime (^{99m}Tc-HMPAO)- or indium-111 (^{111}In)-labelled oxine. The use of ^{99m}Tc-HMPAO is more favourable because of its physical characteristics, less time-consuming labelling, costs and lower radiation burden (de Vries et al. 2010).

3.4.2.1 Indications

Although most frequently seen in orthopaedic surgery and less frequent in sports medicine, common indications for leukocyte scintigraphy include osteomyelitis of the peripheral skeleton, infected joint prosthesis and diabetic foot. In the past, this technique was also used for imaging fever of unknown origin, abscesses, endocarditis and infected devices. However, the introduction of ^{18}F-FDG PET leads to better image quality and higher diagnostic accuracy in these indications. Furthermore, ^{18}F-FDG PET has better test characteristics and is diagnosing spondylodiscitis or osteomyelitis in the central skeleton.

Not many referring clinicians know the usefulness of this technique in sports injuries. Therefore, studies in literature that use labelled leukocytes in sports medicine are scarce. However, since labelled leukocytes accumulate in any infectious process, it could be used when such a process is suspected, e.g. in case of a bursitis.

3.4.2.2 Procedure

The preparation of labelled leukocytes is laborious and time consuming (it takes a laboratory technician more than 2 h) and must be performed in sterile conditions under strict regulations (de Vries et al. 2010). In addition, the need to handle potentially contaminated blood can result in hazards to technicians and patients. It is not advised to perform multiple leukocyte-labelling procedures per day, since there is a risk of exchanging blood material between patients.

The first step is the isolation of mixed leukocytes or (neutrophilic) granulocytes from a sample of peripheral blood, taken from the patient, usually approximately 50 cc. Then the actual labelling takes place. This has to be performed under aseptic conditions, since the leukocytes have to be reinjected into the patient. Finally, quality controls are needed to guarantee safe use in patients. Afterwards, the labelled autologous leukocytes are reinjected into the patient.

Recently, closed systems were developed to avoid the aforementioned disadvantages of the labelling procedure. These devices improve the quality and easiness of the whole labelling procedure and offer higher levels of protection to operator and patients, thereby making this technique available for more clinical centres and more patients (Signore et al. 2012).

3.4.2.3 Imaging Technique and Interpretation

The reinjected labelled leukocytes migrate towards the spleen, liver, bone marrow and sites of infection with neutrophilic infiltration. The leukocytes adhere to the vasculature and then migrate towards the infected area through the endothelium and basal membrane (Signore et al. 2010).

Imaging of ^{99m}Tc-HMPAO-labelled leukocytes occurs at two time points: 3–4 h (early) and 20–24 h (late) after administration. Due to disintegration of ^{99m}Tc, the acquisition time of the late images has to be prolonged to establish identical image quality. Usually scans are made from anterior, posterior and lateral views of the affected regions. In accordance with the bone scintigraphy, a SPECT/CT can be made for exact localization of the leukocyte accumulation.

Accumulation of leukocytes is a dynamic process. In case of an active infection, there will be an increase in leukocyte accumulation over time. The images are negative if no uptake or a significant decrease in uptake is present. Images can also be equivocal, when the uptake on the early images is the same as the late image (Signore and Glaudemans 2011). Semi-quantitative evaluation can be a helpful tool as an addition to visual assessment. Regions of interest are determined over the region with highest intensity and compared to normal tissue (e.g. the contralateral side or a region with normal bone marrow activity). The mean counts per pixel in this region are used to determine the lesion-to-reference ratio on both early and late images. An increase in ratio over time is an additional argument for an active infection (Fig. 3.9).

3.4.2.4 Radiation Dose

The recommended dose of activity administered for leukocyte scintigraphy is 500 MBq. In accordance to bone scintigraphy, a minimum of 40 MBq is needed in children. The effective dose for patients undergoing leukocyte scintigraphy is 0.011 mSv/MBq, which results in 5.5 mSv for using 500 MBq ^{99m}Tc-HMPAO (ICRP 80 1998). This is exactly half of the effective dose when using ^{111}In-oxine.

3.4.3 Anti-granulocyte Scintigraphy

The radiolabelling of autologous leukocytes is an in vitro labelling method. Considerable effort has been devoted to develop in vivo methods of labelling of leukocytes that could eliminate the limitations of the in vitro method. Most efforts have been made in studying monoclonal antibodies (MoAbs) against specific targets on granulocytes, which are expressed in activated state during inflammatory processes.

Advantages of the use of these MoAbs are that they are easier to produce than the radiolabelled autologous leukocytes and they do not need the handling of potentially hazardous biological specimens. Disadvantages are the high molecular weight (resulting in slow diffusion into sites of inflammation), a long plasma half-life and high uptake in the liver and bone marrow. Furthermore, only a minor percentage really binds directly to the cells. The majority will concentrate in the inflammatory focus due to non-specific leakage as a result of increased permeability.

The two most important anti-granulocyte MoAbs are Scintimun® and LeukoScan®. Scintimun® is the commercial name of the ^{99m}Tc-labelled anti-granulocyte antibody besilesomab that binds to the cross-reacting antigen 95 (NCA-95), expressed on human granulocytes. ^{99m}Tc-sulesomab (LeukoScan®) is a fragment of an antibody that binds to NCA-90 on granulocytes.

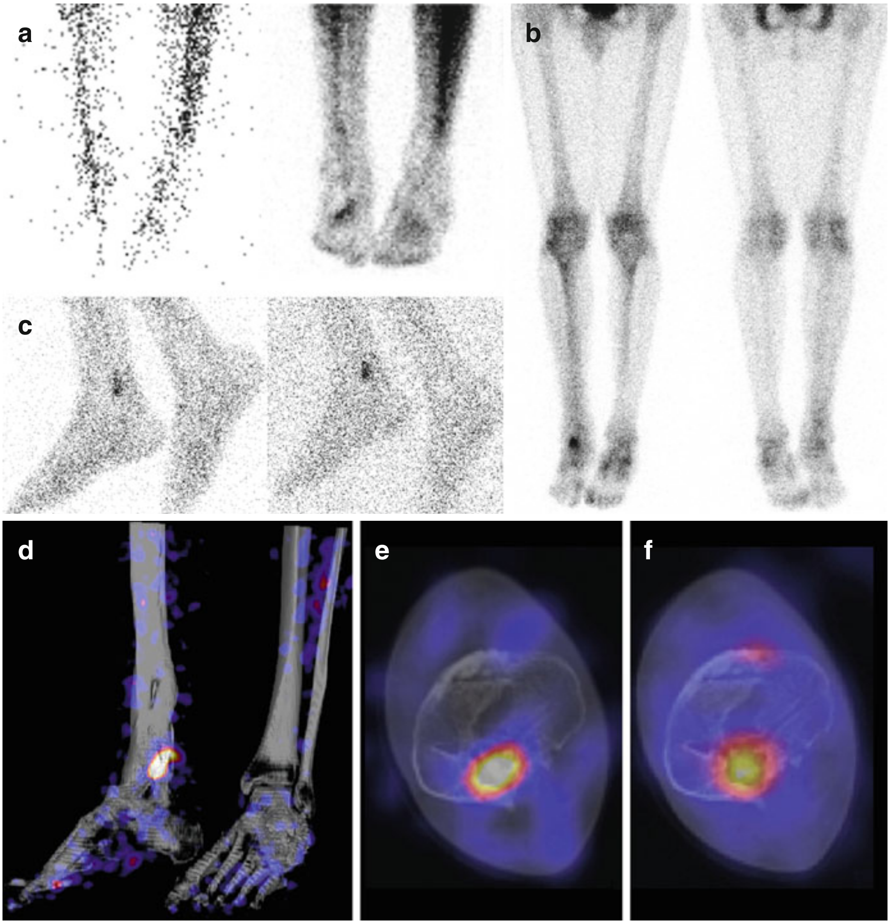

Fig. 3.9 Combination of 3-phase bone scintigraphy (740 MBq ^{99m}Tc-HDP) with leukocyte scintigraphy (214 MBq ^{99m}Tc-HMPAO) in a patient with a pilon fracture of his right tibia, after a high-energy trauma. The flow images are relatively normal; however, the blood pool images show elevated uptake in the right midfoot (**a**). There is intense uptake at the distal end of the right tibia on the late static image (**b**). Additional SPECT images showed vital bone fragments. A leukocyte scintigraphy (**c**) was made. The early image (*left*) shows intense uptake at the distal tibia, which visually accumulates over time (late image, *right*). The ratio of activity of the uptake compared to the contralateral tibia increases from 2.0 to 2.5, indicating an active infection. A 3-dimensional reconstructed SPECT/CT image of the leukocyte scintigraphy shows the exact location of the infection (**d**). Transverse reconstruction of the leukocyte scintigraphy (**e**) and bone scintigraphy (**f**) indicate an exact identical location of the accumulation of the radiopharmaceuticals

Both MoAbs can be used for the same indications, with the same imaging techniques and interpretation criteria, as mentioned in the paragraph about labelled leukocytes. The use of labelled leukocytes is preferable, since it is more specific and directly binds to the leukocytes. MoAbs can be used to avoid the laborious preparation of the labelled leukocytes.

3.5 PET Techniques

PET offers the unique possibility of a 3D image of the whole body, with better spatial resolution compared to SPECT imaging, and the possibility for absolute quantification. The most often used radionuclide in PET imaging is ^{18}F, being a very small nuclide, which is bound to plasma proteins to a lesser extent than the larger ^{99m}Tc-labelled radiopharmaceuticals. Therefore, ^{18}F is extracted to the hydroxyapatite crystal to a larger extent. This makes it a very interesting bone-seeking radiopharmaceutical. This section discusses the use of ^{18}F-labelled radiopharmaceuticals for PET-based bone imaging.

3.5.1 ^{18}F-Sodium Fluoride PET

^{18}F-sodium fluoride (^{18}F-NaF) was already used in the 1950s for bone scintigraphy, using an old general-purpose rectilinear scanner for imaging purposes. It was abandoned due to the fast introduction of ^{99m}Tc, the development of diphosphonates and the introduction of the gamma camera. That was when the 'normal' bone scan became the gold standard in physiological bone imaging. The introduction of the PET camera in the early 1990s led to the rediscovery of the use of ^{18}F-NaF for bone scintigraphy.

A large body of literature is available handling the metabolism and pharmacokinetics of fluoride because of its role in preventing dental caries and as therapeutic agent in osteoporosis. The uptake mechanism resembles that of ^{99m}Tc-labelled diphosphonate complexes. However, the faster blood clearance of ^{18}F-NaF and the twofold higher uptake in developing bone cells of fluoride make it possible to image faster (1 h after injection) and lead to better ratios between uptake in bone with faster turnover and normal bone (Grant et al. 2008). Limitations are the high costs of this technique (five times higher compared to the bone scan) and the non-possibility to perform flow and blood pool imaging. At the moment, the classical bone scan is the gold standard for all indications; however ^{18}F-NaF PET is at least as sensitive and specific as the bone scan and could be considered for the individual patient.

3.5.1.1 Indications

The indications for ^{18}F-NaF PET are basically the same as for the bone scan. In clinical practice, however, the indications for this imaging technique are limited, especially in sports medicine (Segall et al. 2010). In fact, the identification of osseous metastases, including localization and determination of the extent of disease, remains the only common indication (Sheth and Colletti 2012). Several reports are available which described the successful use of ^{18}F-NaF in osteomyelitis, trauma, inflammation, bone graft viability and complications of prosthetic joints. However, one should reconsider the use of ^{18}F-NaF for inflammatory diseases since this technique is not able to perform the normal dynamic imaging and blood pool images, leading to a lower specificity.

3.5.1.2 Procedure

^{18}F-NaF has many identical characteristics as diphosphonate complexes. Both radiopharmaceuticals are normally symmetrically distributed throughout the entire skeleton. Fluorine deposition favours the axial (spine and pelvis) over the appendicular (shoulder girdles and limbs) skeleton and is greater for joints than for shafts of long bones (Bridges et al. 2007). The route of excretion is through the urinary tract. Therefore, the kidneys and urine bladder should be visualized. The degree of uptake of both tracers in the urinary tract depends on the renal function.

In accordance with the ^{99m}Tc-diphosphonate bone scintigraphy, the degree of uptake does not differentiate benign from malignant. However, the pattern may be suggestive for a specific diagnosis. Still, physiological uptake can be more variable in ^{18}F-NaF due to higher resolution of PET/CT camera systems (Fig. 3.10). Another difference is the time point of image acquisition after administration. ^{18}F-NaF PET can be performed within 60 min after injection, whereas late images in conventional bone scintigraphy should be performed at least after 3 h. As stated earlier, ^{18}F-NaF does not offer the possibility of performing a flow and blood pool scan. Finally, PET has the possibility to accurately quantify bone metabolism. At present, the clinical value of this quantification, e.g. using the standard uptake value, is still a matter of debate (Li et al. 2012).

3.5.1.3 Radiation Dose

The recommended dose of activity is 180–370 MBq ^{18}F-NaF. The target and critical organs are the bones. The effective dose of a single ^{18}F-NaF PET scan is much higher than that of a conventional bone scintigraphy: 0.024 mSv/MBq. In an adult administered with 370 MBq, the effective dose is 8.9 mSv, which is threefold higher compared to conventional bone scintigraphy.

An additional whole-body low-dose CT leads to approximately 1.5 mSv higher effective dose. The exact effective dose depends on the CT parameters (i.e. voltage, current, rotation and pitch).

3.5.2 ^{18}F-Fluorodeoxyglucose PET

The glucose analogue ^{18}F-fluorodeoxyglucose (^{18}F-FDG, Fig. 3.11) is used extensively in various malignant and infectious diseases and is also a useful radiopharmaceutical for PET bone imaging. FDG, a glucose derivate, is transported over the cell membrane by glucose transporters (mainly GLUT-1) and phosphorylated by hexokinase (leading to FDG-6-phosphate). However, this FDG-6-phosphate cannot be glycolysed and therefore accumulates within the cell. This characteristic makes ^{18}F-FDG suitable for imaging. However, it is a non-specific tracer since it is taken up in any cell with high glycolytic activity.

The uptake of FDG in normal bone is low, as compared with conventional bone scintigraphy and ^{18}F-NaF PET, since the bone has relatively low glucose utilization rates. The bone marrow, however, produces an appropriate signal on FDG images.

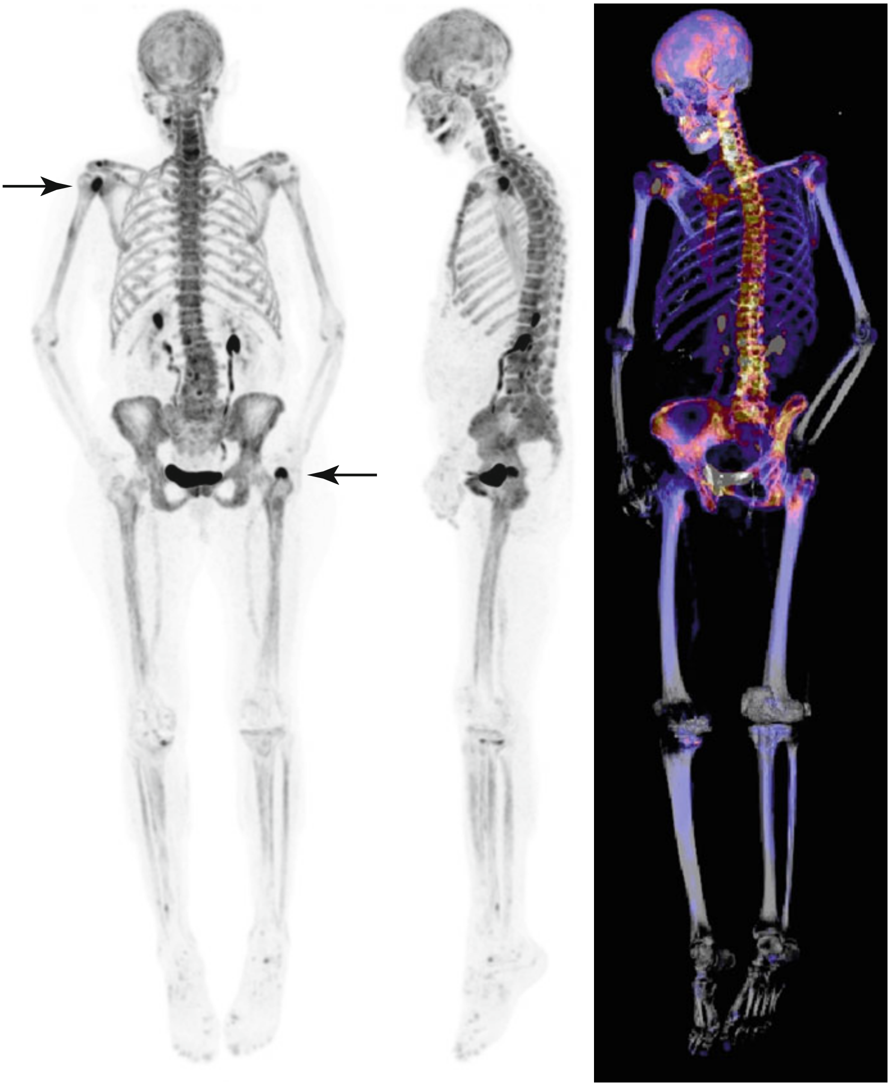

Fig. 3.10 ^{18}F-sodium fluoride PET scan of a female patient. Maximum intensity summation projections, from left to right: anterior view, left lateral view and reconstructed fused PET/CT image, respectively. The distribution of the radiopharmaceutical along the bone, as well as the excretion by the urinary tract, is equal to that of diphosphonates; however, the resolution of the PET images is much better. Note also the higher uptake in the axial skeleton compared to the uptake in the limbs. The intense uptake at the right humerus head and left greater trochanter indicate local insertion tendinopathy (*arrows*)

^{18}F-FDG has great value in identifying osseous metastases of malignant processes due to an acceleration of glycolytic rate of these neoplasms, resulting in focal regions with high contrast compared with the normal background FDG uptake. Also in this PET technique, the uptake of FDG can be quantified, for distinguishing

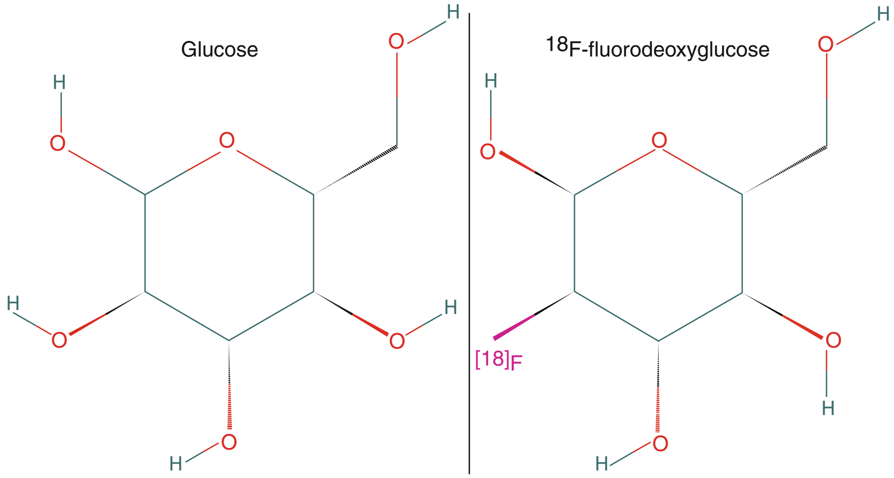

Fig. 3.11 Chemical structure of glucose ($C_6H_{12}O_6$, *left panel*) and ^{18}F-fluorodeoxyglucose ($^{\text{18F-FDG}}$, $^{18}F\text{-}C_6H_{11}O_5$, *right panel*). The only difference between these two is the fact that an OH-group in glucose has been replaced by an ^{18}F atom to form ^{18}F-FDG

benign from malignant background. The role of ^{18}F-FDG PET in benign bone diseases is limited due to the low metabolic rate of these processes. The main role of ^{18}F-FDG PET in sports medicine will be in inflammation and infectious processes.

3.5.2.1 Indications

As mentioned before, ^{18}F-FDG PET is a well-established diagnostic tool in oncology. FDG also accumulates in infection due to high uptake in activated granulocytes. These cells use glucose as an energy source only after activation during metabolic burst. ^{18}F-FDG PET may be used in sports medicine in any patient with suspicion of an infection or inflammatory focus. However, the use of ^{18}F-FDG PET in infection and inflammation still lacks the support of evidence-based data (Glaudemans and Signore 2010). Nevertheless, the use of ^{18}F-FDG has been approved for specific infectious indications as fever of unknown origin, osteomyelitis (especially of the axial skeleton) and other chronic bone infections, spondylodiscitis (Fig. 3.12), inflammatory bowel diseases, vasculitis and infections of vascular prostheses.

Until now, the value of ^{18}F-FDG PET in infections of hip and knee prostheses is limited. Artefacts may be generated, characterized by artificial FDG uptake adjacent to the prostheses (Goerres et al. 2003). Further on, non-specific FDG uptake may be seen for months after surgical intervention. A negative FDG study may spare revision surgery, but a positive scan must be interpreted with caution since long-lasting non-specific uptake may be responsible for false-positive studies (Israel and Keidar 2011). ^{18}F-FDG PET may be used in suspected infected prostheses when results of the leukocyte scintigraphy are equivocal and may help to differentiate between soft tissue infection and bone infection, with help of the CT (Glaudemans et al. 2012). In a clinical setting, at this moment ^{18}F-FDG PET should not be used routinely in patients with suspected infected prosthesis.

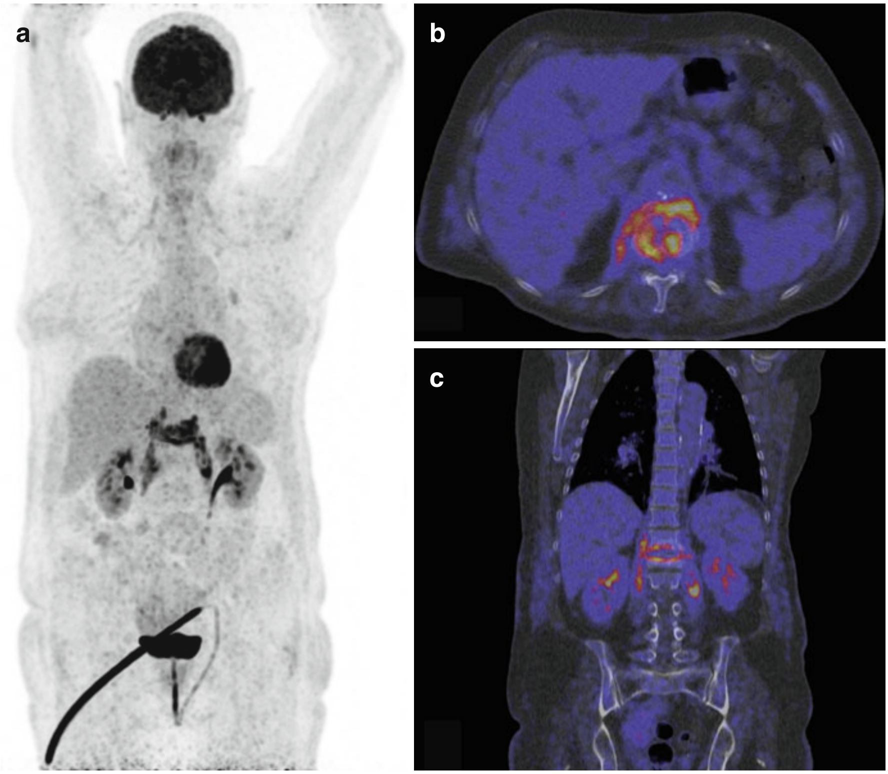

Fig. 3.12 ^{18}F-FDG PET/CT scan of a patient with spondylodiscitis of vertebrae Th12–L1, with also an abscess at the proximal end of the iliopsoas muscles. Maximum-intensity projection (**a**) shows also physiological uptake in the brain, the salivary glands, the myocardium of the left ventricle, the liver and the spleen, as well as physiological excretion by the kidneys to the urine bladder and urinary catheter. Transverse (**b**) and coronal (**c**) reconstructions in which the ^{18}F-FDG uptake is fused with the low-dose CT

3.5.2.2 Procedure

Patients who are referred for an ^{18}F-FDG PET scan should undergo a short fasting period of 4–6 h before intravenous tracer administration. This fasting period stimulates the uptake of FDG into the organs of interest. If an ^{18}F-FDG PET scan is made directly after a meal, all the glucose (and thus also ^{18}F-FDG) accumulates in the muscles and hinders correct image interpretation. The blood glucose level should be 5–10 mmol/L in order to increase sensitivity.

A normal ^{18}F-FDG PET scan shows physiological uptake in the brain, pharynx, tonsils, vocal cords, salivary glands, liver and spleen, digestive tract and urinary tract. To reduce uptake in the muscles, patients are supposed to lay still and are not allowed to talk during 1 h after administration.

Pre-hydration, i.e. drinking 1 l of water after tracer administration, results in lower ^{18}F-FDG concentration in the urine and therefore less artefacts. Furthermore, it reduces the radiation burden to the patient.

After this hour, the PET scan is performed. A patient is scanned in different bed positions, either from the toes to the head (total body) or from the upper legs to the head (torso). Total acquisition time is around 20 min, and the PET scan may of course be performed together with a (low-dose) CT scan for anatomical mapping.

3.5.2.3 Radiation Dose

Different protocols are available for ^{18}F-FDG PET scanning. Usually a dose of 3 MBq/kg is used; however, some institutes use 5 MBq/kg. Also acquisition duration can differ per institution, varying from 1 to 3 min per bed position (normally 7–8 bed positions required per patient). The effective dose of a single ^{18}F-FDG scan varies for each individual patient. Generally, the effective dose is approximately 4.0 mSv (ICRP 80).

An additional whole-body low-dose CT leads to approximately 1.5 mSv higher effective dose. The exact effective dose depends on the CT parameters (i.e. voltage, current, rotation and pitch).

Conclusion

In general, nuclear medicine modalities are very helpful tools in diagnosing patients in sports medicine. Bone scintigraphy, using ^{99m}Tc-diphosphonate complexes, is a well-established technique which has proven to be robust throughout the last decades. It remains the cornerstone in nuclear medicine, even despite technological evolution. The introduction of hybrid SPECT/CT camera systems leads to higher image quality (better spatial resolution) and exact localization of lesions with high uptake.

The combination of bone scintigraphy with leukocyte scintigraphy has the best test characteristics for imaging infectious bone processes, especially in the peripheral skeleton. ^{18}F-FDG PET is a very suitable modality for imaging bone infections (osteomyelitis) of the axial skeleton. ^{18}F-NaF PET may replace bone scintigraphy, since it leads to better ratios between uptake in the bone with faster turnover compared to normal bone and the possibility for quantification. However, the high costs, higher radiation burden and the non-possibility to perform flow and blood pool images make this technique at this moment unfavourable compared to conventional bone scintigraphy. In sports medicine, it is rarely used.

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Sports Injuries

4

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Contents

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Abstract
Regular participation in sports and exercise activities is considered beneficial for health but unfortunately sometimes sports injuries occur. Based on the onset of symptoms and the mechanism, sports injuries can be classified as either acute injuries (due to a single traumatic event) or overuse injuries (due to repetitive microtraumata). In this chapter, the various types and causes of sports injuries of the musculoskeletal system are described. The general principles of acute and overuse injuries of the bone, cartilage, joint, ligaments, muscle, tendon, bursa, and nerves are discussed, and some insight into etiology and pathophysiology is provided.

4.1 Introduction

Regular physical activity is one of the most important things a person can do to stay fit and healthy! However, participation in sports and exercise activities is not without potential side effects. Injuries can occur during any "exercise for health" or sporting activity, either in training or during competition.

A sports injury can be defined as tissue damage that occurs as a result of participation in sports or exercise. Based on the onset of symptoms and the mechanism of injury, sports injuries are commonly classified into acute or overuse injuries (Table 4.1) (Brukner and Khan 2012). Acute injuries are usually the result of a single, traumatic event (macrotrauma). In contrast, overuse injuries are more subtle and occur over time. They are the result of repetitive microtraumata to tendons, bone, and other musculoskeletal tissues (Bahr and Mæhlum 2004).

4.2 Acute Injuries

Acute injuries occur suddenly and have a clearly defined cause or onset. An acute heavy load that exceeds the threshold of tissue tolerability suddenly irreversibly deforms the tissue (e.g., fracture, rupture). Acute injuries most commonly occur in sports characterized by high speed, high risk of falling, and contact sports (Bahr and Mæhlum 2004).

4.2.1 Bone

4.2.1.1 Fracture

Acute fractures are caused by acute traumata that exceed the bone's tolerance. Fractures can occur due to direct trauma such as a kick to the leg or can result from an indirect trauma such as twisting of the lower leg. Avulsion fractures can occur at the site of tendon or ligament insertion, when a piece of bone attached to a tendon or ligament is torn away. In children and adolescent athletes, two particular

Table 4.1 Classification of sports injuries

Musculoskeletal structure	Acute injuries	Overuse injuries
Bone	Fracture	Stress reaction/fracture
	Contusion	Osteitis/periostitis
		Apophysitis
Cartilage	(Osteo)chondral lesion	Chondropathy
	Fibrocartilaginous lesions	Osteoarthritis
Joint	Subluxation	Synovitis/capsulitis
	Dislocation	Impingement
Ligament	Sprain/tear	Inflammation
Muscle	Strain/tear	Chronic compartment syndrome
	Contusion	Focal tissue thickening/fibrosis
	Myositis ossificans	Delayed-onset muscle soreness (DOMS)
	Exercise-associated muscle cramp (EAMC)	
Tendon	Tear (partial/complete)	Tendinopathy
Bursa	Traumatic bursitis	Bursitis
Nerve	Neuropraxia	Entrapment

Adapted from Brukner and Khan (2012)

fractures occur: (1) “greenstick fractures,” in which the bone is bent like a soft twig, and (2) growth plate fractures that require special attention.

The clinical features of a fracture are pain, tenderness, localized bruising, swelling, and, in some cases, malalignment, shortening of an extremity, and restriction of or unnatural movement. Fractures may be closed or open (compound), where the bony fragment punctures the skin. Radiographs are usually made to confirm the diagnosis and for reason of classification of the type of fracture (transverse, oblique, spiral, or comminuted) (McRae and Esser 2008).

Fractures are managed by anatomical and functional realignment. Non-displaced or minimally displaced fractures can be treated with bracing or casting. Displaced fractures require reduction and immobilization. A displaced, unstable fracture requires surgical stabilization. Delayed union or malunion of a fracture causes persistent pain and disability that may require bone grafting, with or without internal fixation.

Soft tissue injury, such as ligament or muscle damage, is often associated with a fracture and may cause more long-term problems than the fracture itself. Thus it is important to address the soft tissue components of any bony injury.

Occasionally a fracture may cause swelling of a muscle compartment that is surrounded by a non-distensible fascial sheath, usually in the flexor compartment of the forearm or the anterior compartment of the lower leg. This condition—acute muscle compartment syndrome—causes pain out of proportion to the fracture, pain on passive stretch, pulselessness, and paresthesia (Shadgan et al. 2010). This may require urgent fasciotomy. Other complications of fractures that require urgent action are infections, associated nerve or vessel lesions, and deep venous thrombosis/pulmonary embolism.

Particularly in athletes, one should realize that complete immobilization causes problems like deconditioning, muscle wasting, and joint stiffness, which are disadvantageous for the rehabilitation process. Muscle stimulation techniques, functional bracing, and internal fixation of fractures might be helpful to facilitate rehabilitation and to prevent these unwanted side effects in order to achieve quick return to play.

4.2.1.2 Contusion

A direct blow from a kick, stick, or ball to, for example, the tibia or iliac crest (hip pointer) can cause a contusion of the bone, which can be extremely painful due to periosteal injury (Hall and Anderson 2013); bone contusion produces microfractures with water signal (bone marrow edema) on T2 or intermediate TE MRI.

4.2.2 Cartilage

The articular surface of most joints is covered by hyaline cartilage that is 1–5 mm thick.

It provides a low-friction gliding surface, acts as a shock absorber, and reduces peak pressures on the underlying bone. Due to increased participation in recreational and competitive sports, articular cartilage injuries are far more common than was previously realized (Flanigan et al. 2010). The articular cartilage can be injured through acute contusion or by shear forces applied to the joint, which frequently occur in relation to acute joint trauma, subluxation, and dislocation. Localized cartilage injuries are diagnosed in 20 % of patients with a rupture of the anterior cruciate ligament of the knee and in over 60 % of patients sustaining a lateral ligament injury of the ankle (Buckwalter 2002). Common sites of chondral and osteochondral injuries are the superior articular surface of the talus, the femoral condyles, the patella, and the capitellum of the humerus. When an apparently “simple joint sprain” remains painful and swollen for longer than expected, an osteochondral lesion must be suspected. Since a radiograph often shows no abnormalities in the acute phase, these injuries should be investigated with MRI. Arthroscopy may be required to assess the degree of damage and to remove loose fragments or to perform an intervention. Using MRI and/or arthroscopy, it is now possible to classify articular cartilage injuries based on size, depth, and surface (Bhosale and Richardson 2008):

1. Disruption of the articular cartilage at its deeper layers with or without subchondral bone damage, while the articular surface itself remains intact
2. Disruption of the articular surface only
3. Disruption of both articular cartilage and subchondral bone

Due to lack of blood supply and low number of cells, articular cartilage has a limited intrinsic capacity to repair itself after an injury, which results in an increased risk that premature osteoarthritis will develop. The larger the lesion or defect, the lower is the probability of healing.

Prognosis is also related to the depth the injury extends toward the underlying bone. Factors affecting return to sport include age, duration of symptoms, number of previous injuries, associated injuries, lesion type, size, and location (Mithoefer et al. 2012).

Fibrocartilaginous structures like the menisci in the knee and the glenoid labrum are also frequently acutely injured. In the specific chapters on knee and shoulder injuries, this pathology will be discussed in more detail. The potential for repair in these lesions also varies with the blood supply. For example, the meniscus of the knee can be divided in a peripheral "red zone" with good blood supply and a central "white zone" with limited blood supply. Especially in younger patients, arthroscopic repair of meniscal lesions in the red zone may be successful (Laible et al. 2013).

4.2.3 Joint

4.2.3.1 Dislocation/Subluxation

The intrinsic stability of a joint depends on its anatomy (bone, cartilage, capsule, ligaments). The active stability is determined by the strength and coordination of the surrounding muscles. Traumatic injury to joint and supporting structures (capsule and ligaments) often results in an episode of instability referred to as dislocation or subluxation.

A dislocation is a complete displacement of joint surfaces so that they no longer make normal contact at all. A subluxation is a partial displacement of joint surfaces in which the articulating surfaces remain partially in contact with each other and is usually transient in nature. It is important to distinguish first time or recurrent dislocations/subluxations.

Joints with less intrinsic stability such as the shoulder and fingers are more likely to dislocate. More stable joints, such as the hip, elbow, and ankle, require much greater forces to dislocate. A dislocation or subluxation implies damage to the supporting structures of the joint like the surrounding joint capsule and ligaments. Complications of dislocations include associated vascular damage (e.g., brachial artery damage in elbow dislocations) and nerve damage (e.g., axillary nerve injury in shoulder dislocations). Radiographs of all dislocated joints should be made to exclude an associated fracture. Dislocated joints, in most cases, can be reduced relatively easily. After reduction, the joint needs to be protected to allow the joint capsule and ligaments to heal. Afterward exercise therapy (strength and coordination training) should be encouraged to increase active joint stability.

4.2.4 Ligament

Ligaments are made up of closely packed collagen fibers that connect one bone to another and provide passive joint stability. They also have an important proprioceptive function. Ligaments may be intra-articular (e.g., the cruciate ligaments), capsular (as a thickening of the joint capsule, e.g., the anterior talofibular ligament),

Table 4.2 Classification of ligament injuries

Severity	Injury	Signs and symptoms	Stress testing of the ligament
Grade 1, mild	Sprain	Slight local tenderness	Normal range of motion
Grade 2, moderate	Partial tear	Swelling	Increased laxity but definite end point
		Notable tenderness	
Grade 3, severe	Complete tear	Swelling	Instability, no end point
		Painful or pain-free[a]	

[a]Pain-free as sensory fibers are completely divided in the injury

or extracapsular (e.g., calcaneofibular ligament). Healing tendency of capsular ligaments is better because of their better blood supply (Frank 2004).

Injuries occur when a ligament is under excessive load. Typically there is a sudden overload, stretching the ligament, while the joint is in an extreme position. The most common example is traumatic ankle inversion, which causes the lateral ligaments—primarily the anterior talofibular ligament—to rupture. Partial or total tears may occur in the midsection of the ligament or at the ligament-bone junction. Avulsion fractures (a piece of bone pulled away by the ligament) also occur, more commonly in children.

Ligament injuries range from mild injuries involving the tearing of only a few fibers to complete tears of the ligament, which may lead to instability of the joint (Woo et al. 2006). Ligament injuries are divided into three grades (Table 4.2).

Ligament injuries can be visualized using ultrasound and MRI. Management of acute ligament injuries consists of the RICE principle (rest, ice, compression, and elevation) in the acute phase to minimize bleeding and swelling. For grade I and grade II sprains, treatment aims to promote tissue healing, prevent joint stiffness, protect against further damage, and strengthen muscle to provide additional joint stability. The healing of collagen in a partial ligament tear takes 6 weeks to 12 months. Pain subsides but many athletes continue to have objective mechanical laxity and subjective joint instability. Therefore, protection of the joint using a brace or tape for external support should be considered on return to sport in order to prevent reinjury. The treatment of severe grade 3 ligament injuries may be either conservative or surgical.

4.2.5 Muscle

Muscle injuries are common in athletes. The frequency of muscle injuries ranges from 10 to 55 % of all sustained sporting injuries (Delos et al. 2013). Muscle injuries can occur in two ways: (1) by distension leading to strains/tears and (2) by a direct blow leading to a contusion of the muscle.

4.2.5.1 Strain/Tear

Muscles that are commonly affected are the hamstrings, quadriceps, hip adductors, and gastrocnemius. Muscles are strained or torn when the load exceeds what some or all of the fibers can tolerate. A muscle is most likely to tear during a bout of

Table 4.3 Classification of muscle strain injuries

Severity	Injury	Signs and symptoms	Strength
Grade 1	Strain of small number of muscle fibers	Localized pain	No loss of strength
Grade 2	Tear of significant number of muscle fibers	Pain and swelling	Loss of strength
		Pain with contraction	Movement limited by pain
Grade 3	Complete tear of the muscle	Pain and swelling	Severe loss of strength
		Pain with contraction	Movement limited by pain

maximal eccentric contraction (involving muscle contraction while muscle is lengthening). The athlete experiences acute pain during his action and sometimes feels a bump in the muscle directly after the injury moment. Pain reproduced with muscle contraction, swelling, and loss of strength are the clinical features which ensue. Muscle strains/tears can be classified into three grades (Table 4.3).

MRI scans and ultrasound can be helpful in the elite athlete but should not replace important clinical assessment. In the specific chapter on muscle injuries, the classification model, predisposing factors, mechanisms of injury, and healing process of muscle strains/tears are described in more detail. Patients with grade 1 or 2 strains characteristically develop pain during active muscle resisted contraction. They do not present with rest pain.

After a significant muscle injury, there often is little muscle tissue regeneration. The injured muscle tissue is replaced by noncontractile scar tissue, which is more prone to re-rupture. Early return to sporting activities can cause re-rupture at the original muscle injury site and therefore appropriate assessment of severity and adequate rehabilitation are essential. Since re-ruptures cause the greatest amount of time lost from sporting activity, return to play should be determined by extent of muscle strain, muscle group, and demands of the sport placed on the individual athlete.

4.2.5.2 Contusion

Muscle contusions most commonly occur in the front of the thigh in the quadriceps muscle. This injury is known as a "charley horse," "cork thigh," and also "dead leg" (Trojian 2013). A muscle contusion usually results from a direct blow from an opponent (often the kneecap) or firm contact with equipment in high-contact sports such as football and basketball. The blow causes vascular damage and diffuse internal bleeding in the musculature, which is often highly vascularized at the moment of injury. Most of these injuries are relatively minor and do not limit sport participation. However, especially if the player continues to play after a severe contusion this may lead to a big hematoma. This results in swelling with characteristic muscle pain at rest. Muscle tear is not prominent in patients with muscle contusion.

4.2.5.3 Myositis Ossificans

An occasional complication of a muscle hematoma (and thus of muscle contusion and not of muscle strain) is myositis ossificans (Cushner and Morwessel 1992). This can be defined as ectopic ossification of the injured muscle tissue. The incidence is highest in collision sports and the location most frequently affected is the thigh. Myositis ossificans is most common following severe muscle contusions, but it can also occur in relatively minor muscle bleeding. The pathophysiology of ectopic bone formation has not been completely elucidated. If a muscle contusion does not resolve within 7–14 days, myositis ossificans should be suspected. Two to four weeks after the injury, characteristic ringlike calcifications of the muscle may already be visible on radiographs and ultrasound; not all patients with these calcifications will develop symptoms of pain and abnormal muscle function. Management of myositis ossificans is conservative and recovery is usually slow.

4.2.5.4 Cramp

A muscle cramp is a sudden, involuntary, painful contraction of a muscle or part of it, is self-extinguishing within seconds to minutes, and is often accompanied by a palpable knotting of the muscle. Muscle cramp either during or immediately after exercise is commonly referred to as “exercise-associated muscle cramping” (EAMC) (Minetto et al. 2013). Despite their “benign” nature, cramps are often very uncomfortable and can be temporarily debilitating. Moreover, exercise-associated muscle cramps may significantly impair athletic performance.

The lifetime prevalence of cramps in athletes has been reported to be as high as 30–50 % (Miller et al. 2010). Norris et al. reported a high prevalence of benign cramps in a wide group of healthy young subjects enrolled in an exercise class; 115 (95 %) of 121 had experienced spontaneous muscle cramps at least once (Norris et al. 1957). They preferably occur in calf and foot muscles, followed by the hamstrings and the quadriceps.

The etiology of EAMC remains unclear. The main risk factors for exercise-associated muscle cramps include family history of cramping, previous occurrence of cramps during or after exercise, increased exercise intensity and duration, and inadequate conditioning for the activity. Dehydration (and/or electrolyte depletion) often is given as an explanation for muscle cramps occurring in athletes, although this claim is not supported by scientific evidence. Recent experimental findings have proved unambiguously the relevance of spinal mechanisms and altered neuromuscular control in the generation and development of muscle cramps. However, several unresolved issues in cramp pathophysiology and management still remain and require further investigation (Minetto et al. 2013).

4.2.6 Tendon

Complete or partial tendon ruptures may occur acutely without a warning, usually in older athletes without a history of injury in that particular tendon. The two most commonly ruptured tendons are the supraspinatus tendon of the shoulder and the Achilles tendon (Longo et al. 2013; Murray and Gross 2013). Injuries to tendons generally occur at the musculotendinous junction. However, the Achilles tendon usually ruptures 2–5 cm above the insertion, which is considered the point of least blood supply. Partial tears are characterized by the sudden onset of pain and by localized tenderness, but they may be difficult to distinguish from tendinopathy. When investigation is indicated, ultrasound and MRI can be useful.

4.2.7 Bursa

The body contains many bursae situated usually between bony surfaces and overlying tendons and skin. A direct fall onto a bursa may result in acute traumatic bursitis due to bleeding into the bursa (Aaron et al. 2011). A septic bursitis may develop when bacteria enter through abrasions or a small wound over the bursa. The patient reports anterior knee pain and swelling. On physical examination, there is a prepatellar area of tenderness and a fluctuating swelling. In case of an infection, the area will be warm and red. Diagnosis can be confirmed by ultrasound.

4.2.8 Nerve

Acute nerve injuries are uncommon in athletes. The nerves most often injured are the ulnar nerve at the elbow and the common peroneal nerve at the neck of the fibula, as they are located superficially and susceptible to injury from a direct blow. Symptoms like tingling, numbness, and pain in the distribution of the nerve usually diminish quickly.

In case of "neuropraxia," there will be paralysis or weakness of the muscles innervated by that nerve, in addition to sensory loss and/or pain in the sensory distribution of the nerve. These symptoms usually resolve spontaneously but slowly (Toth 2009).

4.3 Overuse Injuries

Overuse injuries occur gradually and their cause is not always evident. Repeated overloading causes an accumulation of small deformations of the tissue that finally lead to injury and pain when over time the tissue threshold is exceeded (Fig. 4.1).

Overuse injuries are frequently seen in endurance sports like running, cycling, and cross-country skiing, characterized by monotonous training sessions of long duration, or in technical sports like tennis or javelin throwing, in which the same movement has to be repeated over and over again (Bahr and Mæhlum 2004). Despite the magnitude of the problem of overuse injuries, high-quality scientific data on etiology are limited. The potential causes of overuse injuries can be divided into intrinsic and extrinsic

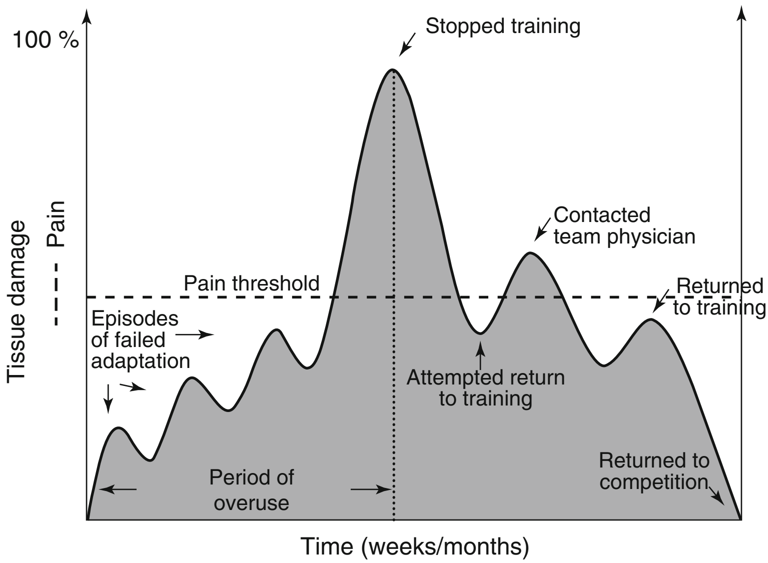

Fig. 4.1 Hypothetical overview of the onset of tissue injury and pain in a typical overuse injury. From Bahr (2009)

Table 4.4 Overuse injuries: risk factors

Extrinsic factors	Intrinsic factors
Training errors	Sex
Technique errors	Size and body composition
Shoes	Genetics
Equipment	Endocrine factors and metabolic conditions
Surfaces	Muscle weakness/imbalance
Environmental conditions	Lack of flexibility
Inadequate nutrition	Malalignment
Medication	Psychological state
Coach	
Team	
Psychological factors	

factors (Table 4.4). Some of these factors are modifiable (e.g., training load, technique, muscle strength) which can be useful in the prevention and management of overuse injuries. For example, malalignment seems to be an important factor in the etiology of overuse injuries and includes different entities (such as pes planus, pes cavus, rearfoot varus, tibia vara, genu valgum, genu varum, patella alta, leg length discrepancy, femoral neck anteversion, tibial torsion) that might influence the kinetic chain in a negative way, predisposing athletes to overuse injury. However, further prospective research is necessary to determine the exact causal mechanism and role in overuse injuries.

4.3.1 Bone

4.3.1.1 Stress (Fractures)

Bone constantly remodels through a balance between the processes of osteoclastic resorption and osteoblastic bone synthesis, both of which are under hormonal control. As part of this remodeling process, the greatest amount of bone is laid down in areas of greatest applied stresses, according to Wolff's law. The rate of remodeling also responds to the loads through the bone. High levels of bone stress, through an increase in activity, may lead to an imbalance in the remodeling response in which the osteoclastic activity surpasses the rate of osteoblastic new bone formation, resulting in temporary weakening of the bone (Patel et al. 2011; Pegrum et al. 2012). If repetitive overloading continues, this then manifests clinically as a continuum of bone stress injury that ranges from mild (bone strain) to severe (stress fracture). The clinical and imaging features of bone strain, stress reaction, and stress fractures are summarized in Table 4.5.

As in other overuse injuries, a combination of various factors contributes to bone stress. Two important risk factors are (1) training errors (too much, too often, and too quickly with too little rest) and (2) an energy imbalance between calories expended and taken in. Energy imbalance causes menstrual irregularity and impaired bone health. This combination of energy deficiency, menstrual disturbances, and bone loss is often referred to as the "female athlete triad" (De Souza et al. 2014). Other potential risk factors are white race, female sex, malalignment, muscle fatigue, training surface, and footwear.

Stress fractures are not uncommon. Ten to twenty percent of consultations in sports medicine clinics are for stress fractures. Stress fractures occur either

Table 4.5 Clinical and imaging findings of the continuum of bony changes with overuse

Clinical features	Bone strain	Stress reaction	Stress fracture
Local pain	Nil	Yes	Yes
Local tenderness	Nil	Yes	Yes
Radiographic appearance	Normal	Normal	Late abnormal (periosteal reaction or cortical defect in cortical bone, sclerosis in spongious bone)
CT scan appearance	Normal	Normal	Features of stress fracture (as for X-ray)
Ultrasound	Normal	Normal	Early: hyposonant (non-calcified) periosteal thickening with angiogenesis on Doppler Late: irregular lining of the surface of the bone which in fact is the calcified periosteal reaction
MRI appearance	May show increased high signal	Increased high signal	Increased high signal ± cortical defect, fracture line, periosteal reaction
Radioisotopic bone scan appearance	Mildly increased uptake	Increased uptake	Intense increased uptake

Table 4.6 Stress fractures with a low risk and high risk of nonunion

Low risk of nonunion	High risk of nonunion
Femoral neck fractures of the medial cortex	Femoral neck fractures of the superior cortex
Tibial shaft fractures of the posteromedial cortex	Tibial shaft fractures of the anterior cortex
Fractures of the distal second to fifth metatarsals	Fifth metatarsal, at the diaphyseal-metaphyseal junction
Calcaneal fractures	Navicular fractures
Fractures of the fibula	Proximal fractures of the second metatarsal
Fractures of the pubic ramus	Fractures of the talus
Cuboid fractures	Fractures of the medial malleolus
Cuneiform fractures	Sesamoids

secondary to bone fatigue or bone insufficiency. Fatigue stress fractures occur when normal bone is unable to keep up with repair when repeatedly damaged or stressed. Insufficiency stress fractures, however, occur in bone that is under normal strain but structurally abnormal because of metabolic bone disease or osteoporosis.

The most common locations for stress fractures are the tibia (23.6 %), tarsal navicular (17.6 %), metatarsal (16.2 %), fibula (15.5 %), femur (6.6 %), pelvis (1.6 %), and spine (0.6 %). Although less common, upper extremity stress fractures can occur in persons who participate in sports involving a lot of throwing or other overhead activities. Rib stress fractures have been described in rowers.

The typical history of a stress fracture is that of localized pain which comes on during or after exercise and persists or increases if exercise is continued. The physical examination typically reveals local tenderness over the involved bone and in some cases also swelling. Imaging options, including plain radiography, CT, ultrasound, bone scan, and MRI, play a significant role in the diagnosis (Table 4.5) and will be discussed throughout this book in several chapters in more detail.

Stress fractures can be stratified into those with a low risk or high risk of nonunion on the basis of location, direction of loading through the fracture during ambulation, and natural course of fracture healing (Table 4.6) (Patel et al. 2011; Pegrum et al. 2012). Stress fractures classified as being at high risk of nonunion occur in zones of tension or have poor blood supply.

Management depends on the risk of nonunion. Low-risk fractures generally require no treatment other than rest and respond well to activity modification. High-risk stress fractures do not have an overall favorable natural history. With delay in diagnosis or with less aggressive treatment, high-risk stress fractures tend to progress to nonunion or complete fracture, require operative management, or recur in the same location.

Osteitis and Periostitis

Osteitis and periostitis are also considered overuse injuries but the exact pathogenesis of these injuries remains controversial, and they are often part of a more complex pain syndrome, like adductor-related groin pain or the medial tibia stress syndrome.

Osteitis pubis is an inflammation of the pubic symphysis and is characterized by deep-seated pain and tenderness of the symphysis pubis and often groin and lower abdominal region (Hiti et al. 2011).

Inflammation of the periosteum, a layer of connective tissue that surrounds the bone, causes periostitis. The condition is generally chronic and is marked by tenderness and swelling of the bone and an aching pain. This occurs commonly, mainly, at the medial border of the tibia, a condition often known as "shin splints" or medial tibia stress syndrome (Moen et al. 2009).

Apophysitis

In skeletally immature athletes, traction injuries can affect the apophysis in acute and overuse situations. In a condition called "apophysitis," bony injury occurs due to repeated stress at the tendinous insertion to the growth areas. The most common examples are Osgood-Schlatter disease at the attachment of the patellar tendon to the tibial tuberosity and Sever's disease at the attachment of the Achilles tendon to the calcaneus (Gholve et al. 2007; Gillespie 2010).

4.3.2 Cartilage

The cause of primary osteoarthritis is still unknown. Participation in sports has evolved as a cause of osteoarthritis (OA), especially in hip and knee joints (Buckwalter and Martin 2004). Overuse injury can affect the articular cartilage lining of the joints (chondropathy). Changes range from microscopic inflammatory changes to softening, fibrillation, fissuring, and ultimately to gross visible changes. OA often occurs at a relatively early age in adult life, in certain sports (soccer, rugby, racket sports, and other track and field sports), and under certain conditions (high level of practice). Joint overuse even without notable trauma is likely the main mechanism of OA in these sports, depending chiefly on the category of sport and on the level and duration of practice. Irregular or sudden impacts, heavy load application on the dominant weight-bearing lower limb, and the preexisting state of the joint including dysplasia, dystrophy, or previous trauma are risk factors for OA (Takeda et al. 2011). However, recreational sport activities at a reasonable level are not likely to be harmful for most individuals, in most sports and exercise activities.

4.3.3 Joint

Overuse can also cause inflammatory changes of the synovium in joints, which are classified as synovitis or capsulitis. Examples are the sinus tarsi syndrome of the subtalar joint and synovitis of the hip joint (Do 2000; Klausner and McKeigue 2000).

Impingement syndromes occur when a bony abnormality, either congenital or acquired, causes two bony surfaces to impinge on each other (e.g., posterior impingement at the ankle or at the elbow, femoroacetabular impingement at the hip) or impinge on a structure passing between them (e.g., supraspinatus tendon in the shoulder) causing damage to that structure (Harrison and Flatow 2011; Sankar et al. 2013).

4.3.4 Ligament

Overuse injuries of ligaments are rare but may sometimes occur whenever a ligament is overstretched due to repeated stress and microtraumata. A typical example is the "breaststroker's knee," an overuse injury of the medial collateral ligament of the knee at its femoral attachment, resulting from the repetitive breaststroke kick (Vizsolyi et al. 1987). Repetitive throwing with valgus loading can give rise to overuse injury of the medial collateral ligament of the elbow (Chen et al. 2001).

4.3.5 Muscle

4.3.5.1 Focal Tissue Thickening/Fibrosis

Muscle imbalances are commonly associated with muscle overuse injuries. Repetitive microtraumata to the muscle, due to overuse, may cause changes to the muscle fibers leading to focal tissue thickening or fibrosis. These changes may be palpated as firm, thickened bands arranged in the direction of the stress or as large areas of increased muscle tone and thickening. These lesions may cause local pain or compromise the ability of the affected muscle to contract and relax rapidly. Entrapment of the sciatic nerve between muscle fibrosis has been described in the hamstring syndrome (Puranen and Orava 1991).

4.3.5.2 Chronic Compartment Syndrome

Chronic exertional compartment syndrome is an uncommon phenomenon caused by intermittent and reversible pathologic elevation of the intra-compartmental pressure, which leads to decreased tissue perfusion (George and Hutchinson 2012). The syndrome is usually related to repetitive physical activity, usually in young people and athletes. The physical activity performed by the patient causes a rise in intra-compartmental pressure and thereby causes pain. The patient discontinues the activity and the pain subsides within minutes of rest. Chronic exertional syndrome is reported to occur in the thigh, shoulder, arm, hand, foot, and gluteal region but most commonly in the lower leg, especially the anterior compartment. The involved muscles are divided into a number of compartments by fascial sheaths, which are relatively inelastic thickenings of collagenous tissue. Exercise raises the intra-compartmental pressure and may cause local muscle swelling and accumulation of fluid in the interstitial spaces. The tight fascia prevents expansion. This impairs the blood supply and causes pain with exertion. Compression of neurological structures may also contribute to the clinical presentation. Muscle hypertrophy may also precipitate chronic compartment syndrome.

The diagnosis of chronic exertional compartment syndrome is primarily based on patients' medical history, supported by intramuscular pressure measurement of the specific compartment involved. MRI immediately after eccentric muscle activity my show specific muscle edema patterns (Gielen et al. 2009).

4.3.5.3 Delayed-Onset Muscle Soreness (DOMS)

Following unaccustomed physical activity, a sensation of discomfort, predominantly within the skeletal muscle, may be experienced in the elite or novice athlete. The intensity of discomfort increases within the first 24 h following cessation of exercise, peaks between 24 and 72 h, subsides, and eventually disappears by 5–7 days postexercise. This exercise-induced phenomenon is referred to as delayed-onset muscle soreness (DOMS) and is perhaps one of the most common and recurrent forms of sports injury (Lewis et al. 2012). It appears to be more severe after eccentric exercise, such as downhill running. The intensity and duration of symptoms are also important factors. The exact underlying mechanism of DOMS is still unknown (Schwellnus et al. 2008). DOMS results in temporary decrease in muscle force production, increase in passive tension, and increase in muscle soreness which may be accompanied by localized swelling. It occurs less in those who train regularly, although even trained individuals may become sore after an unaccustomed exercise bout.

4.3.6 Tendon

Tendon disorders comprise 30–50 % of all sports-related injuries (Ackermann and Renstrom 2012). The clinical presentation is straightforward in many cases—the patient presents with tendon pain during or after activity. In the early stages of the condition, athletes can "run through" the pain or the pain disappears when they warm up, only to return after exercise when they cool down. The athlete is able to continue to train fully; however, when continuing normal training routines, function will be progressively impaired. Loading tests demonstrate increased pain with increased load, and palpation can localize tendon pain accurately and reveals thickening of the tendon.

The terminology used to describe chronic tendon disorders has changed in the past few decades. For many years, this condition was defined as "tendinitis," denoting inflammation of the tendon as the main underlying pathology. These terms have been abandoned, as there are no signs of a prostaglandin-mediated inflammation in chronic painful tendons analyzed after biopsy or with microdialysis (Khan et al. 2002). Histopathological studies showed that chronic painful tendons are frequently characterized by degeneration of the tendon tissue, also referred to as "tendinosis." The term tendinosis is based on histopathological characteristics and should only be used after histopathological confirmation (Khan et al. 1999). In clinical use it is therefore better to use the term tendinopathy.

Mechanical loading of tendon tissue is anabolic by increasing synthesis of collagen. This peaks around 24 h after exercise and remains elevated for up to 70–80 h. However, exercise also results in degradation of collagen proteins, although the timing of this catabolic peak occurs earlier than the anabolic peak. This results in a net loss of collagen around the first 24–36 h after training, followed by a net gain in collagen. Thus, a certain restitution time interval in between exercise bouts is critical for the tissue to adapt and to avoid a net catabolic situation (Magnusson et al. 2010).

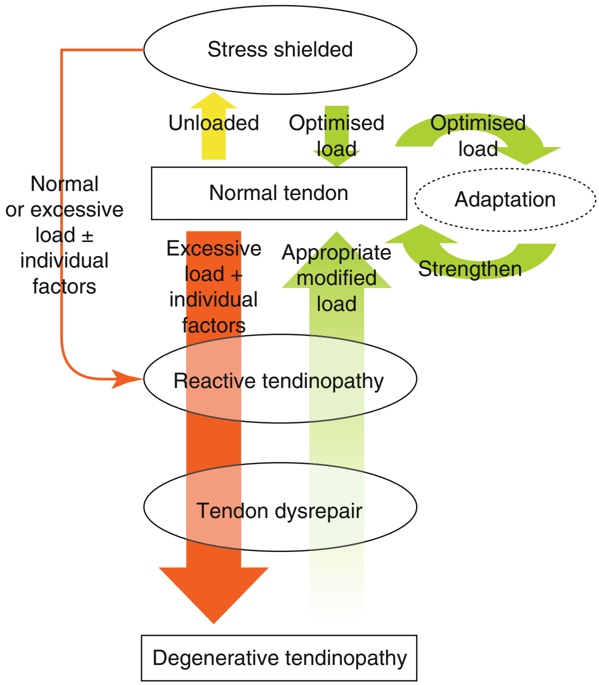

Fig. 4.2 Continuum of tendon pathology (Cook and Purdam 2009)

Repetitive microtrauma due to overload and insufficient restitution time may be considered as the initial disease factor; micro-ruptures of tendon fibers occur and several molecules are expressed including inflammatory cytokines, which act as disease mediators, while other released factors promote the healing process. Neural ingrowth that accompanies the neovessels explains the occurrence of pain and triggers neurogenic-mediated inflammation. This complex and not fully elucidated pathophysiologic process of (neuro)inflammatory and degenerative changes finally leads to a painful tendon with a failed healing response (Rees et al. 2014).

However, this rather simplified description of a complex pathophysiologic process does not fully explain the heterogeneity in presentation and variability in recovery. Cook and Purdam recently proposed a new model of tendinopathy, which is based on available evidence from pathology, clinical, and imaging studies (Cook and Purdam 2009). This "continuum of tendon pathology" (Fig. 4.2) describes three distinct stages: (1) reactive tendinopathy, (2) tendon disrepair (failed healing), and (3) degenerative tendinopathy. The load applied to the tendon is the crucial factor in this continuum.

Clinical and imaging features allow a tendon to be classified as one of these stages (Table 4.7). However one should keep in mind that there is continuity between these stages and that combined stages can exist within a tendon.

Although there have been many advances in the understanding of the histopathology, imaging techniques, and both conservative and surgical treatment for this condition over the past two decades, successful management of athletes with tendinopathy remains a major challenge for both the practitioner and patient. The high

Table 4.7 Clinical and imaging features of different stages of tendon pathology

	Clinical manifestation	Ultrasound Imaging
Reactive tendinopathy	Acute overload in athlete	Fusiform swollen tendon, collagen fascicles intact with in between hypo-echogenic zones
Tendon disrepair	Chronic overload in young athlete	Discontinuity of collagen fascicle and small focal areas of hypo-echogenicity, vascularization
Degenerative tendinopathy	Chronic overload in older or elite athlete	Extensive hypo-echogenicity and vascularization, few reflections from collagen fascicles

prevalence, the impairment of function, and the chronic character of this condition mean that tendinopathy might have substantial impact on an athlete's career. For some athletes it is even a reason to retire from sports.

4.3.7 Bursa

The body contains many bursae. Bursae are flat sacs of synovial membrane that contain synovial fluid. They are located between tissue planes (e.g., between bone and tendons) and help to reduce frictional stress between those structures.

All bursae are susceptible to injury (Aaron et al. 2011). Overuse injuries resulting from repetitive excessive shearing and/or compressive forces to the bursae are quite common. They usually occur in connection with other local pathology like tendinopathy and impingement syndromes. Typical bursal injuries in the sporting population include subacromial bursitis (in overhead athletes), trochanteric bursitis proposed to be linked to gluteus medius tendinopathy and/or weakness, iliotibial band friction syndrome (frequently seen in runners and cyclists), and retrocalcaneal bursitis, which is often associated with insertional Achilles tendinopathy. Symptoms include localized pain and swelling and typically increase with activity. Ultrasound can be used to confirm the diagnosis. Management involves removal of irritating loads, reduction of inflammation, and a progressive return to pain-free activity.

4.3.8 Nerve

Repetitive and vigorous use or overuse makes the athlete vulnerable to disorders of the peripheral nerves (Toth 2009). They occur in athletes as a result of swelling in the surrounding soft tissues or anatomical abnormalities. Additionally sports equipment may cause compression of the nerves. Nerve entrapment syndromes associated with physical activity may affect both lower and upper extremities, and all nerves for which entrapment syndromes are known can be involved. Most commonly diagnosed is Morton's neuroma, an entrapment with fibrosis surrounding the interdigital nerves especially between the third and fourth toes. This condition is not a true neuroma but rather a nerve compression related to fibrosis. Other lower extremity nerves that can be affected are the obturator nerve in the groin and the posterior tibial nerve at the tarsal tunnel on the medial aspect of the ankle.

In volleyball players, entrapment of the suprascapular nerve has been described. Also the posterior interosseous and the ulnar and median nerves in the upper extremity can be affected. These entrapment syndromes manifest with pain, tingling, numbness, and loss of muscle function. Making a precise diagnosis is not always easy. Peripheral nerve lesions are serious and may delay or preclude the athletes' return to sports, especially in cases with a delayed diagnosis.

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The Role of Radiologic Imaging Techniques in Pathophysiology of Sports Injuries (Including Follow-Up)

5

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Abstract

The incidence of sports-related injuries is increasing. While radiologic techniques have improved and the need for early diagnosis is rising, imaging plays a more prominent role in the management of these sports-related injuries. The choice of the imaging modality depends on costs, availability, radiation dose and accuracy for specific tissues or injuries. Comprehension of the underlying pathophysiologic and biomechanical mechanisms of the injury in a multidisciplinary setting is essential for choice of modality and image interpretation.

5.1 Introduction

The use of imaging techniques in sports injuries is thought essential. Both the development of innovative, soft-tissue-depicting techniques and the higher incidence of sports injuries lead to an increasingly important role of imaging in the diagnostic and follow-up phase of sports-related injuries. The higher incidence of sports injuries can mainly be contributed to a higher number of people participating in sports. Today's society gives much attention to movement in a broader population, to keep them from becoming physically inactive and unhealthy. Therefore imaging in sports injuries is not only requested for the essential quick diagnosis and recovery in elite athletes but also in case of unclear clinical presentation in the general population.

The choice of the most suitable imaging modality is dependent on several factors, e.g. costs, availability and radiation dose. As there is an increasing tendency towards creating sports-oriented multidisciplinary treating team of physicians, the preference of these experts partly determines the imaging modality to be used. Another important decisive factor is the accuracy of the various imaging techniques to depict the actual injury or typical concomitant abnormalities. Every imaging technique has specific qualities to depict the different tissues, i.e. bone, cartilage, tendon/ligaments and muscle. Knowledge on the underlying pathophysiologic mechanisms of sports-related injuries is essential to understand the (dis)advantages of every radiologic imaging technique and to choose the right imaging approach. The objective of this chapter is to provide a pathophysiology-based overview of the role of each radiologic imaging technique in the diagnostic and follow-up phase of sports injuries.

5.2 Bone Injuries

This paragraph will focus on sports-related stress injuries, as it represents a homogeneous majority of all bone injuries in athletes. Stress fractures account for up to 20 % of all injuries presented in sports medicine (Fredericson et al. 2006). The underlying pathophysiology of stress injuries is represented as a continuum starting with a stress reaction, caused by bony remodelling and periostitis, and resulting in the actual stress fracture with cortical break (Demeijere and Vanhoenacker 2007). The multidisciplinary treating team needs to be aware of the wide spectrum of abnormalities belonging to this continuum. Although the diagnosis of stress injuries is mostly based on clinical findings, radiologic imaging studies are routinely obtained to prevent progression in the stress reaction continuum, by an objective judgement on exclusion or confirmation of the diagnosis (Royer et al. 2012).

5.2.1 Imaging Abnormalities of Stress Injuries

Plain radiography has low sensitivity of 10 % in early stages of stress injuries (Matheson et al. 1987). The so-called 'grey cortex' sign is an area of decreased density of the cortex, most probably caused by focal hyperaemia and oedema (Mulligan 1995). Compensation for the weak cortex results in radiographic abnormalities with endosteal thickening and/or formation of new periosteal bone. In the last phase of the pathologic continuum, an actual fracture line can appear on radiography in 50 % of cases (Fig. 5.1) (Demeijere and Vanhoenacker 2007; Fredericson et al. 2006).

Fig. 5.1 Minimal fracture line (*white arrow*) visible in the ventral cortex of the tibia on conventional radiography of a 26-year-old female

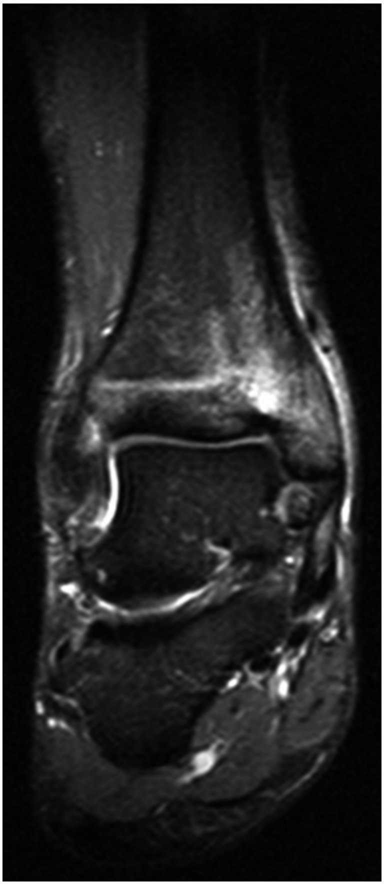

Fig. 5.2 Medial tibia stress fracture in a 19-year-old professional tennis player, indicated by high signal intensity on a coronal T1 TIRM sequence

The chronological findings on magnetic resonance imaging (MRI), as golden standard in the diagnosis of stress injuries, are oedema followed by a cortical fracture line (Fredericson et al. 2006). Pathophysiologically, repetitive stress causes disbalance in the bone remodelling process with microfractures, extensive oedema and haemorrhage. This oedema, either periosteal or in the bone marrow, is represented by increased signal intensity on STIR or fat-saturated T2-weighted MR images (Fredericson et al. 2006; Gaeta et al. 2005) (Fig. 5.2).

Ultrasound can also be helpful in the detection of stress injuries, by showing cortical defects and a hyporeflective layer of oedema, indicative of non-ossified periosteal reaction (Allen and Wilson 2007). The sensitivity and specificity of ultrasound were 81.9 and 66.6 %, respectively, in comparison with MRI in the detection of stress injuries in the lower limb of athletes (Papalada et al. 2012).

In the clinical setting, MRI is frequently followed by computed tomography (CT) to tailor the individual approach in radiologic-orthopaedic multidisciplinary setting (Fig. 5.3). The major advantage of CT over MRI is the direct visualisation of calcified periosteum and bony structures to show the possible cortical fracture line.

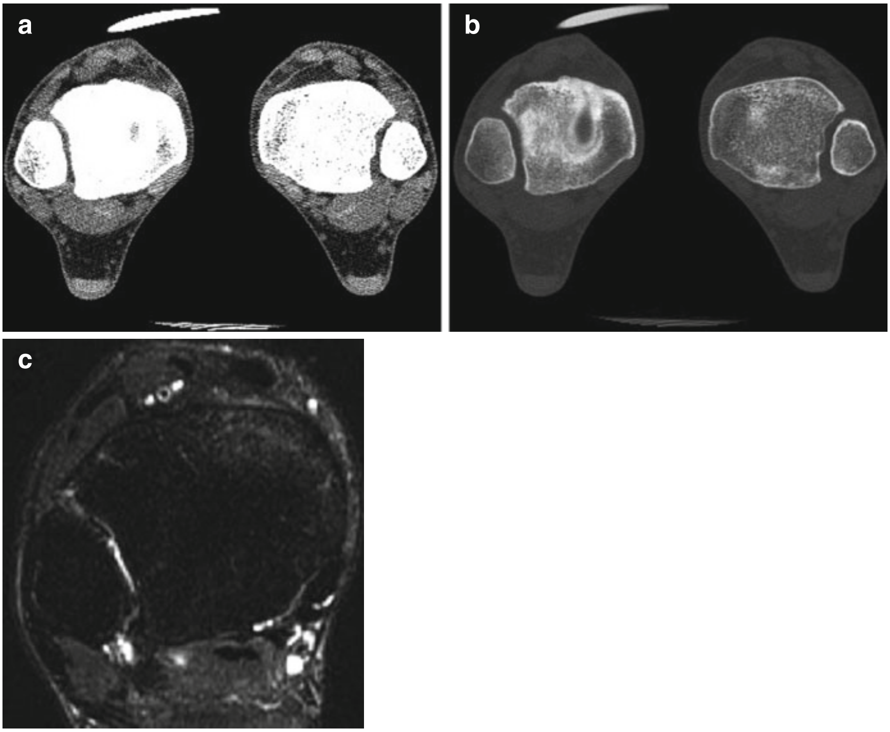

Fig. 5.3 CT of the ankle shows subtle abnormalities belonging to bone contusion at the distal tibia in an 18-year-old female gymnast. The importance of adequate windowing is emphasised by the difference between (**a**) soft-tissue window and (**b**) bone window setting. An axial T2-weighted MR image (**c**) with fat saturation at the same level shows very subtle high signal intensity, indicative of bone marrow oedema. This abnormality might not be obvious enough for the diagnosis of a bone bruise, thereby emphasising the need for additional CT in this case

CT is also valuable for stress injuries in complex anatomical sites, for longitudinal stress fractures and in the differential diagnosis with tumoral lesions, for instance, osteoid osteoma (Demeijere and Vanhoenacker 2007).

Despite the specific (dis)advantages of each imaging technique, they share a potential additional value in the diagnostic and follow-up process of stress reactions. To assort the heterogeneous presentation of the stress-related bone disease and its imaging presentation, a general modality- and site-independent grading system for stress fractures has recently been developed (Kaeding and Miller 2013).

5.2.2 Imaging in the Follow-Up of Stress Injuries

Imaging can predict the course of stress injuries in their follow-up period. Besides the location of the stress injury, prognostic factors like MRI grade at diagnosis can be very valuable in predicting the time to full return (Dobrindt et al. 2012; Nattiv et al. 2013). The duration of the rest period after the diagnosis of stress injury depends on the location, the patient's individual characteristics and the type of sport.

Repeated imaging is not an absolute requirement before return to activity. If plain radiography is performed, no more abnormalities besides callus should be present (Royer et al. 2012). When MRI is repeated, one should carefully interpret the findings and always correlate with clinical symptoms, because firstly the presence of features mimicking stress injuries is present in approximately 43 % of asymptomatic athletes (Bergman et al. 2004). Other studies state that MRI features of stress injuries resolve at longer term and are also hampered by susceptibility artefacts of the thick sclerotic cortical bone next to the original fracture line. CT is believed to be more accurate in the long-term detection of stress fractures than MRI (Fig. 5.4) (Burne et al. 2005).

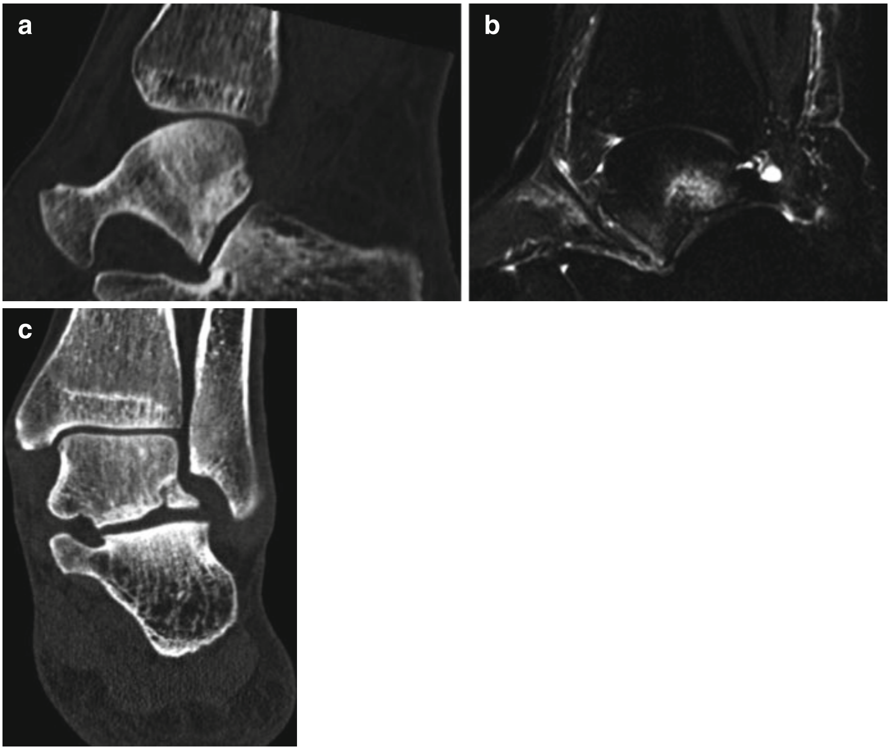

Fig. 5.4 Stress fracture of the lateral process of the talus on CT of the ankle in a 60-year-old male runner visualised on CT (**a**) and MRI (**b**). The CT shows sclerosis in the talus with a subtle fracture line, which may be hard to detect. On a sagittal T2-weighted MR image with fat saturation, an evident area of high signal intensity is present, clearly indicating the stress fracture. Follow-up CT (**c**) performed 17 months later (**c**) shows no complete healing of the abnormalities in the coronal orientation. Bone resorption in the original fracture line is visible

5.3 Cartilage Injuries

Cartilage is a frequently affected tissue in athletes. Spontaneous healing of cartilage injuries is extremely rare and persistent damage can lead to osteoarthritis. Imaging is a key player in the management of cartilage injuries in athletes, as adequate depiction of abnormalities enables good decision-making both in the diagnostic and follow-up phase.

Currently the imaging of cartilage injuries in sports medicine is based on MRI and MR arthrography as golden standards. The MRI field strength of 3.0 T is superior to 1.5 T in both morphologic and compositional imaging of the cartilage. The use of 7.0 T in cartilage imaging is still restricted to research purposes (Roemer et al. 2011). Although MRI is used more often in daily practice for cartilage injuries, there is no significant difference of diagnostic accuracy between MRI and CT in, for example, the detection of osteochondral defects (Verhagen et al. 2005). Plain radiography can be helpful for, for example, assessing weight-bearing joint space width. Arthrography without subsequent CT or MRI is no longer performed (Huysse and Verstraete 2007). The comparable diagnostic accuracy of CT arthrography to MR arthrography is overruled by drawbacks like radiation dose and inability to visualise bone marrow oedema (Waldt et al. 2005). CT arthrography is indicated when patients cannot undergo MRI due to contraindications (De Filippo et al. 2009).

5.3.1 Cartilage-Specific MRI Sequences

5.3.1.1 Morphologic Assessment of Cartilage

There is a large group of sequences available for morphologic assessment of cartilage, roughly to be divided in (fast) spin echo (FSE) and gradient-recalled echo (GRE) sequences. Besides the more conventional SE sequences, recently many new MRI techniques with high accuracy for depicting cartilage have been developed. The vast majority of the cartilage-specific MRI sequences perform similarly with respect to diagnostic accuracy. Other characteristics such as acquisition time, utility for other structures and susceptibility to artefacts are distinctive and summarised in Table 5.1.

Optimal visualisation of cartilage with MRI encompasses several challenges: adequate depiction of accompanying bone marrow oedema, avoiding MRI artefacts, short acquisition time, etc. Some disadvantages can be addressed to a group of sequences. For example, the fat suppression and concomitant adequate depiction of bone marrow abnormalities is particularly achieved with non-GRE-type sequences (Roemer et al. 2009). Additionally, GRE-type sequences are also more prone to susceptibility artefacts caused by, for example, metal. Furthermore two-dimensional sequences are hampered by obligatory acquisition in multiple planes, which increases the total scanning time. On the other hand, the longer duration of three-dimensional sequences goes together with higher susceptibility to motion artefacts.

In clinical practice, the standard sequence mostly used for the evaluation of cartilage is a two-dimensional (2D) fast spin echo (FSE) sequence, preferable T2- or

Table 5.1 MRI techniques for morphologic evaluation of cartilage

	Technique	Diagnostic accuracy for cartilage lesions[a]	Other structures	Acquisition time	Signal intensity	
					Cartilage	Fluid
(F)SE	2D FSE (T2 or PD)	Sens 68.2 % Spec 92.8 % (Kijowski et al. 2009a)	+	–	Intermediate	High
	3D FSE	Sens 72.8 % Spec 88.2 % (Kijowski et al. Kijowski et al. 2009b)	+	+	Intermediate	High
	SPACE	Sens 82.3 % Spec 80.2 % (Notohamiprodjo et al. 2012)	Unknown	–	Intermediate	High
	3D DEFT *(DRIVE)*	Sens 100 % Spec 58.3 % (Yoshioka et al. 2004)	Unknown	–	Intermediate	High
GRE	3D SPGR	Sens 96.7 % Spec 85.3 % (Yoshioka et al. 2004)	–	–	Very high	Low
	FLASH	Sens 62.4–74.2 % Spec 77.6–89.4 % (Duc et al. 2007)	Unknown	–	Very high	Low
	3D DESS	Sens 55.9–72.0 % Spec 95.3–77.6 % (Duc et al. 2007)	Unknown	+	Intermediate	Very high
	3D bSSFP *(trueFISP)*	Sens 51.6–64.5 % Spec 80.0–94.1 % (Duc et al. 2007)	+	+	High	Very high
	VIPR	Sens 76.5 % Spec 92.2 % (Kijowski et al. 2009a, b)	+	+	Intermediate	Very high

(F)SE (fast) spin echo, *GRE* gradient-recalled echo, *2D* two-dimensional, *3D* three-dimensional, *T2* T2-weighted images, *PD* proton density-weighted images, *SPACE* sampling perfection with application-optimised contrast using different flip-angle evolutions, *DEFT* driven equilibrium Fourier transform, *SPGR* spoiled gradient-recalled echo, *FLASH* fast low-angle shot, *DESS* dual-echo steady state, *bSSFP* balanced steady-state free precession, *VIPR* vastly undersampled isotropic projection reconstruction
[a]Compared to arthroscopy

PD-weighted sequences. T1-weighted FSE images are avoided due to poor capability of depicting other structures besides cartilage and lack of contrast between joint effusion and cartilage. The development of three-dimensional (3D) FSE sequences with multiplanar reconstruction capabilities improves acquisition time and is very promising for future clinical use (Roemer et al. 2011).

5.3.1.2 Compositional Imaging of Cartilage

Very early damage to the articular cartilage cannot be reliably detected by any of the MRI sequences from Table 5.1 (Huysse and Verstraete 2007). Novel MRI imaging techniques depicting the changes on biomechanical or structural level can be of great additional value in the detection of this early cartilage degeneration in athletes. The most important compositional imaging techniques include T2 mapping, delayed gadolinium-enhanced MR imaging of cartilage (dGEMRIC), T1ρ imaging, sodium imaging and diffusion-weighted imaging. They are all based on assessment of collagen network, water content and/or glycosaminoglycans (Crema et al. 2011). However, these quantitative MRI techniques need further refinement before any additional value in cartilage imaging in sports can be guaranteed.

5.3.1.3 MR Arthrography

MR arthrography can be performed in a direct and indirect manner. The former includes direct intra-articular injection of contrast solution, mostly under fluoroscopic visualisation. Indirect MR arthrography is the intravenous contrast administration followed by MRI. In cartilage imaging, direct MR arthrography is useful in smaller joints and joints with thinner cartilage surfaces. The most frequently imaged joints by direct MR arthrography in the athletic population are the hip and the shoulder joint. Diagnostic accuracy for the detection of cartilage lesions for both the hip and shoulder joint is dependent on the level of training of the performing radiologist (McGuire et al. 2012; Theodoropoulos et al. 2010). Nevertheless, sensitivity and specificity of direct MR arthrography for the detection of cartilage injuries in the hip and shoulder are mostly reported to be superior to conventional MRI (Blankenbaker and De Smet 2010; Lee et al. 2013; Magee 2009).

5.3.2 Cartilage Abnormalities on MRI

The underlying pathophysiologic mechanisms of the cartilage defects on MRI can roughly be divided into acute/traumatic and chronic for every joint. An MRI abnormality indicative of acute cartilage injury is subchondral bone marrow oedema. Bone marrow oedema accompanying a chondral defect reflects the response of the subjacent bone to acute injury, following impact or shear forces on the cartilage. In case of subcortical broad-based bone marrow abnormalities on MRI, an osteochondral fracture needs to be ruled out. An osteochondral fracture is characterised by involvement of both the cartilage and the subchondral bone, visualised as an interruption of the subchondral ‘black line’ on MRI (Black et al. 2009). Bone marrow oedema can also be present in a focal cartilage lesion (also referred to as ‘transchondral fracture’), in which there exists only a partial- or full-thickness interruption of the cartilage on MRI (Black et al. 2009). Furthermore osteochondritis dissecans and chondral delamination have an acute injury mechanism as well. Abnormalities as sclerosis of the subchondral bone, gradual lesion edges and absence of bone marrow oedema shift probability more towards a chronic cartilage lesion (Huysse and Verstraete 2007) (Fig. 5.5).

5.3.3 Radiologic Follow-Up of Cartilage Injuries

As cartilage has very limited intrinsic repairing capabilities, surgical repair is often warranted to prevent osteoarthritis at long term. For the evaluation of this cartilage

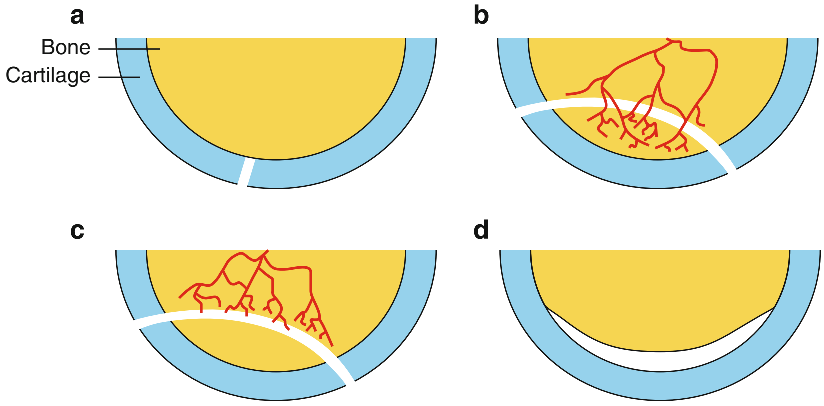

Fig. 5.5 (**a**–**d**) Schematic representation of injuries involving cartilage: (**a**) focal cartilage lesion, (**b**) osteochondral fracture, (**c**) osteochondritis dissecans and (**d**) cartilage delamination

repair on MRI, several classification systems have been developed. The magnetic resonance observation of cartilage repair tissue (MOCART) score is reliable, reproducible and accurate, and therefore most frequently used (Marlovits et al. 2004; Marlovits et al. 2006). Graft failure is more likely when MRI signs like persistent marrow oedema (>8–12 months), subchondral cyst formation, extensive subchondral sclerosis, narrow thickness of graft and delamination of the cartilage are present. Despite the reliability as a cartilage repair MRI evaluation tool, the capability of the MOCART score to predict clinical outcome is questionable (de Windt et al. 2013).

5.4 Tendon and Ligament Injuries

Tendons and ligaments share their longitudinal orientation of dense connective tissue. However, ligaments have more interweaving of collagen fibres in comparison with tendons.

Sports-related tendon injuries can be divided in tendon tears, tendinopathy (the former tendinosis), tendon subluxation and tenosynovitis. The term ‘tendinitis’ is confusing, because it implies inflammation of the tendon but refers to the same noninflammatory degenerative condition as tendinosis (Maffulli et al. 1998). Tendinopathy is a more descriptive umbrella term comprising the clinical syndrome (Chang and Miller 2009).

Recently, a pathology model has been developed to explain the tendinopathy presentation (Cook and Purdam 2009), in which tendinopathy is suggested to be a continuum, ranging from reactive tendinopathy to tendon disrepair and ultimately to degenerative tendinopathy. Tendon ruptures are more likely to occur at the weak point in the kinetic chain suffering from, for example, repetitive overuse (Kainberger and Weidekamm 2005), i.e. the so-called degenerative tendinopathy stage (Cook and Purdam 2009). For the performing radiologist, it is important to look for unique and distinguishing features of each individual tendon abnormality (Fig. 5.6).

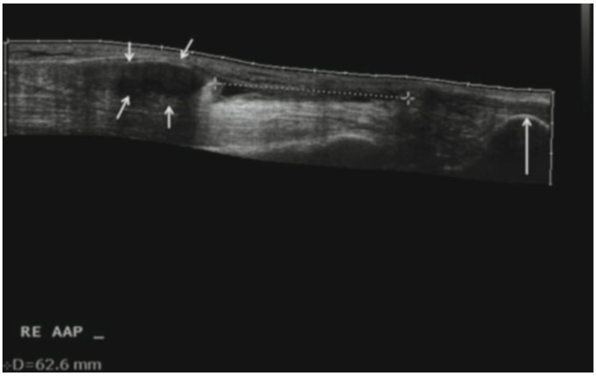

Fig. 5.6 Sagittal image in 56 year old male patient with sudden painful snap at the right calf during running activity. The patient has a history of chronic activity (several months) related pain at the right calf. Sagittal US extended-field-of-view-scan shows retracted tendon with empty paratenon (*cross marks*). Proximal retracted and thickened tendon (*short arrows*), distal tendon insertion at tuber calcanei (*long arrow*) has a normal appearance (Image provided by JLMA Gielen, University of Antwerp)

Ligament injuries of an athlete include both acute and chronic conditions but can also be classified as intra- and extra-articular injuries. Typical examples of sports-related tendon and ligament injuries include the rotator cuff and Achilles tendinopathies, jumper's and runner's knee, tennis and golfer's elbow, climber's finger and ankle sprains.

5.4.1 Imaging Tendon Injuries

The majority of tendon and ligament abnormalities are detected in soft-tissue structures, limiting the utility of plain radiography or CT in these injuries. It is stated that CT is only useful in case of bone trauma, for the detection and assessment of subtle fractures. However, in our experience CT is also necessary to rule out tiny bone fragments accompanying the tendon injury. These bone fragments are not easily detected with MRI or US but can cause chronic irritation and suboptimal recovery.

Both ligaments and tendons are susceptible to anisotropy on ultrasound when the ultrasound beam is not projected perpendicular to the fibres of the tendon or ligament. This phenomenon is visible on ultrasound as loss of echogenic appearance and may simulate disease of the tendon or ligament (Garcia et al. 2003). Although ultrasound is easy to use and allows dynamic evaluation, MRI has certain advantages in imaging tendon disease as well. Besides the ability to evaluate deeper located structures, abnormalities in surrounding tissue accompanying the tendon disease (e.g. bone marrow oedema) can also be detected (Kainberger and Weidekamm 2005). However, also on MRI an anisotropic prolongation of relaxation time can occur on short echo sequences when the tendon is oriented approximately 55° to the magnetic field. This phenomenon is called the magic angle phenomenon and mimics tendinopathy because of the artificial high signal intensity in the tendon (Erickson et al. 1991). Both modalities show high accuracy in the detection of various tendon abnormalities (Chang and Miller 2009).

5.4.1.1 Tendon Abnormalities on US

A full-thickness tendon tear can also be accompanied by a haematoma and needs to be differentiated from partial-thickness tear or tendinopathy, due to the need for surgical intervention (Tok et al. 2012). Dynamic US can be very helpful in showing a gap in the tendon in case of a tear and to dynamically assess tendon subluxation (Allen and Wilson 2007; Neustadter et al. 2004).

Tendinopathy is visualised on ultrasound by features as tendon thickening, heterogeneous echotexture, focal hypoechogenicity and calcifications (Ahmed and Nazarian 2010). An abnormality which tendinopathy has in common with tenosynovitis is increased power Doppler flow in the tendon. In case of tenosynovitis, this neovascularisation depicted as increased Doppler flow can also be detected in the tendon sheath. Though the feature on ultrasound is the same, the underlying pathophysiologic mechanism of the neovascularisation is different: inflammation in tenosynovitis and attempt of repair in tendinopathy (Allen 2007).

5.4.1.2 Tendon Abnormalities on MRI

The most common MRI abnormalities that can be present in every pathophysiologic phase of sports-related tendon disease include increased intratendinous signal intensity and thickening of the tendon. Tendon sheaths or paratenons which enhance after intravenous contrast or surrounded by fluid are more specific for tenosynovitis. In case of partial- or full-thickness tendon tear, the radiologist should look for discontinuity of the fibres and a tendon gap, filled with either fluid, fat or scar tissue (Chang and Miller 2009; Hodgson et al. 2012).

5.4.2 Imaging Ligament Injuries

The modality of choice for ligament injuries depends on the suspected anatomic location and injury mechanism: intra-articular ligament injuries are exclusively properly visualised with MRI, while extra-articular ligaments can also be visualised by US (Allen 2007). Although MRI may be technically more difficult (e.g. small section thickness needs to be obtained), the capability to assess other abnormalities (e.g. microfracturing) is advantageous.

The radiologist needs to be aware of the injury mechanism, as acute and chronic ligament sprains require other imaging techniques and represent with other imaging characteristics. An acute ligament sprain often shows fluid around the ligament, presenting as hypoechoic on US and with increased signal intensity on STIR or T2-weighted MR images. Moreover the original fibre structure of the ligament is disturbed. In case of an acute injury mechanism possibly leading to ligament rupture, imaging is the key player in distinguishing partial from complete ruptures. The latter are characterised by discontinuity of the ligament, a haematoma and instability or gaps at dynamic US examination. Chronically damaged ligaments show laxity and irregularities on imaging. Also residual features like calcifications or even nonunion can be visualised both on US and MRI (Allen 2007; Hodgson et al. 2012).

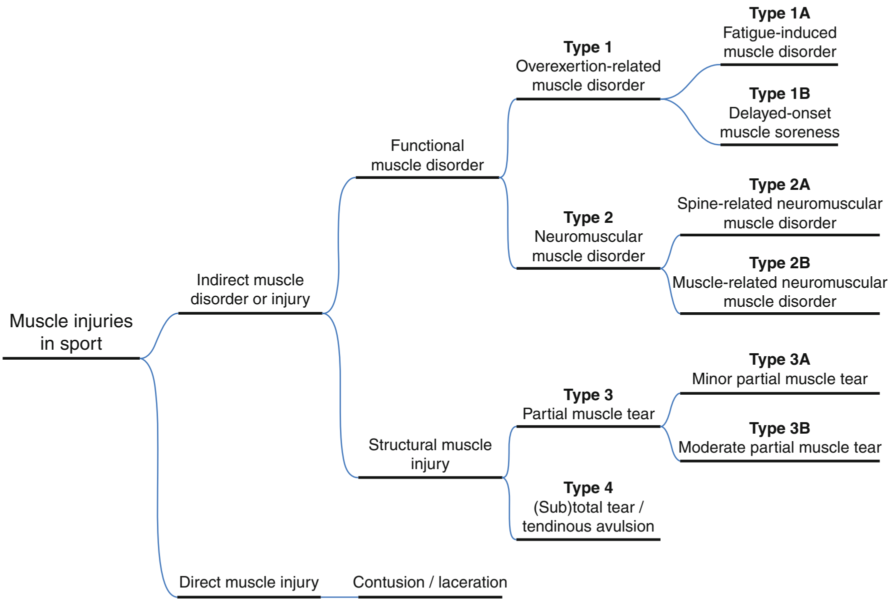

Fig. 5.7 Classification of the muscle injuries in sports based on a recently established new classification system (Mueller-Wohlfahrt et al. 2013)

5.5 Muscle Injuries

The muscle is affected in approximately one third of all injuries in athletes (Junge and Dvorak 2013). Although the clinical examination may sometimes be sufficient, imaging is very important for the diagnosis, prognosis and monitoring of muscle injuries in athletes. Muscle lesions in athletes are mostly divided based on injury mechanism: direct, indirect or late complications of muscle injuries, as visualised in Fig. 5.7 (Mueller-Wohlfahrt et al. 2013). Also imaging-based classification systems have been developed for both MRI (Ahmad et al. 2013) and US (Peetrons 2002). MRI is considered as the golden standard technique, as it is more sensitive in follow-up imaging (Connell et al. 2004). Nevertheless US also has some interesting advantages in the evaluation of muscle injuries, further specified in Sect. 5.5.2.1. Additionally, the development of novel imaging techniques, like diffusion-tensor imaging (DTI) and US-related techniques (e.g. elastography), provides new perspectives in the research field of muscle injuries.

5.5.1 Muscle Abnormalities on MRI

5.5.1.1 Conventional MRI

The conventional MRI protocol for muscle injuries includes both fluid-sensitive sequences (e.g. short tau inversion recovery (STIR), fat-saturated T2-weighted, fat-saturated proton density) and T1-weighted sequences (mainly for the anatomic correlation). There are several common features on MRI, shared by different kind of muscle injuries. For example, oedema and perifascial fluid (both high signal intensity on fluid-sensitive sequences) are frequently seen. However, the injury-specific imaging abnormalities and correlation with clinical history are important, because each individual injury has its own implications for, for example, rest period and management.

The so-called functional muscle disorders in sport (types 1 and 2) are generally characterised by muscle tightness/stiffness. Pathophysiologically only the oedematous swelling can cause some abnormalities on MRI. The structural muscle injuries (type 3) following indirect mechanisms are represented by a broader spectrum of imaging abnormalities on MRI as shown in Fig. 5.8. Direct muscle injuries, i.e. contusion and laceration, cause feather-like oedema due to muscle compression against the underlying bone. If the impact of the object is sufficient, haematoma is very likely to be detected on MRI and US. The imaging abnormalities typical for haematoma depend on the time between the imaging and the injury, because different blood products are predominantly present in the process of degradation of the haematoma (Lee et al. 2012). This fluctuating imaging pattern of a haematoma after contusion or laceration muscle injury is represented in Table 5.2.

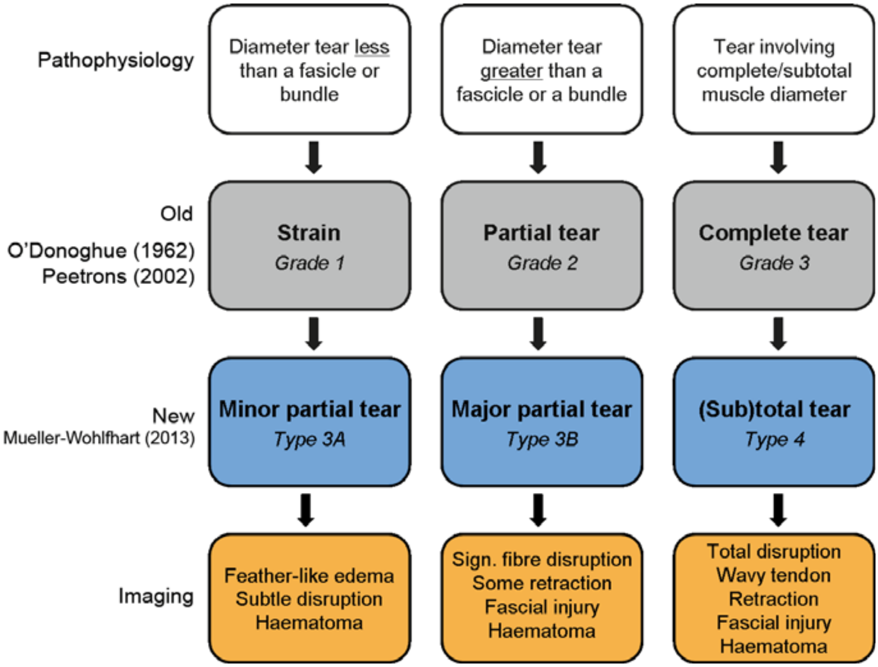

Fig. 5.8 Schematic representation of the acute, structural muscle injuries

Table 5.2 Time-dependent pattern of haematoma on both MRI and US

Haematoma following direct muscle injury		MRI		Ultrasound
		T1 signal[a]	T2 signal[a]	
Acute	4 h	Isointense	High	Isoechoic, swollen muscle, fascial boundaries crossed
	4–6 h	Isointense	Low	
Subacute	6–72 h	High	Low	Hypoechoic, more clearly delineated
	72 h to 4 weeks	High	High	
Chronic	4 weeks	Low	Low	(Ultimately disappearance)

[a]Signal intensity relative to muscle tissue

5.5.1.2 Diffusion-Tensor Imaging

Muscle injuries are adequately and reproducibly detected with DTI (Froeling et al. 2010; Zaraiskaya et al. 2006). DTI provides several parameters quantifying the (directional) diffusivity. The so-called eigenvalues and eigenvectors provide information on three directions, which can ultimately lead to a 3D projection of the fibre muscle organisation. Furthermore fractional anisotropy and the apparent diffusion coefficient each provide important quantifiable values on the diffusivity of water. Muscle injuries are visualised as disorganised muscle fibre structures on DTI images, generally leading to higher apparent diffusion coefficient and lower fractional anisotropy, both representing less restricted diffusivity (Zaraiskaya et al. 2006).

5.5.2 The Use of Ultrasound in Muscle Injuries

5.5.2.1 Advantageous Specificities of US in Muscle Injuries

Besides obvious advantages such as cost-efficiency and real-time clinical correlation, some other specificities of ultrasound can be very useful in the assessment of muscle injuries in athletes. The high spatial resolution of ultrasound, achieved with high-frequency transducers of 12–17 MHz, is an advantage compared to MRI in the imaging of muscle injuries. Additionally, the extended field-of-view ultrasonography enables the radiologist to tract and measure the pathology in muscle fascicles along large muscle sections (Bucklein et al. 2000). The colour and power Doppler function of US can detect muscle injuries by increased blood flow at the injury site (Lee et al. 2012). Dynamic evaluation has added value in the confirmation of a muscle hernia and in the differentiation of minor from major partial tear (Allen and Wilson 2007; Kramer et al. 2013).

5.5.2.2 Muscle Abnormalities on US

The imaging characteristics of a direct muscle lesion on ultrasound, visible as a haematoma, are summarised in Table 5.2. Indirect muscle lesions following an intrinsic injury mechanism can be evaluated by means of a validated classification

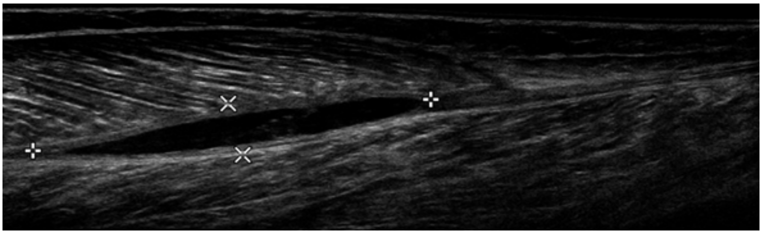

Fig. 5.9 Ultrasound in a panoramic view of a professional tennis player shows a minor partial tear of the rectus femoris. A small haematoma is visualised as a hypoechogenic area (Image provided by JLMA Gielen University of Antwerp)

system (Peetrons 2002). Abnormalities of these injuries due to muscle strain vary from general hyperechogenicity and some perifascial fluid (visualised as a hypo- or anechoic rim) to haematoma, muscle retraction and the 'bell clapper' sign (muscle fibres floating in haematoma) (Fig. 5.9). Functional muscle disorders are by definition without macroscopic evidence of structural damage on MRI or US. Therefore US abnormalities of this group of muscle disorders in athletes are rarely seen (Mueller-Wohlfahrt et al. 2013).

5.5.3 Imaging Follow-Up of Muscle Injuries

5.5.3.1 Normal Healing Process

The healing process of muscle injuries knows a pattern of imaging abnormalities, exemplified in Fig. 5.10. Longer-term features of muscle injury consist of residual abnormalities of acute injury and the formation of scar tissue. Scar tissue becomes visible as hypointense signal on all MRI sequences from 14 days after the injury (Greco et al. 1991). The abnormalities of the prior injury (i.e. hyperintensity on T2-weighted images) slowly diminish but can still be detected on MRI 6 weeks after injury in approximately one third of the athletes (Connell et al. 2004).

5.5.3.2 Complications of Muscle Injuries

Possible complications of muscle injuries include scar tissue, myositis ossificans and muscle hernia.

Scar tissue is grouped under complications as it may alter muscle mechanics and therefore increase the risk of repeat injury (Silder et al. 2008). The scar tissue will develop at the original site of the injury and will show low signal intensity on all MRI frequencies, which makes it difficult to distinct from normal tendons. On ultrasound it will appear as hyperechoic or heterogeneous.

Myositis ossificans is a confusing term, as this condition does not involve inflammation but is defined as the heterotopic non-neoplastic bone or cartilage formation

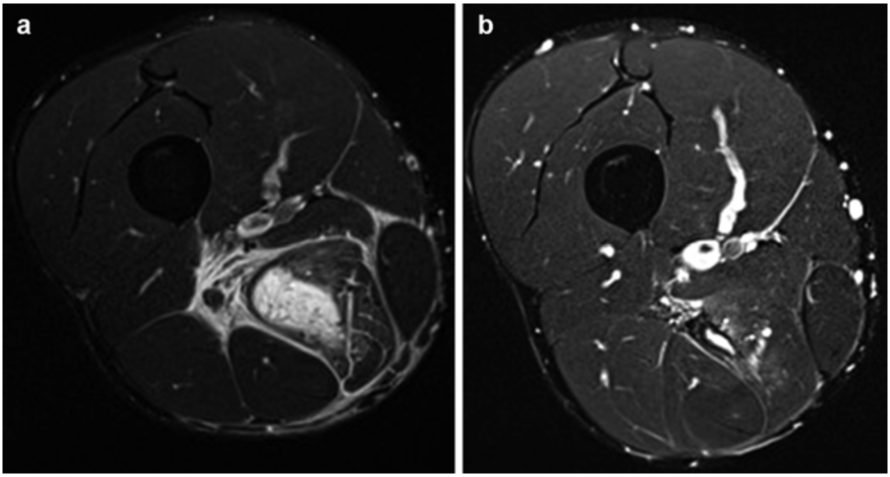

Fig. 5.10 Transversal T2-weighted fat-saturated MRI sequence shows acute muscle injury in a 30-year-old male judoka. (**a**) Extensive hyperintense signal is seen in the semimembranosus muscle, accompanied by an intramuscular fluid collection, indicative of a type 3C muscle tear. (**b**) The follow-up MRI after 4 weeks (no return to play yet) shows significant improvement of the abnormalities, but remaining hyperintensity in the muscle belly left

in or adjacent to a muscle and in proximity to a bone (Fornage and Eftekhari 1989). Ultrasound is the highly sensitive preferred imaging modality for the diagnosis and monitoring of myositis ossificans. Myositis ossificans also has clearly defined imaging features, for example, an oval hypoechoic mass without infiltrative borders is indicative of both early and mature myositis (Abate et al. 2011).

Muscle hernia predominantly occurs after muscle injury through laceration. Muscle fibres are forced through a gap, which is adequately with dynamic ultrasound.

5.5.3.3 Prognostic Value of Imaging

In daily practice, the prognostic capacities of imaging, mainly of MRI, are used very often. Based on several imaging features, a reliable prediction on recovery time can be made. This prediction is essential for the managing of expectations of the athlete and preventing the risk of reinjury in case the activities are resumed too soon after injury.

Many studies have tried to identify MRI features known for their association with recovery time. The most important features include the grade or type of the injury, extent of the intramuscular oedema (length, cross-sectional area or volume) and involvement of the proximal tendon (Table 5.3) (Askling et al. 2007, 2013; Connell et al. 2004; Ekstrand et al. 2012; Gibbs et al. 2004; Kerkhoffs et al. 2013; Silder et al. 2013; Slavotinek et al. 2002; Verrall et al. 2003).

Table 5.3 Prognostic MRI features associated with time to return to play

Article								
Author	Askling	Askling	Connell	Ekstrand	Gibbs	Silder	Slavotinek	Verrall
Year	2007	2013	2004	2012	2004	2013	2002	2003
Sport	Running	Football	Football	Football	Football	Running	Football	Football
N	17	75	58	207	31	25	30	83
MRI features								
Measurement								
Length		+	+		+	+		
CS area	+		+		+		+	
Volume	+						+	
Proximity to origin	+	+				+		
AP extent	+							
Involvement								
Prox. tendon	+	+						
MT junction			+					
Other								
Grading				+				
No hyperintensity		+	+	+	+		+	+
Number muscles						+		

CS area cross-sectional area, *AP extent* anteroposterior extent, *MT junction* musculotendinous junction

Conclusion

Radiology is a key player in optimal management of sports injuries. As the incidence of sports injuries is rising, also in the non-professional athletes, adequate knowledge in multidisciplinary teams of experts is warranted. The expanding capabilities and novel developments of different imaging techniques are essential for further implementation of imaging in the diagnostic process of the athlete. Most importantly, knowledge on injury-specific pathophysiologic mechanisms and concomitant characteristics on imaging is indispensable for adequate diagnosis and monitoring of sports injuries.

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Overview of the Role of Bone Scintigraphy in the Pathophysiology of Sporting Injuries

6

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Abstract

Bone scintigraphy is ideally placed to detect early and subtle manifestations of bone and soft-tissue injury in the context of sporting injuries. The pathophysiology of such injuries is easily reflected in the binding of the bone-seeking pharmaceuticals utilised in the technique. The addition of fused tomographic images from the scintigraphic tomograms and x-ray computed tomography (CT) enhances the sensitivity and specificity for detection of injury by marrying the high contrast resolution of scintigraphy to the spatial resolution of CT scanning. However, the accurate interpretation of images depends on a good history and physical examination together with careful planning of the study to extract the maximum value out of such studies.

Abbreviations

99mTc-MDP	Technetium 99m methylene diphosphonate
ACL	Anterior cruciate ligament
CT	Computerised tomography
MRI	Magnetic resonance imaging
MTP	Metatarsophalangeal joint
OLT	Osteochondral lesion of the talus
SPECT	Single-photon emission computerised tomography

6.1 Introduction

Professional and social sporting injuries have seen the birth of sports medicine as a mature specialty in the last decade. Progressive enablement of a number of unique skills and responsibilities in the medical, social and public health spheres has sharpened the utility of the specialty. The two main pillars of influence in amateur and professional sport have been added to recently with inclusion in Public Health Policy (Blair et al. 2012). In 2007, the American College of Sports Medicine and American Medical Association launched the "Exercise is Medicine" initiative in recognition of the fundamental importance of physical activity to health and well-being. This was a concerted effort to create a global movement to reduce sedentary lifestyles, foster implementation of exercise counselling into clinical practice and disseminate exercise therapy on a global scale. It is in response to the epidemic of obesity (Smith et al. 2005) that has been shown to change injury patterns (Yard and Comstock 2011), affect cartilage (Jones 2009) and joints (Vincent et al. 2012) and increase mortality in later life (Toss et al. 2012). Nuclear medicine has much to offer on the molecular level for the detection of injury and associated metabolic abnormalities.

Between mid-1970s and mid-1980s, the young specialty of nuclear medicine saw a salutary interest in the investigation of sporting injury and generation of a vast number of studies on all aspects of sports medicine. This interest gradually declined as magnetic resonance imaging (MRI) began dominating all other modalities as a result of its superb contrast and spatial resolution, especially for soft-tissue injury. The advent of hybrid instruments that combine single-photon emission computed tomography with x-ray computed tomography (SPECT/CT) has again reawakened interest in molecular imaging in sporting injuries. It exploits the exquisite contrast resolution of SPECT with the high spatial resolution of CT. There is a growing body of literature that demonstrates significant improvements over either SPECT or CT as stand-alone devices (Nadel 2010; Gnanasegaran et al. 2009).

However, while the interest in sporting injuries has been revitalised, there have been many fundamental changes in sports medicine as a specialty. These changes reflect the modulating influence by which society has altered. Furthermore the elite athlete has evolved into a full-time profession, as opposed to the previous dominant role as an amateur. The elite athlete is part of a multimillion dollar industry which has been fostered by the bewildering rate of change in information technology. Interactions with the elite athlete now involve the sporting coach, trainer, business manager, sporting club board, sports medicine physician, physiotherapist and sometimes athlete's legal representative. Individuals who participate in imaging must now give consideration to how these reports are made, as there are implications for the athlete and a number of other interested parties.

6.2 An Approach to Sporting Injury

A fundamental change in imaging strategy for most sporting injuries is the realisation that the imaging specialist is part of a team that contributes to the welfare of the athlete in terms of injury prevention and detection (Brukner and Khan 2001). A high level of competence and good communication skills are critical. There must be flexibility and an awareness of the limitations of imaging. Interaction with the clinician is important in reaching the final diagnosis based on the history and examination and the likely cause of injury. Alternate diagnoses need to be excluded. Evidence for imaging in particular anatomical regions is critically important. Ultimately, the investigations must provide a rapid and accurate diagnosis that *influences management* (Brukner and Khan 2001).

6.3 Pathophysiology

All trauma leads to a series of stereotypic responses that characterise tissue injury. Biochemical and immunological changes from tissue trauma favour the localisation of bone-seeking pharmaceuticals. Any acute injury usually involves haemorrhage, tissue necrosis and calcification followed by healing. Bone-seeking radiopharmaceuticals localise at any sites of either soft-tissue or bone injury. These changes invariably result in localised hyperaemia that is readily apparent in the early flow and blood pool phases of the triple-phase bone scan. Both bone and soft-tissue injuries may be detected, often involving muscles, ligaments, joint capsule or synovium. These sites do not necessarily demonstrate uptake in the late phase of the study. Bone scintigraphy is sensitive for detecting bone bruising, an injury that is not normally evident on plain x-rays or CT but is easily detected by MRI. The fundamental pathophysiology of bone bruising encompasses trabecular microfractures, articular cartilage damage and haemorrhage, without frank cortical or subchondral lamella disruption (Rangger et al. 1998). While osteochondral fractures of the articular and subchondral bone can be detected at an early stage, MRI or CT with multiplanar and three-dimensional reconstruction is critical for staging of the fracture.

6.4 Biomechanics

6.4.1 Acute Injury

In simple terms, bone is an elastic tissue that demonstrates a dynamic response when subjected to stress. When stress increases, there is progressive deformity over a defined elastic range, with return to the resting state if the stress terminates (Fig. 6.1). If the elastic range is exceeded, plastic deformity occurs due to microfractures. Repetitive injury can eventually progress to cracks and cortical or subchondral bone lamella fracture with displacement (Fig. 6.1) (Carter and Caler 1983).

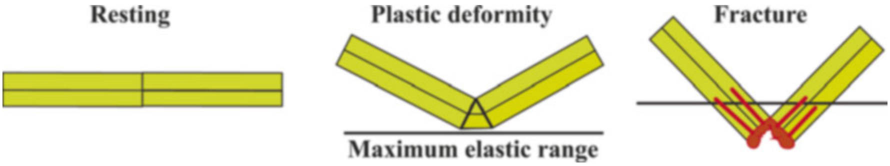


Fig. 6.1 Acute fracture. Schematic representation of progression to fracture when the elastic limit of bone is exceeded. The bone may return to the resting state when the deformity is within the elastic limit

Fractures have a stereotypic response to injury. Repair occurs by laying down periosteal callus by apposition with formation of new bone in layers at a metaphyseal or diaphyseal level. There is remodelling in a synchronised manner, with osteoclasts removing dying osteons and osteoblasts producing new osteoid. Osteoid is mineralised by calcium phosphate with the development of hydroxyapatite.

Periosteal tissue responds within 48 h of injury, creating a splinting callus of trabecular and cartilaginous tissue. The soft-tissue response is characterised by angiogenesis and intense cellular activity. Calcification of the newly formed cartilage begins within days of the injury. Endosteal ossification occurs at a slower rate. Trabecular bone regains a mature laminar structure that after remodelling possesses the mechanical strength of the original tissue.

6.4.2 Chronic Injury

A dynamic balance between bone formation and resorption that is biochemically and biomechanically coupled was the basis of Wolff's law. While this was first documented in 1892, it has been republished in 1986 (Wolff 1986). The biochemical and biomechanical understanding of this process has progressed markedly in the last 120 years. The current understanding is that osteocytes are the primary mechanosensors that regulate load-induced bony remodelling (Chen et al. 2009). Osteocytes live in an interstitial fluid milieu and are connected to each other by the canaliculi. If pressure gradients are applied to the bone, the hydrostatic pressure of the interstitial fluid changes and alters the flow in the canalicular systems, activating osteocytes (Chen et al. 2009). With chronic increase in bone stress, the microtrabecular architecture changes to accommodate the stress by laying down new bone parallel to the stress (Wolff's law) (Frost 2004). This manifests as thickening of the medullary trabeculae and cortex (Chappard et al. 2008). However, thickened bone is less elastic and more prone to microcracks (Sahar et al. 2005), and persistent stress leads to osteocyte apoptosis (O'Brien et al. 2005). An imbalance in the osteocyte/osteoclast equilibrium leads to overactivity of the osteoclasts, making the preconditions for fracture more favourable (Fig. 6.2). When the stress exceeds the capability of the bone to respond appropriately, there is delamination of the cement lines in the cortical bone (Sahar et al. 2005) and eventual propagation of microcracks through the cortex with progression to frank fracture (Fig. 6.2).

Significantly less trauma to osteoporotic or pathologically abnormal bone can lead to fracture at low levels of force. This is most common in the vertebral column and pelvis. Abnormalities of mineralisation will be reflected by prolonged uptake of the scintigraphic agents.

6.5 Epidemiology

Bone injury is the most important form of sporting and exercise-induced injury, particularly due to overuse. Studies indicate a significant delay in detection of stress fractures (Courtenay and Bowers 1990), unlike with acute fracture and soft-tissue injuries.

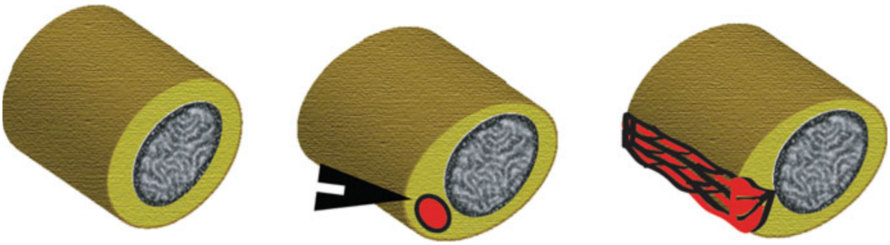


Fig. 6.2 Chronic fracture. Schematic representation of the response of the bone to chronic stress with cortical thickening and progression to delamination of cement lines with microfractures and eventual cortical disruption

Epidemiology of stress fractures has been the subject of a study by (Bennell and Brukner 1997) in which pooled data from a number of recent studies that met reasonable criteria for validity were included. Stress fractures accounted for up to 15.6 % of all injuries in an athletic population. Track and field accounted for 64 % of stress fractures in females and 50 % in males. In military recruits training over an 8-week period, the reported incidence rates varied from 1.1 to 13.9 % in women and 0.9 to 3.2 % in men. Six studies of athletic populations found that there was either no difference between females and males or a slightly increased risk for females (3.5 times the risk for males). The overall recurrence rates were quite high at 12.6 %. In those sustaining a fracture, 60 % gave a history of previous stress fracture. A retrospective study of 20,422 military recruits showed a positive association between increasing age and the incidence of stress fractures in both men and women (Brudvig et al. 1983).

If analysed by site, pooled data from18 studies ($n = 2{,}254$ cases) found 42 % of stress fractures in the tibia, 22 % in the metatarsals and 13 % in the fibula. The rest were distributed unevenly in the pelvis, navicular, femur, spine and upper limbs. Marked variation was shown between recreational and professional athletes. Of 368 fractures, stress fractures of the tibia were more common in professional athletes and stress fractures of the pelvis and metatarsals more common in recreational athletes (Hulkko and Orava 1987; Orava 1980). These studies also found that females sustained more metatarsal, pelvic and navicular fractures than males.

Approximately 9 % of fractures occur in children under 15 years of age, 32 % between 16 and 19 years and 59 % in patients over 20 years (Orava et al. 1981). Distribution of stress fractures in the paediatric population, extracted from pooled data, shows 51 % in the tibia, 20 % in the fibula, 15 % in the pars interarticularis, 3 % in the femur and 2 % in the metatarsals (Yngve 1988).

6.6 Scintigraphy: Technical Issues

Each scintigraphic study should be guided by the patient's history and physical examination, regardless of the later use of SPECT/CT. Dynamic and blood pool studies are essential, particularly over the region of symptoms. Three-phase studies

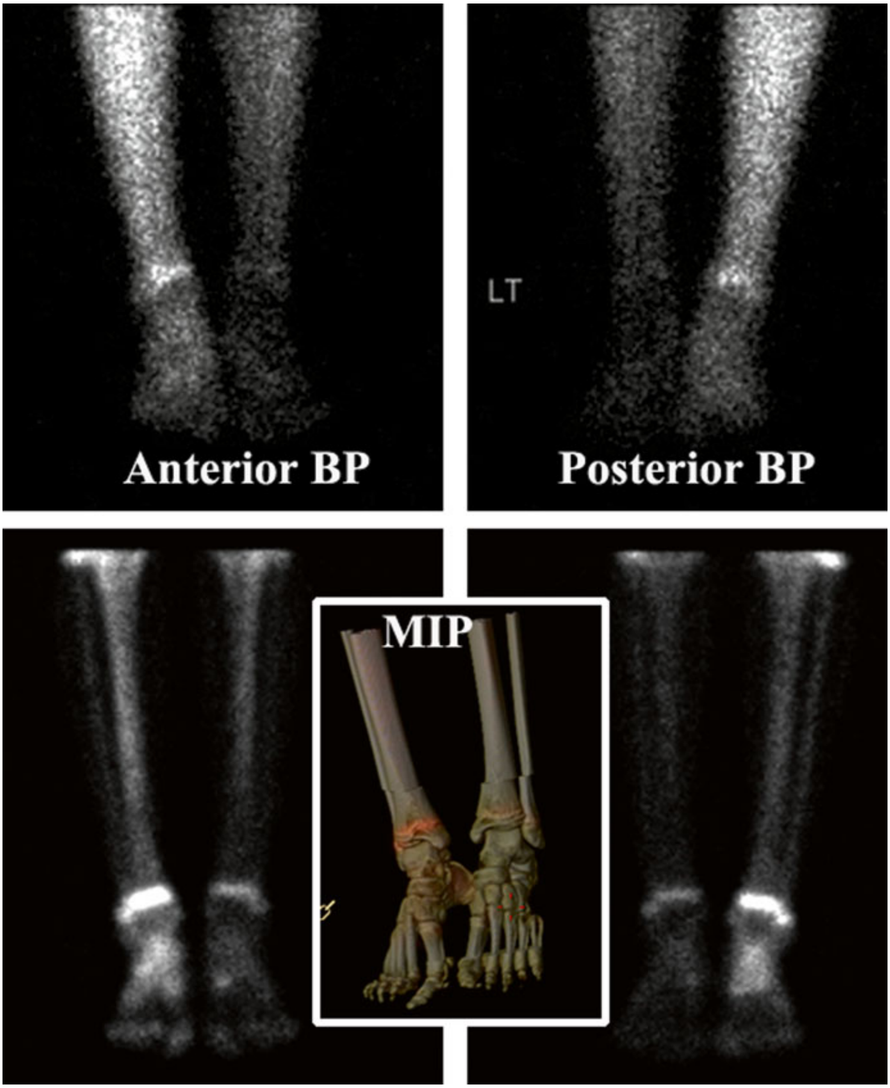


Fig. 6.3 Complex regional pain syndrome (reflex sympathetic dystrophy). Minor injury to the left foot led to burning pain and intermittent numbness in the left foot. Plain films were reported as normal. The scintigraphic study demonstrates globally reduced blood flow and delayed uptake in the left leg which is well illustrated in the MIP image. This is the "cold" variant of the syndrome. The more common manifestation is of diffuse increase in blood flow and delayed uptake, particularly in the periarticular areas

are important and will also increase the diagnostic yield for the complex regional pain syndrome (reflex sympathetic dystrophy) (Fig. 6.3). Positioning of the patient and the site of initial tracer injection are determined from a careful history (e.g. upper limb pathology is evaluated after intravenous injection in the foot). The face of the camera must be perpendicular to the growth plates in children to examine the metaphyseal regions carefully and look for asymmetry in the growth plates (Fig. 6.4). The blood pool is important in the decision regarding a diagnosis of fracture versus soft-tissue injury. It can provide incremental information on soft-tissue pathology involving the tendons, bursae, fasciae and synovial structures.

6.7 Imaging Children

The most vulnerable part of the paediatric skeleton to trauma is the growth plate. The zone of provisional calcification is the most common site of trauma and has the potential for growth arrest if it extends into the germinal zones. Specific injuries can affect the apophysis, a growth plate that does not contribute to longitudinal growth. Salter-Harris staging system (I to V) is used in metaphyseal fractures with increased risk for longitudinal growth disturbance in type V (decreased width of the growth plate related to axial trauma). The most common sites involved are the distal radial and proximal humeral physis in the upper limb and the distal femoral and distal tibial physis in the lower limb. While injuries to the distal femoral physis account for only 2 % of all physeal injuries, they account for ~40 % of the causes of bony bridging (Peterson 1996). The most commonly affected apophyses are in the medial epicondyle (Little Leaguer's elbow), olecranon, coracoid, acromion, vertebrae and around the pelvis. Radiographic evidence of damage includes widening of the growth plate and evidence of apophyseal separation. The scintigraphic equivalent is asymmetric increase in uptake in the affected growth plate (Fig. 6.4) (Connolly et al. 2001).

Great caution should be exercised in children with atypical symptoms as malignant tumours should be kept in mind and the practice of scanning the joint above and below the site of symptoms can yield surprising results.

6.8 Injury by Site

6.8.1 Soft-Tissue Injuries of the Ankle and Foot

The blood pool phase is crucial for detection of soft-tissue injuries. Hyperaemia in the affected structure may only show delayed uptake if there is a significant injury or close apposition to adjacent bony structures that react to the injury, as with the medial malleolus in tibialis posterior tendinopathy.

Such injuries affect the tendons, ligaments, joint capsule and bursae. Scintigraphy can demonstrate enthesopathy or traction injury of the Achilles tendon, the most commonly injured tendon (Fig. 6.5b). The tibialis posterior tendon is the second most frequently injured tendon, usually in ballet dancers and gymnasts. Tibialis posterior tendinopathy may also be seen in association with increased uptake in the accessory navicular bone, constituting the accessory navicular syndrome (Crisp 1998). A similar

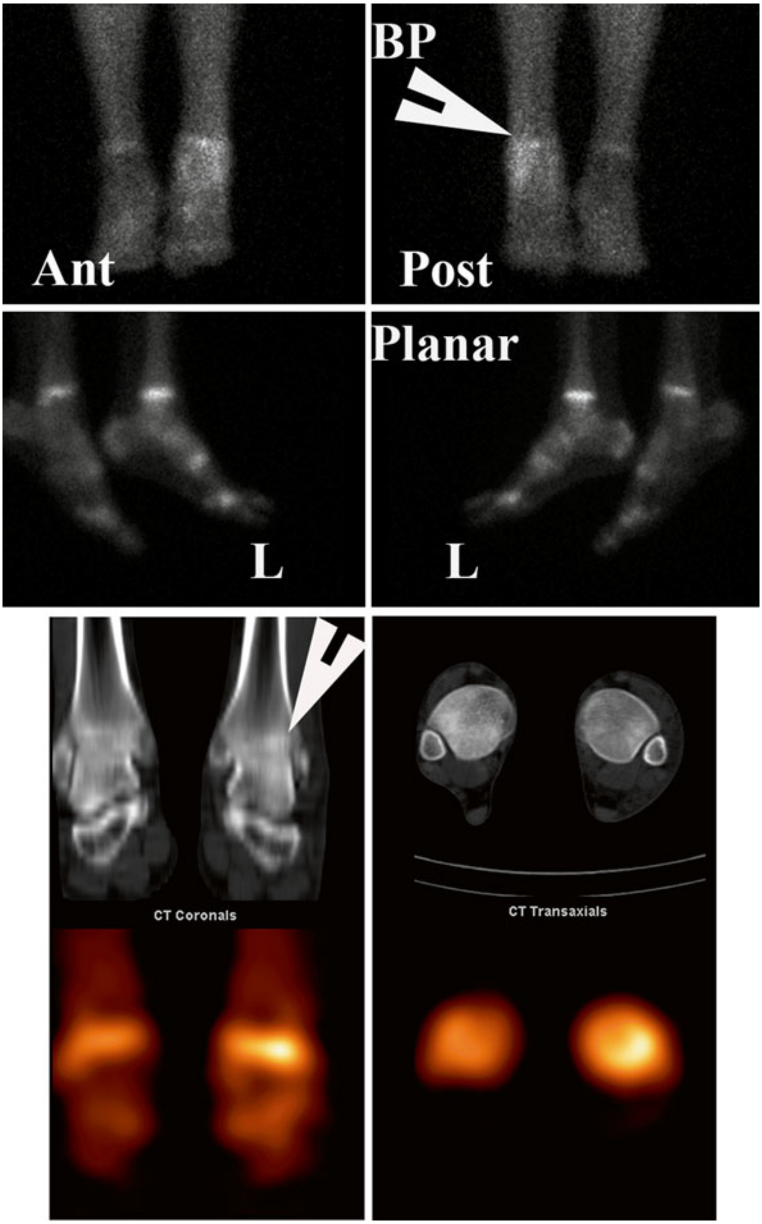


Fig. 6.4 Tibial growth plate injury. This 13-year-old male had a complex left ankle injury at football and could not weight-bear on the left leg due to ankle pain. Plain x-ray was reported as normal. The patient was scanned 3 weeks later. The blood pool image shows hyperaemia in the lateral aspect of the distal left tibia (*arrowhead*). The delayed and SPECT/CT studies reveal intense uptake in the lateral aspect of the left distal tibial growth plate with the CT study showing mixed lucency and sclerosis (*arrowhead*), compatible with a growth plate injury

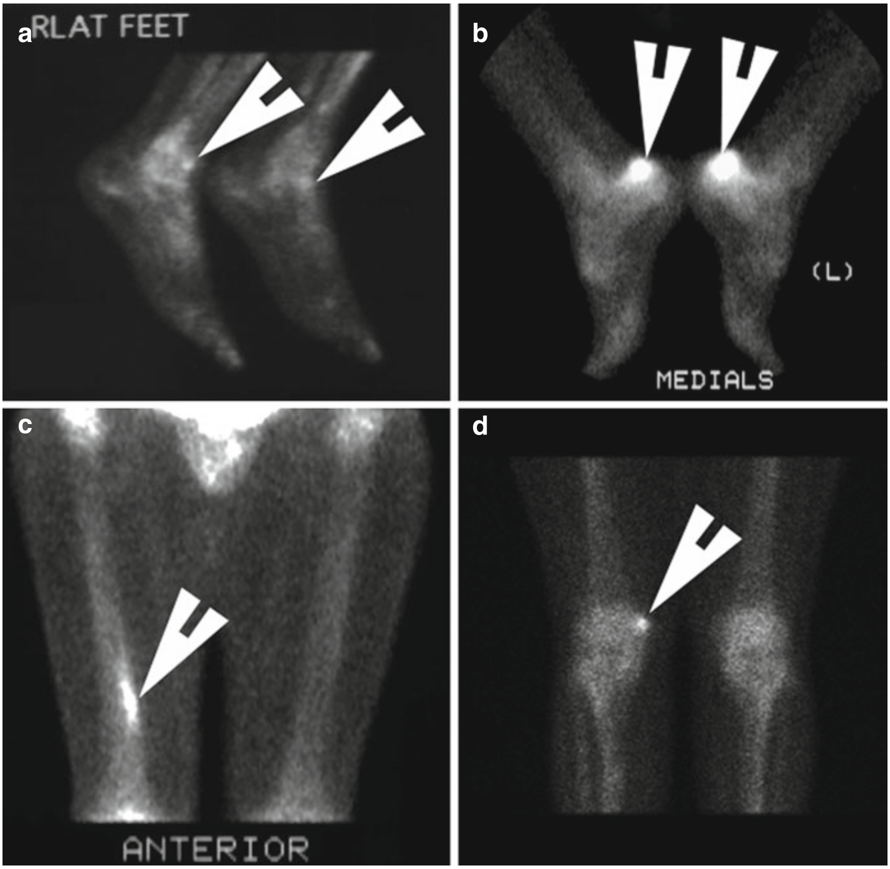


Fig. 6.5 Miscellaneous injuries of the lower limb. (**a**) Anterior impingement syndrome. Intense focal uptake in the anterior aspect of the ankles (*arrowheads*) due to repetitive traction on the anterior joint capsule and direct impingement of the anterior tibial plafond on the anterior talus. (**b**) Bilateral Achilles tendinopathy. Intense uptake around the Achilles tendons with associated bursitis (*arrowheads*). (**c**) Thigh splints due to overuse enthesopathy of the adductor muscles at the insertion into the distal femur (*arrowhead*). (**d**) Pellegrini-Stieda disease. Intense uptake at the medial collateral ligament insertion into the right medial condyle (*arrowhead*) after a ligament injury

pattern of blood pool activity in the distribution of the tendon has also been described with the peroneal tendons (Fig. 6.6) (Sinha et al. 2000).

Posterolateral pain is usually due to posterior impingement syndrome, impingement of the os trigonum or peroneal tendinopathy. An os trigonum is present in approximately 3–13 % of the population. Posterior impingement may occur with forced plantar flexion of the ankle, as happens in ballet dancers. Posterior impingement can also be caused by an enlarged posterior talar process, prominent posterior calcaneal process, loose bodies or avulsion of the posterior tibiotalar ligament (Umans 2002). The scintigraphic appearance (Johnson et al. 1984) is characterised by intense uptake in the posterior talus.

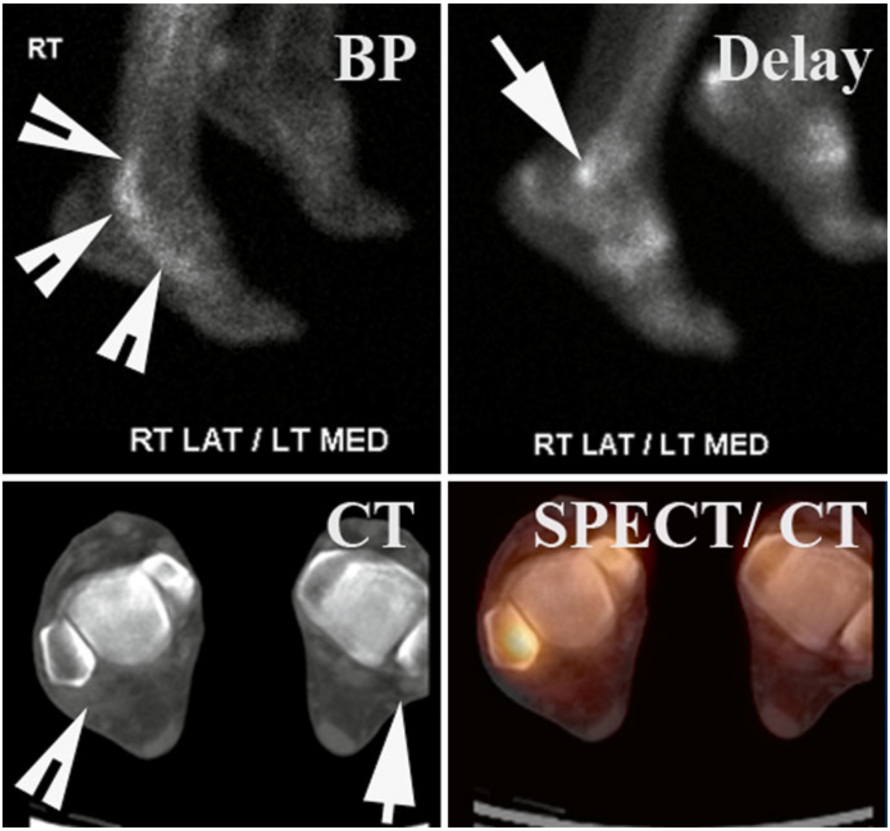


Fig. 6.6 Peroneus brevis tendinitis. Intense hyperaemia is present along the distribution of the right peroneus brevis tendon in the blood pool image (*arrowheads* in BP). Intense uptake is present in the immediately adjacent posterior lateral malleolus (*arrow* in delay). The SPECT/CT image confirms these findings, and the CT study shows increased density and thickening of the tendon and its adnexae (*arrowhead*) compared with the unaffected side (*arrow*)

The anterior impingement syndrome is caused by repeated traction of the anterior ankle joint capsule and impingement of the talus against the tibia. The chronic process leads to calcific deposits along the lines of the capsular fibres and spur formation on the dorsum of the anterior talus and tibia (Umans 2002). A pattern of intense increase in uptake of tracer is seen in the anterior aspect of the ankle (Fig. 6.5a).

6.8.1.1 Plantar Fasciopathy

Heel pain is one of the most common presentations in sports medicine, plantar fasciitis being the most common cause (Huang et al. 2000). Scintigraphy can offer information that can decide suitability for corticosteroid injection into the calcaneal enthesis (Frater et al. 2006). Other causes of heel pain that may be elucidated by scintigraphy include Achilles distal and insertional tendinopathy and bursitis

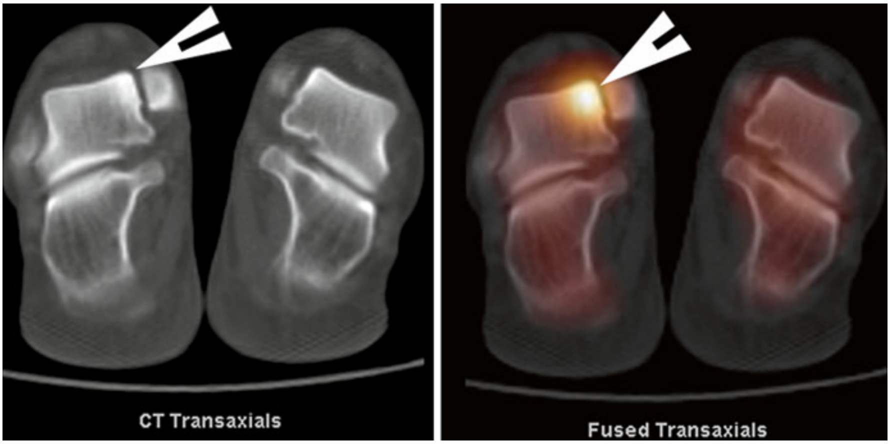


Fig. 6.7 Talar dome fracture. Intense uptake and sclerosis of the medial talar dome (*arrowhead*) in a patient who had an "ankle sprain" at soccer and could not weight-bear for several weeks

(Fig. 6.5b), retrocalcaneal bursitis, apophysitis of the calcaneus and calcaneal stress fracture. SPECT/CT can accurately show the site of tendon attachment and its relationship to uptake. Incremental information in Achilles tendinopathy includes opacification of the Kager fat pad on CT.

6.8.2 Ankle and Foot: Bony and Ligamentous Injury

Multiple studies have evaluated the performance of SPECT/CT in the lower limbs over the last few years. The intraobserver/interobserver variability in 20 consecutive patients with foot pain and degenerative disease of various joints was found to be good (Pagenstert et al. 2009) with a kappa score of 0.86 (Cohen 1968). A good recent review of the technical and clinical applications of SPECT/CT in the foot and ankle in a variety of conditions is well illustrated in a recent publication by Mohan et al. (Mohan et al. 2010).

The ankle is the dominant focus of acute injury in up to 75 % of participants in sport (Yeung et al. 1994) with 15 % having serious sequelae (Fallat et al. 1998). Approximately 70 % of acute injuries are inversion "sprains" with injury to the lateral ligamentous complex of the ankle and less often on the medial side. A small proportion of patient will incur serious injuries to the talus (Fig. 6.7), tibio-fibular syndesmosis, cuboid, calcaneus (Figs. 6.8 and 6.9) or navicular bones.

6.8.2.1 Talar Dome Fractures

Osteochondral fractures complicate acute ankle sprains in up to 6 %, most commonly in the posteromedial talar dome followed by the anterolateral talar dome (Shea and Manoli 1993); these lesions are generally known as osteochondral lesion of the talus (OLT). Plain x-ray may miss up to 33 % of fractures (Stroud and Marks

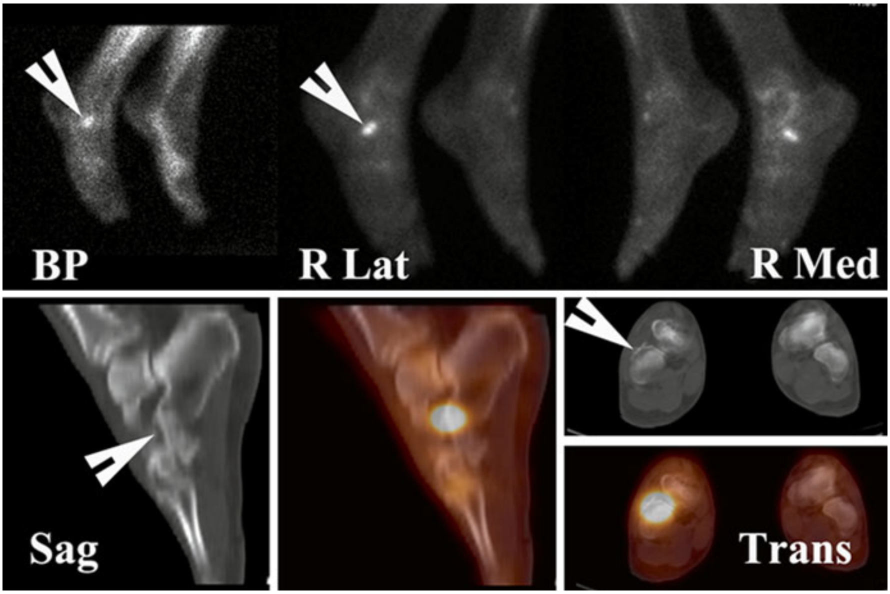


Fig. 6.8 Anterior calcaneal fracture. Footballer who had a complex rotational injury of the right foot and could not weight-bear. The blood pool study (*BP*) shows intense hyperaemia and uptake in a vertical distribution in the anterior aspect of the right calcaneum (*arrowheads*) in the upper panel. The SPECT/CT images in the lower panel confirm intense uptake in the anterior aspect of the right calcaneum with disruption of the cortex (*arrowhead*) at the site of fracture

2000). Plain radiography has an accuracy of 25 % when correlated with arthroscopy (Stroud and Marks 2000). Scintigraphy is a good screening test in the presence of a normal radiograph, as was shown in a small series of 24 patients (Anderson et al. 1989). In a larger series of 122 patients, bone scintigraphy was shown to have a sensitivity of 94 % and specificity of 76 % for detecting talar dome fractures (Urman et al. 1991). Blood pool abnormalities were associated with higher grade and unstable fractures. The obvious additional advantage of SPECT/CT is that it can provide a more accurate site of uptake in the talus and stage the fracture in terms of instability of the fracture fragment. There are no available series to provide a critical assessment of performance of the technique, particularly against MRI.

6.8.2.2 Acute Fractures of the Plafond and Interosseous Membrane

A study of 639 cases of ankle sprains found that 15 % had either avulsion or compression fractures and 5 % had significant injuries to the interosseous membrane (Fallat et al. 1998). These lesions are related to a more uncommon type of ankle injury with eversion. Bone scintigraphy shows hyperaemia in the posterior aspect of the ankle, extending superiorly into the interosseous membrane. Delayed images demonstrate increased uptake in the posterior plafond (avulsion or chip fracture) and medial edge of the posterior fibula (avulsion fracture) and extension into the distal syndesmosis (Frater et al. 2002). This injury is often associated with a fracture

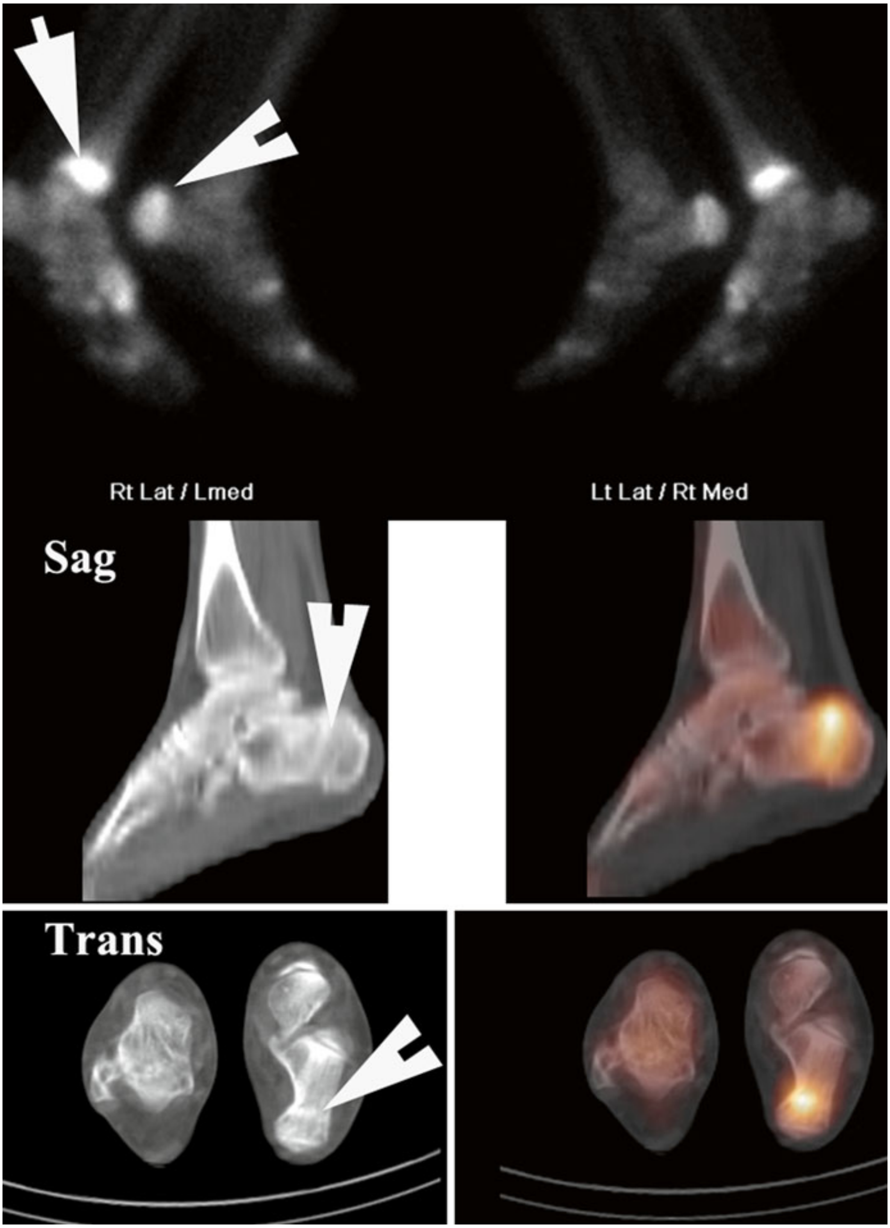


Fig. 6.9 Posterior calcaneal fracture. This triathlete had previously developed a stress fracture of the right distal tibia (*arrow* in *upper panel*) and refused to stop training. He subsequently complained of pain in the left heel. Planar images showed vertical increase in uptake extending through the left posterior calcaneum (*arrowhead* in *upper panel*) with the SPECT/CT images showing both increased uptake and sclerosis (*arrowheads* in *lower panels*) compatible with a stress fracture

Fig. 6.10 Accessory navicular fracture. This older weightlifter dropped a weight on the dorsum of the right foot and complained of increasing pain in the foot. Plain films reported an incidental accessory navicular but could not detect a fracture. The planar image shows increased uptake of tracer in both accessory navicular bones (*arrowheads*) which is more marked on the right side. However, the SPECT/CT images clearly identify more intense uptake and irregular sclerosis around the articulation, in keeping with a fracture through the syndesmosis

of the proximal fibula (Maisonneuve fracture). In theory, SPECT/CT should increase the accuracy with which such fractures are detected and allow staging of the fracture stability and the need for surgical intervention.

6.8.2.3 Fractures of the Tarsal Bones

Stress fracture of the talus is rare. Although rare in overall terms, acute navicular fractures are the most common mid-foot fracture and require careful treatment in order to avoid long-term morbidity. The dorsal ligament avulsion fracture is the most common navicular fracture and presents with pinpoint tenderness after eversion or inversion injury on a plantar-flexed foot. Navicular stress fractures are being seen with increasing frequency due to the increasing participation of women and adolescents in various sports. Fractures are easily detected by scintigraphy, CT and MRI in nearly all cases (Orava et al. 1991; Boden and Osbahr 2000). Fracture of the accessory navicular bone may be seen in association with tibialis posterior tendinopathy in the accessory navicular syndrome (Conti 1994). The accessory navicular bone may be bilateral, and injury is easily diagnosed by scintigraphy by comparing the sides (Fig. 6.10).

Cuboid fractures are unusual and account for approximately 5 % of all tarsal fractures (Lee and Donatto 1999). Cuneiform fractures comprise approximately 4 % of all mid-foot fractures (Fig. 6.11) (Lee and Donatto 1999). Acute fractures of the anterior process of the calcaneus have been reported to account for up to 15 % of all calcaneal fractures (Fig. 6.8) (Hodge 1999). The Lisfranc injury should always be considered in cases where there is an inability to weight-bear associated with mild swelling of the mid-foot and bruising of the arch of the foot. Weight-bearing plain films of the foot are generally diagnostic, but scintigraphy may prove to be useful in approximately 15 % of cases with more subtle injury to the joint that is not apparent on plain film.

Stress fractures of the calcaneus have been reported in approximately 20 % of male and 40 % of female military recruits undergoing basic military training

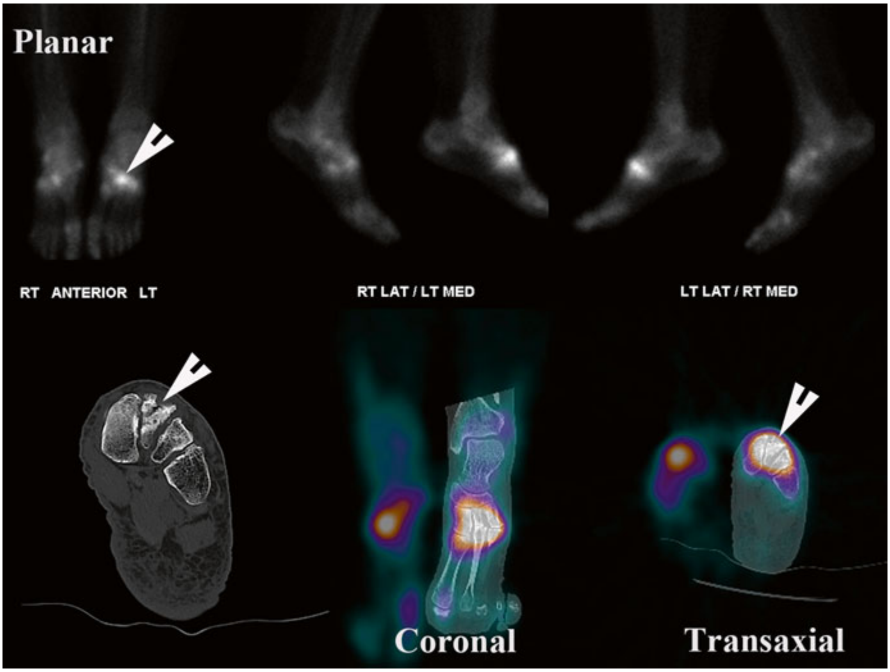


Fig. 6.11 Cuneiform stress fracture. Long-distance runner who presented with increasing pain in the left mid-foot region. Plain films 3 weeks previously had been reported as normal. Intense uptake is seen in the left intermediate cuneiform bone (*arrowheads*). SPECT/CT confirms this, with the CT study clearly demonstrating the fracture site (*arrowhead*). Note multiple other sites of increased uptake which were asymptomatic, as is commonly found in high-level athletes

(Greaney et al. 1983; Pester and Smith 1992). The most common site of fracture is the posterior calcaneal tubercle (Fig. 6.9).

SPECT/CT should increase the accuracy with which such fractures are detected and allow staging of the fracture stability and the need for surgical intervention.

6.8.2.4 Metatarsal Stress Fracture

Metatarsal fractures are the most common stress injury in the foot and ankle. In a large series of 295 subjects with 339 stress fractures, 28 % were in the metatarsals (Brudvig et al. 1983). These injuries occur in athletes who participate in high-impact sports involving mainly running and jumping. Stress fractures predominantly (90 %) occur in the second (Fig. 6.12) and third metatarsal bones. There is also a high level of stress through the fifth metatarsal, although less than in the second (Donahue and Sharkey 1999). Fractures of the fifth metatarsal are usually through the shaft and more rarely, proximally located (Jones fracture) (Hulkko et al. 1985). Synovitis of the metatarsophalangeal (MTP) joints should not be confused with stress fracture, particularly when the second MTP joint is involved (Smith and Reischl 1988; Thompson and Hamilton 1987). The condition is more common than

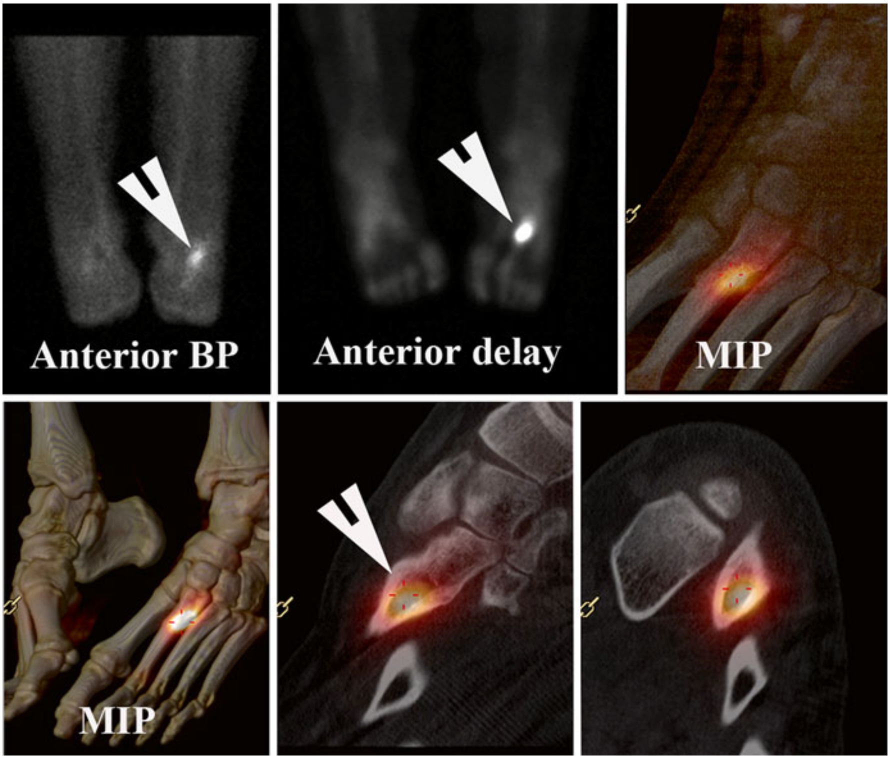


Fig. 6.12 Metatarsal stress fracture. Runner presenting with pain in the left foot which worsened after tripping. Tenderness of the left second metatarsal bone in left foot. The blood pool image (*BP*) shows intense hyperaemia in the base of the left second metatarsal. The delayed study confirms intense uptake in this metatarsal (*arrowhead* in anterior delay). This is confirmed in the MIP images and the SPECT/CT fused study which shows intense uptake with cortical thickening and sclerosis of the base of the left second metatarsal (*arrowhead*)

was previously recognised, and awareness is important in order to avoid misdiagnosis (Smith and Reischl 1988).

6.8.2.5 Sesamoid Injuries

The sesamoid bones beneath the first metatarsal head are within the capsule of the first metatarsophalangeal (MTP) joint and may be multipartite in 5–30 % of people. Stress fractures may therefore be difficult to diagnose radiologically. Scintigraphy has been found to be useful in the diagnosis of injury to the sesamoids in case studies (Georgoulias et al. 2001).

6.8.2.6 Tarsal Coalition

Failure of segmentation of the mesenchymal tissue of the hindfoot bones in the embryo is thought to be the cause of tarsal coalition. An autosomal dominant inheritance pattern has been established, and tarsal coalitions occur in approximately 1 %

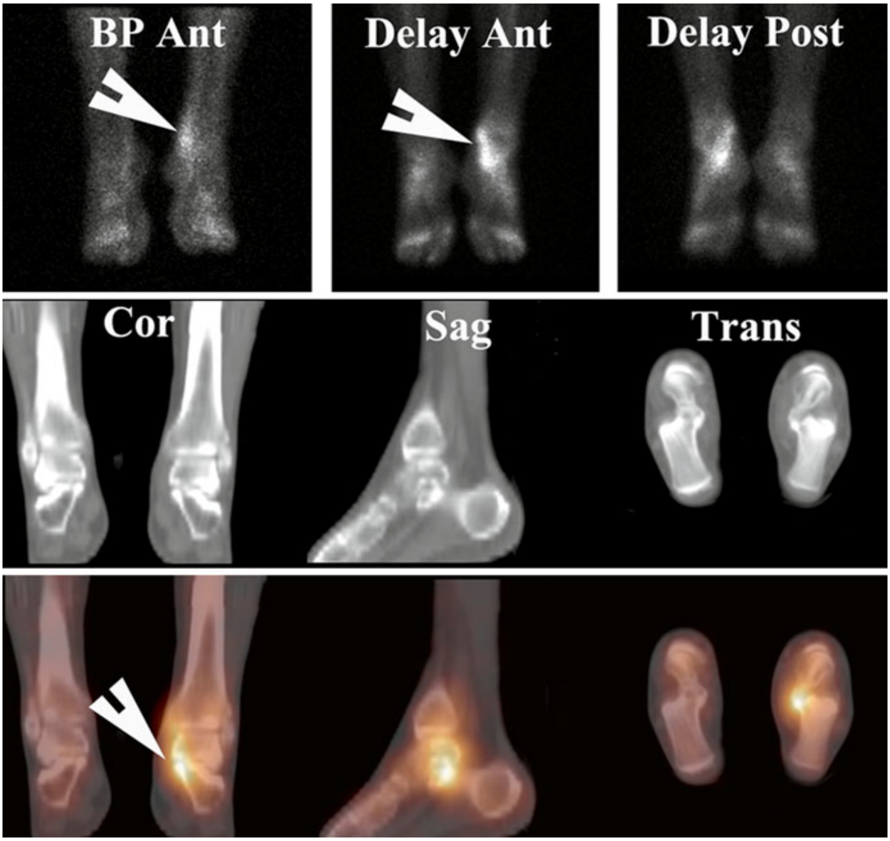


Fig. 6.13 Talo-calcaneal coalition. Runner who had a minor injury to the left ankle and complained of disproportionate pain. Plain films were reported as normal. The planar images in the upper panel demonstrate intense hyperaemia in the left medial ankle in the blood pool image (*arrowhead*). Delayed images also show intense uptake in the medial aspect of the left ankle which could plausibly be due to a ligament injury. However, SPECT/CT images confirm uptake around the medial facet of the articulation between the talus and navicular (*arrowhead*), and the CT image clearly demonstrates the coalition

of the population. Fifty percent will be bilateral and a significant proportion has multiple coalitions (Bohne 2001). Coalitions of the talo-calcaneal (Fig. 6.13) and calcaneo-navicular bones are the most common, followed by the talo-navicular and calcaneo-cuboid bones. These coalitions may be fibrous, cartilaginous or bony. Symptoms usually occur when the coalitions ossify and present with pain in the early to middle teens with ankle pain in the lateral and anterolateral aspects of the ankle. Physical examination shows a valgus hindfoot and patients may have a flatfoot. The flatfoot is usually associated with peroneal muscle spasm due to hindfoot rigidity. Mandell et al. (1990) reported the successful localisation of 7/9 fibrous talo-calcaneal coalitions using pinhole scintigraphy.

SPECT/CT offers a window into a complex anatomical region and would allow the early detection of uptake at the site of coalition and allow the detection of complicating osteoarthritis as well as occult coalitions (Mohan et al. 2010).

6.9 Tibia and Calf

Stress fractures of the tibia are the single most common fracture in sports medicine (McBryde 1975, 1985; Devas 1975). The diagnosis must be distinguished from the medial tibial stress syndrome (shin splints) and compartment syndrome. Stress fractures of the fibula are less common but may occur in association with other injuries.

6.9.1 Tibia and Calf: Soft-Tissue Injury

The two major chronic soft-tissue injuries are shin splints (medial tibial stress syndrome) and the chronic compartment syndromes. Other causes of pain include entrapment of arteries and nerves, deep venous thrombosis, rupture of the gastrocnemius muscle, fascial herniations and muscle strains. Muscle strains are probably the single most common cause of acute pain in the lower limbs (Kortebein et al. 2000).

6.9.1.1 Shin Splints (Medial Tibial Stress Syndrome)

Shin splints have been called the medial tibial stress syndrome due to the localisation of exercise-induced pain to the posteromedial aspect of the distal two thirds of the tibia (Kortebein et al. 2000). Considerable controversy surrounds the aetiology of so-called shin splints. Biopsy evidence shows inflammation of the crural fascia and increased bony metabolism with vascular ingrowth in the majority (Kortebein et al. 2000). The triple-phase bone scan appearance was well described by Holder and Michael (1984) as showing low-grade uptake in the distal posteromedial tibia on the delayed phase only (Fig. 6.14), with no alterations in blood flow. Scintigraphic studies currently define the diagnosis.

6.9.2 Tibia and Calf: Bone Injury

6.9.2.1 Tibial Stress Fractures

A variable incidence of tibial stress fractures has been reported, reflecting the heterogeneity of the study populations. While incidence does vary from 4 to 31 %, it accounts for over 50 % of all stress fractures, particularly in military recruits (Devas 1975; McBryde 1985). Predisposing factors include altered biomechanics in the lower limb, changes in footwear or rapid acceleration in the level of activity.

The utility of bone scintigraphy in the early diagnosis of tibial stress fractures has been well established since the description of early detection compared to plain radiology in the mid-1970s (Geslien et al. 1976). The usual scan appearance is of hyperaemia with intense transverse uptake at the site of fracture. More recent

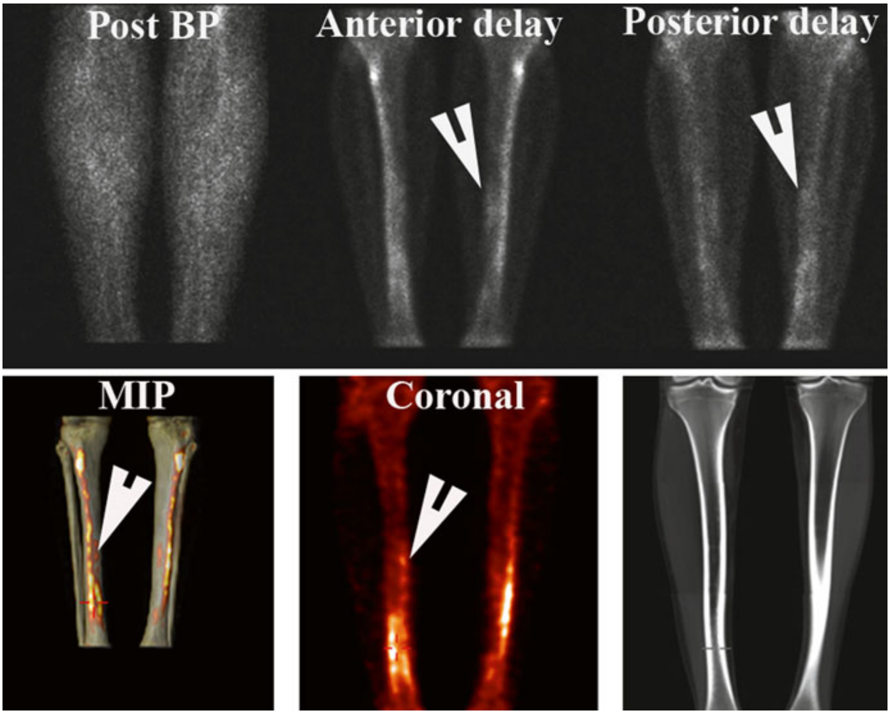


Fig. 6.14 Medial tibial stress syndrome (shin splints). Typical appearance of long segment low-grade uptake in the posteromedial cortex of the tibia (*arrowheads*) with normal blood pool image. The SPECT/CT image confirms irregular cortical uptake in the posteromedial surface of the tibiae, which is also well shown in the MIP image (*arrowheads*)

literature has shown an equivalence with MRI for early diagnosis (Brukner and Bennell 1997; Ishibashi et al. 2002) with scan findings of periosteal and bone-marrow oedema. The posterior aspect of the upper third of the shaft is the most common site of fracture in children and the elderly. The distal third is the most common site in long-distance runners (Fig. 6.15).

In a large series (Zwas et al. 1987), 164 of 280 fractures occurred in the mid-shaft. This group described a classification of tibial stress fractures into four grades, extending from poorly defined cortical uptake (Grade I) to well-defined intramedullary transcortical uptake (Grade IV). The scintigraphic grade of uptake gave valuable prognostic information regarding the period of rest required for healing, being more prolonged in the higher grades. Plain radiography can also indicate poor prognosis with the dreaded black line, indicating osteolysis at the fracture site, a poor prognostic indicator for healing with high likelihood for surgical intervention (Miyamoto et al. 2009).

SPECT has been shown to be a sensitive method of detecting early tibial stress fractures, especially in high-level athletes with minimal symptoms (Yildirim et al. 2004). This study found abnormal uptake in 28 of 42 high-level soccer players,

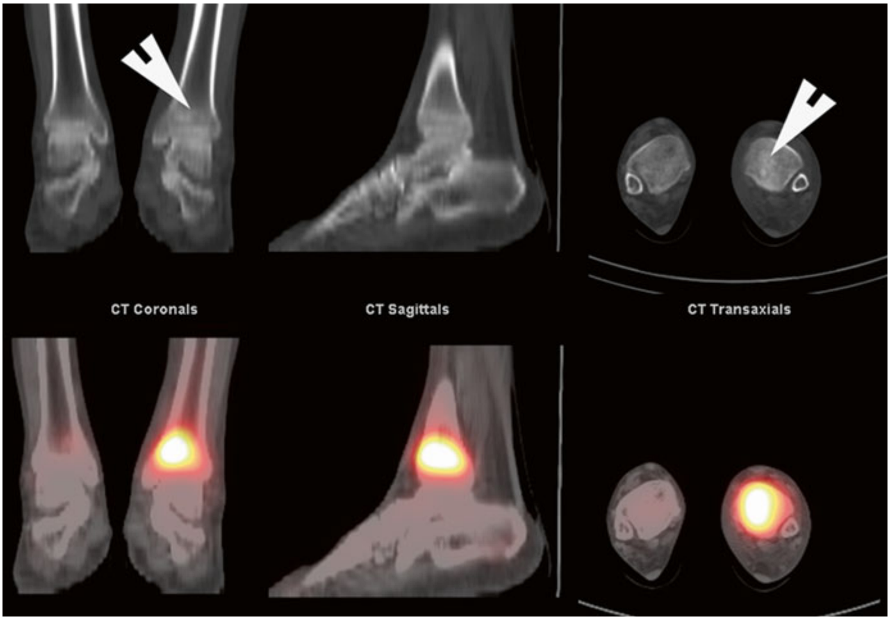


Fig. 6.15 Tibial stress fracture. Typical tibial stress fracture in a long-distance runner who progressively developed pain in the left ankle with increasing activity to the point where she was unable to run. The SPECT/CT study shows intense uptake in the distal left tibia with a sclerotic band in the CT study (*arrowheads*) at the site of fracture

62 % being in the tibia. Although there are no critical studies of SPECT/CT, CT would add to the staging information and allow better treatment planning.

6.9.2.2 Fibula Stress Fractures

Stress fractures of the fibula account for 20 % of paediatric (Yngve 1988) and up to 30 % of adult stress fractures (Bennell and Brukner 1997). The vast majority develop in the distal third (Fig. 6.16), with the proximal and middle third being rare. Scintigraphy has been established as a reference standard since the earliest experiences with athletic injuries (Geslien et al. 1976).

6.9.3 Knee Injury

The knee is susceptible to injury in any activity that involves rapid changes in direction. The menisci separate the femoral condyles from the tibial plateau. The cruciate ligaments, medial and lateral collateral ligaments, joint capsule and muscles afford joint stability. Planar imaging can yield a number of diagnoses such as bursitis, enthesopathy, osteochondritis dissecans, bone bruises or fractures of the tibial plateau. Internal derangements of the knee may be detected by SPECT images but are a subject of redundancy, given the far better capability of MRI in detecting and

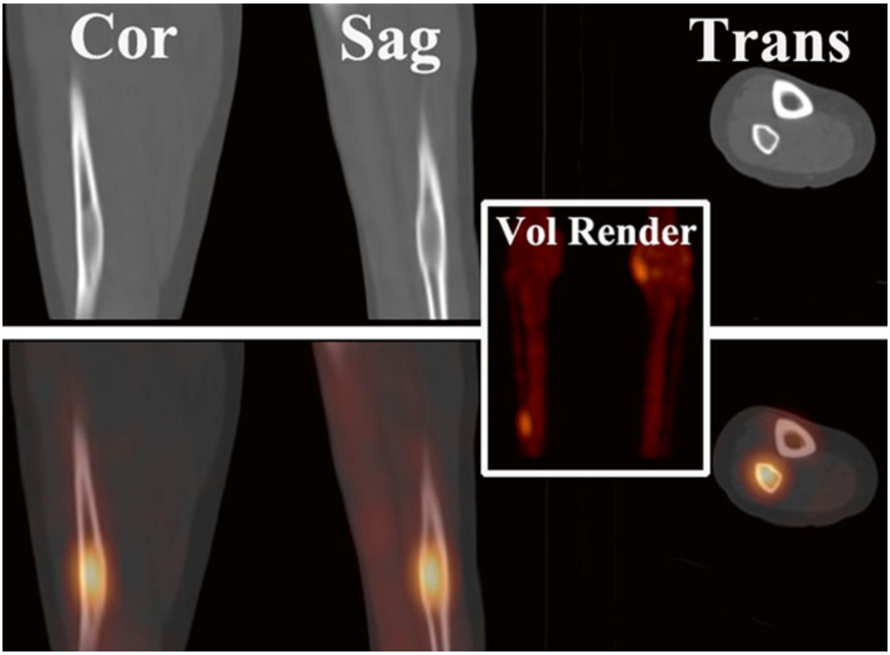


Fig. 6.16 Fibula stress fracture. Triathlete who complained of increasingly disabling pain in the right leg. The SPECT/CT study clearly shows intense uptake and sclerosis in the distal third of the right fibula at the site of stress fracture. This is well illustrated in the volume-rendered image in the *central panel*

surgically staging most injuries. While there is potential for SPECT/CT to improve the accuracy of diagnosis and staging of knee injuries, it is likely to remain an orphan imaging modality or research tool, as MRI is unlikely to be abandoned.

6.9.3.1 Acute and Chronic Injury

Knee SPECT has a defined role in the assessment of both acute and chronic knee pain (al-Janabi 1994; Ryan et al. 1996; So et al. 2000; Ryan et al. 1998; Murray et al. 1990). Good to excellent performance has been shown (Ryan et al. 1996) in a variety of knee disorders in 158 patients in which knee SPECT made the correct diagnosis in 89 %. Even if SPECT does not provide a specific diagnosis, it may be helpful in directing arthroscopy and shortening the examination (Ryan et al. 1996; Murray et al. 1990). A recent series of three case reports indicates the potential utility of SPECT/CT in the post-operative knee that is painful (Hirschmann et al. 2010).

6.9.3.2 Meniscal Injury

Knee SPECT has been evaluated in the setting of chronic and acute meniscal tears (Collier et al. 1985; al-Janabi 1994; Ryan et al. 1996, 1998, 2000; Murray et al. 1990). Meniscal tears are characterised by peripherally increased uptake in a crescent in the tibial plateau (Fig. 6.17) as well as focal posterior femoral condylar

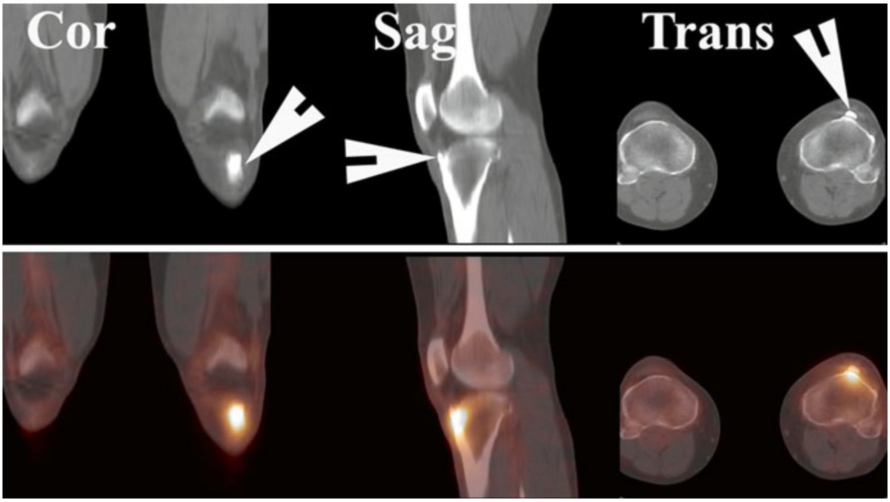


Fig. 6.17 Chronic patella tendinitis. Triathlete with long history of recurrent pain in the proximal left tibia in spite of multiple corticosteroid injections. The SPECT/CT images demonstrate sclerosis of the tibial tubercle and calcification of the adjacent patella tendon in the CT images (*arrowheads*) with intense uptake at both sites

uptake (Ryan et al. 1998, 2000; Murray et al. 1990). Ryan et al. (1998) in a study of 100 patients with undiagnosed knee pain showed a sensitivity of 84 %, specificity of 80 %, positive predictive value of 88 % and negative predictive value of 76 % for SPECT, with similar values for MRI. However, recently published prospective MRI studies (Van Dyck et al. 2013) show a much higher accuracy for the detection of meniscal tears of 92–95 % with sensitivity 93 % and specificity 90 % for medial meniscal tears. Sensitivity was 82 % and specificity 98 % for lateral meniscal tears.

6.9.3.3 Cruciate Ligament Injury

Knee SPECT can detect cruciate ligament injuries. The characteristic feature providing primary evidence of anterior cruciate ligament (ACL) injury is focal uptake at the insertion sites, more commonly at the femoral than the tibial attachment (So et al. 2000; Ryan 2000). Corollary evidence is provided by uptake in the lateral femoral condyle or posterolateral tibial plateau due to bone bruising at these sites, which often occurs during the process which produces ACL injury (So et al. 2000; Chung et al. 2000; Ryan 2000). So et al. (2000) showed relatively poor results in ACL injury using primary or corollary evidence alone, but a sensitivity of 84 % and positive predictive value of 81 % when combined.

6.9.3.4 Miscellaneous Injuries

Collateral ligament injuries are characterised by focal uptake at both attachments of the ligament, often accompanied by an arc of blood pool activity around the centre of the knee (Ryan 2000; Murray et al. 1990; Cook and Fogelman 1996). Avulsion may lead to focal uptake in the proximal attachment and is called Pellegrini-Stieda disease (Fig. 6.5d).

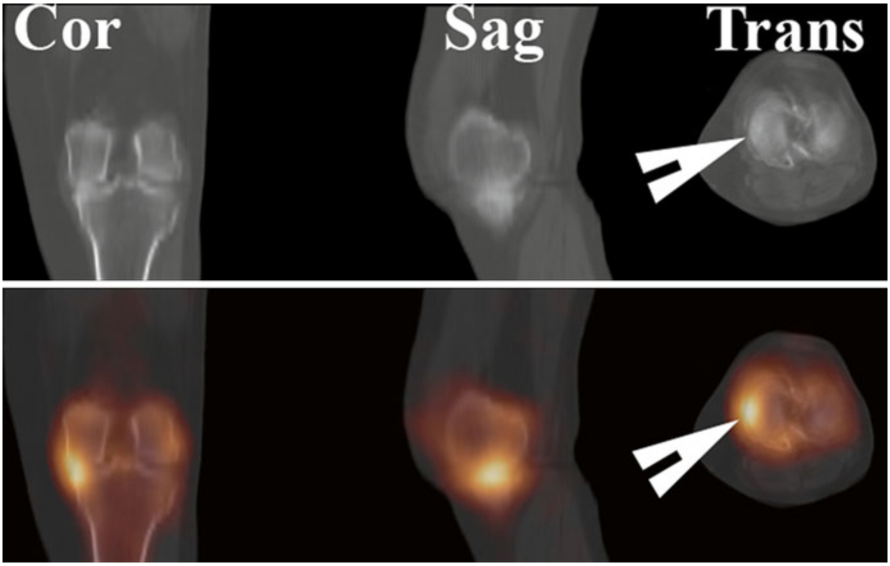


Fig. 6.18 Medial meniscus tear. This was a surgically proven injury in a patient being assessed for patella tendinitis. The SPECT/CT study shows a region of intense uptake and sclerosis in the mid-body of the crescent of the medial meniscal subchondral bone (*arrowheads*) in keeping with a tear of the meniscus and adverse remodelling of the underlying tissues

Scintigraphic studies are useful in confirming the site of patella tendinopathy, either at the upper or lower pole of the patella or at its insertion point into the tibia (Fig. 6.17). There are both case reports of the condition (Kahn and Wilson 1987) and histological correlation with the scintigraphic findings in a group of 34 patients undergoing surgery for the condition (Green et al. 1996). Eight of the 34 patients had diffuse patella uptake and 16 lower pole uptake. Scan-positive patients had severe histological changes on the post-operative specimens. Some false negatives were reported in this series (10/34).

Osteochondritis and focal condylar erosions are easily visualised with knee SPECT, perhaps better than by MRI (Ryan 2000). Osteochondritis dissecans occurs at different sites, most frequently at the lateral aspect of the medial femoral condyle to subchondral infractions which occur in weight-bearing regions, usually in the lateral compartment (Marks et al. 1992).

6.10 Thigh, Hip and Pelvis

6.10.1 Thigh, Hip and Pelvis: Soft-Tissue Injury

A variety of soft-tissue injuries have been reported in the thigh. Adductor splints are an overuse injury of the adductor muscles, manifested by a periosteal reaction at the insertion into the cortex of the femur as with shin splints (Fig. 6.5c) (Charkes et al. 1987). Direct muscular trauma with or without haematoma formation may also be

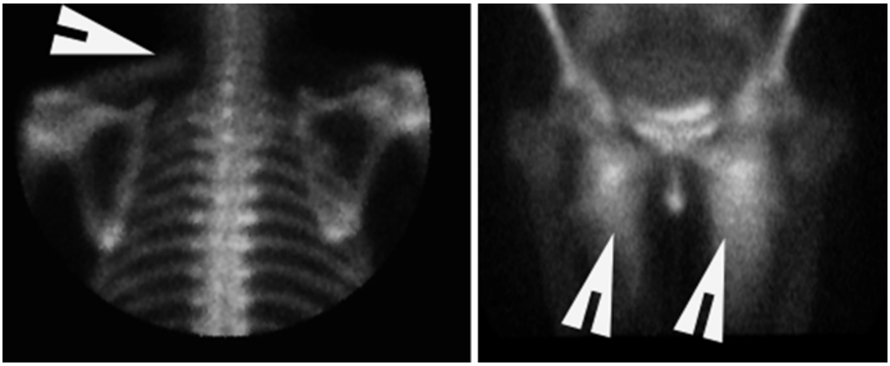


Fig. 6.19 Muscle uptake. Significant muscle injury due to weightlifting damage in the trapezius and adductor muscle groups of the medial thighs (*arrowheads*). Biochemical evidence of elevated muscle enzymes was also apparent in these patients

detected due to muscular uptake at the sites of damage. In patients with symptomatic muscle pain after ultramarathon competition, up to 90 % will have evidence of rhabdomyolysis (Fig. 6.19) (Matin et al. 1983).

Other causes of scintigraphic alterations in the region include bursitis of the iliopsoas bursa, greater trochanteric bursa and ischial bursa. Numerous tendon insertion enthesopathies have also been described (Fig. 6.20d) (Huang et al. 2000).

6.10.2 Thigh, Hip and Pelvis: Bone Injury

6.10.2.1 Stress Fractures of the Hip

Fractures of the hip account for approximately 4.5 % of all stress fractures (Volpin et al. 1990). Two principal patterns of fracture have been described, transverse and compression (Fig. 6.21). Transverse fractures are in the superior or tension side of the femoral neck and occur in older individuals. The rate of complications is much higher with these fractures (Amendola and Wolcott 2002). Compression fractures occur on the medial side of the femoral neck in younger patients (Fig. 6.22). The fracture heals well with rest if undisplaced but requires more aggressive therapy if displaced (Amendola and Wolcott 2002).

A rarely reported fracture in the hip occurs in the acetabular side of the joint and may be associated with femoral neck fracture. This injury can be detected equally well by bone SPECT and MRI. Williams et al. (2002) reported acetabular stress fractures in 12 of 178 military recruits subjected to high-level training. Two patterns were evident, one showing increased uptake in the acetabular roof and the other at the junction of the acetabulum and inferior pubic ramus.

6.10.2.2 Avulsion Fractures of the Pelvis

Avulsion fractures are a common injury in adolescent athletes. These injuries occur through the apophysis and are equivalent to physeal fractures. The usual mechanism involved is a sudden violent contraction of a large muscle attached to the bone,

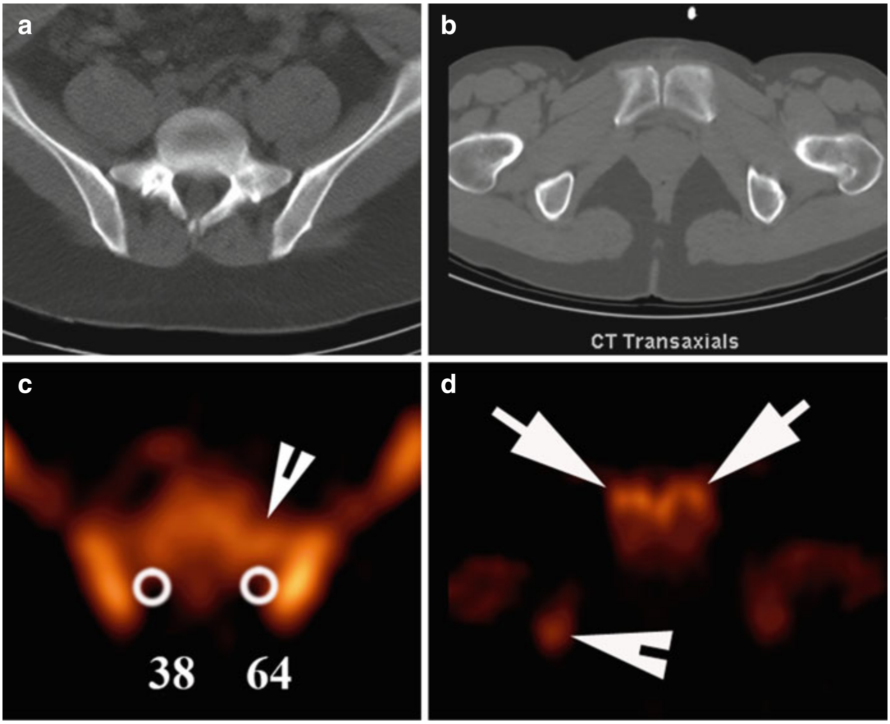


Fig. 6.20 Sacroiliac joint incompetence. This female patient complained of left buttock pain after a fall from a horse during showjumping, landing heavily onto her left buttock. MRI studies on two occasions had shown only disc bulges at L4/L5 and L5/S1 without radicular impingement and no other abnormality. The SPECT/CT study demonstrates increased sacroiliac joint uptake on the left (**c**) with extension into the posterior soft tissues (*arrowhead*). Raised counts are present in the soft tissues on the left as indicated in **c** (R38 V L64). There is also evidence of bilateral adductor (*arrows*) and right hamstring (*arrowhead*) enthesopathy in panel **d**. No significant changes are present in the CT images in **a** and **b**

resulting in tearing of the attached tendon and bone through its weakest point, the provisional zone of calcification (Amendola and Wolcott 2002). Presentation is with sudden onset of localised pain. The degree of displacement of the fragment is important for prognosis.

6.10.2.3 Pelvic Stress Fracture

Pelvic stress fractures are rare but positive when tested with bone scintigraphy (Shah and Stewart 2002). Fracture of the inferior pubic ramus has been reported in female military recruits (Hill et al. 1996) and is thought to be due to repetitive strain of the large muscles on the pubic bones (Amendola and Wolcott 2002). Stress fractures of the sacrum are well recognised in the general sporting population (McFarland and Giangarra 1996) but may not be readily considered in adolescents (Patterson et al. 2004) and female athletes (Johnson et al. 2001).

Fig. 6.21 Schematic representation of sites of principal femoral stress fractures

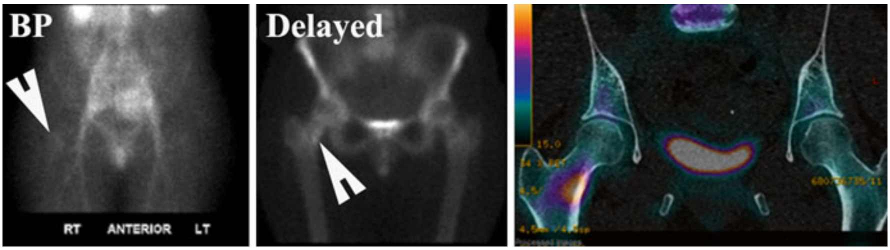


Fig. 6.22 Femoral stress fracture. Hyperaemia (*arrowhead* in BP) and increased uptake in the inferior or compression side of the femoral neck (*arrowhead* in delayed) in a female long-distance runner with the CT study demonstrating minor sclerosis which was initially not reported

6.10.2.4 Sacroiliac Joint Insufficiency

This is a recently described phenomenon which is a traumatic extension of the pelvic girdle syndrome (Cusi et al. 2013) which was initially described in peri-partum women (Albert et al. 2002; Larsen et al. 1999; Ostgaard et al. 1991). Patients present with unilateral buttock pain and hip and/or anterior pelvic pain after trauma to the posterior pelvis or due to repetitive injury such as landing on the same leg in gymnastics. While there was previously no imaging test for the diagnosis, there is now a validated SPECT/CT scintigraphic study. Findings are of sacroiliac joint and posterior ligament uptake, enthesopathy of the adductor and hamstring tendons (Fig. 6.20) and associated hip impingement (Fig. 6.23). Hip impingement may lead

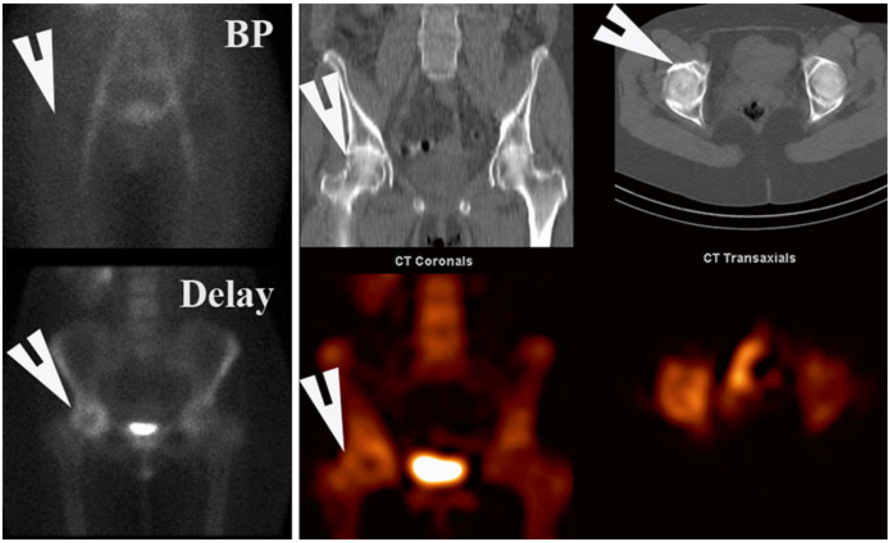


Fig. 6.23 Hip impingement. Increasing right hip pain in a motocross bike rider which worsened after a number of falls. Hyperaemia (*arrowhead* in BP) and intense uptake around the right hip (*arrowhead* in delay) with the SPECT/CT image showing the site of impingement between the anterior-superior acetabulum and lateral femoral head (*arrowheads*)

to accelerated degenerative disease of the hip and has been defined in the scintigraphic literature (Lee et al. 2008) and general radiologic literature (Chakraverty et al. 2013; Sink and Kim 2012).

6.10.2.5 Osteitis Pubis

This is mainly reported in runners and soccer and football players and presents with groin, pubic, perineal or scrotal pain. The mechanism is thought to be due to the action of the large adductor muscles on the pubic bones as weight is transferred from one leg to the other during running. The diagnosis is easily made by scintigraphy (Le Jeune et al. 1984) and may often be diagnosed in the asymptomatic elite athlete (Frater 2001). A subpubic or squat view is important in order to overcome confounding activity in the urinary bladder (Frater 2001). This is easily overcome by SPECT/CT which will separate urinary activity from bony uptake and allow the assessment of chronicity by sclerosis/cyst formation around the symphysis.

6.11 Chest Injury

Rib stress fractures occur in 5.3 % of all injuries in female and male rowers and account for 39.5 % of chronic chest injuries in female rowers (Hickey et al. 1997). These injuries are readily apparent on bone scintigraphy. There is some low-level evidence for the utility of SPECT/CT in the assessment and staging of rib injuries (Ananos Gimenez et al. 2009).

6.12 Spine Injury

6.12.1 Cervical and Thoracic Spine

The availability of multiheaded gamma cameras has lead to major improvements in the imaging of the cervical spine. The normal anatomy has been well defined (Murray and Frater 1994; Seitz et al. 1995) and the utility assessed in the setting of acute neck trauma in a small series (Seitz et al. 1995). In 16 patients with abnormal results, SPECT detected occult fractures in 7 of 35 patients (27 %), including 3 with normal radiographs and 4 with equivocal radiographs. Recent fractures were excluded in 6/9(67 %). None of the patients with normal SPECT studies had CT or MRI evidence of recent fractures.

We have found SPECT/CT to be of utility in identifying degenerative zygapophyseal and uncovertebral joint disease in the cervical spine. It has helped in identifying joints that can be injected with local anaesthetic and corticosteroids to provide pain relief with good results.

Little work has been published about the utility of scintigraphy in the thoracic spine. Several case reports document detection of fractures of the vertebral bodies and posterolateral elements. We have however found great utility for SPECT/CT in identifying sites of degenerative disease of the costotransverse and costovertebral joints in explaining thoracic pain that has evaded diagnosis by other modalities including MRI and CT as stand-alone investigations.

6.12.2 Lumbar Spine

Low back pain is common among athletes. The causes vary and must be distinguished from stress fracture of the pars interarticularis which has an incidence of 6 % in the general population and accounts for about 15 % of paediatric stress fractures. Most pars fractures occur at the L5 and, to a lesser degree, L4 levels of the spine. Young athletes are at most risk, particularly those involved in tennis, gymnastics, cricket (fast bowling) and throwing. Careful scintigraphic imaging is important as 15 % of evolving fractures may not be evident on CT scanning (Congeni et al. 1997). Pars lesions must also be distinguished from facet joint pathology. SPECT can show 20–50 % greater lesion detection than planar imaging (Gates 1996). These issues will progressively lose relevance as SPECT/CT becomes the routine method of scintigraphic imaging of patients with low back pain. This has already been indirectly addressed by Campbell et al. (2005). They combined SPECT and CT and compared it to MRI in juvenile or young adults (average age 16 years). Forty pars defects were found in 22 patients from a scanned group of 72 patients with low back pain. There was good interobserver agreement between MRI and SPECT/CT with a kappa score of 0.79. While MRI was good for acute pars defects, chronic established pars defects and excluding pars defects in ~75 %, a small group of patients exhibited abnormal pars uptake on SPECT without CT or MRI abnormalities. Conversely, a number of cases showed marrow oedema on MRI and had normal SPECT/CT studies. It is difficult to

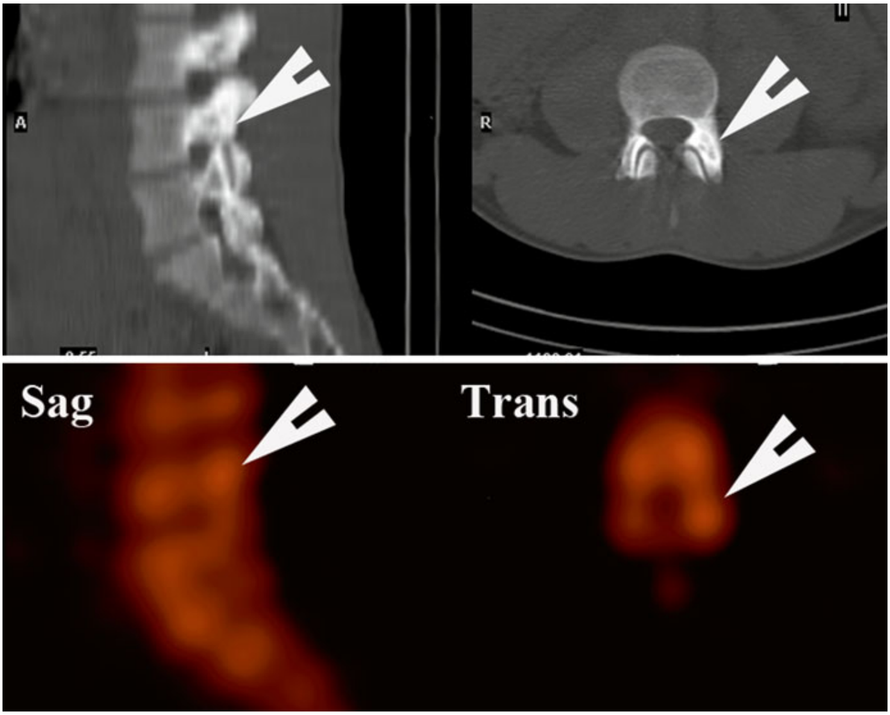


Fig. 6.24 Stress reaction of the pars. This right arm cricket fast bowler (cricket) presented with lower back pain and a suspicion of a pars fracture of L4 on plain film. The SPECT/CT study confirms moderate increase in uptake (*arrowhead*) and sclerosis of the left pars of L4 (*arrowhead*) without evidence of lysis

ascribe a stress reaction in these circumstances as others have described similar findings in asymptomatic patients (Matheson et al. 1987).

A comparative study of CT with reverse gantry tilt (CT with axial scanning in the plane of the pars interarticularis) and SPECT demonstrates similar disparate findings between CT and SPECT in 213 patients (Gregory et al. 2005). Spondylolysis was identified on CT scan in 81 patients with a total of 143 pars defects identified (multiple in 44), 105 being complete fractures and 38 incomplete fractures. SPECT showed increased uptake corresponding to the CT lesion in 72 cases. However, 9 patients with bilateral complete pars defects with sclerotic edges on CT did not show increased uptake on SPECT. SPECT showed increased uptake, and the CT showed sclerosis of the pars with no spondylolysis in 20 patients, very likely representing a stress reaction (Fig. 6.24). Increased uptake with no sclerosis or spondylolysis was present in 46 patients. Eight patients had sclerotic pars on CT with no SPECT abnormality (Fig. 6.25). SPECT and CT were normal in 56 patients. These results are similar to the findings in the study of Campbell et al. (2005) with ~25 % of cases showing disparate findings that are difficult to explain in terms of a stress reaction.

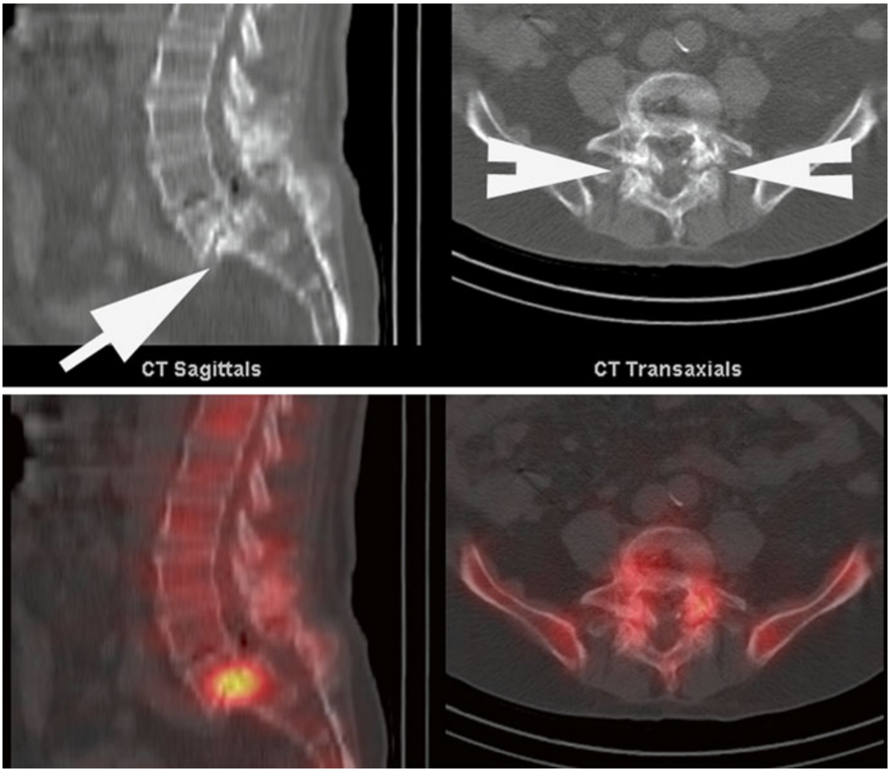


Fig. 6.25 Bilateral inactive pars fractures with spondylolisthesis. This patient presented with right buttock pain after falling off a horse. He was suspected of having sacroiliac joint incompetence which was shown on the SPECT/CT study. The lumbar findings were incidental and dated back to his youth when pars fractures were diagnosed. The study shows bilateral pars defects with sclerotic fracture margins (*arrowheads*) and no significant metabolic activity in the corresponding SPECT image. The slip of L5 on S1 (*arrow*) is associated with intense uptake around the disc space

The two illustrations show the fundamental importance of bone scintigraphy in deciding if a pars fracture is of long standing and has no potential for healing (Fig. 6.25) or is metabolically active and has capability for healing (Fig. 6.24) (Ryan and Fogelman 1994). One study that examined surgical outcomes for spondylolysis based on preoperative SPECT clearly showed that those with positive studies had a better outcome than those with negative SPECT (Raby and Matthews 1993). However, findings should be tempered with a knowledge of the natural history of spondylolysis/spondylolisthesis, as has been shown in a longitudinal study of 500 juveniles (Fredrickson et al. 1984). This study showed that 6 % of juveniles will carry inactive and painless pars fractures into adulthood (Fig. 6.25).

Rarely, rotational movements may lead to avulsion/traction injuries of the multifidus muscles of the lumbar spine, presenting as increased uptake in the spinous processes and posterolateral vertebral bodies (Howarth et al. 1994).

6.12.3 Bertolotti's Syndrome

Bertolotti's syndrome (Bertolotti 1917) is low back pain associated with a transitional lumbar vertebra. It is rare and has been reported in 140 cases out of 2000 adults with low back pain (Elster 1989). There can be asymmetric fusion of the transverse processes of L5 with the sacrum, which is rarely a cause of pain unless a pseudoarthrosis develops. More often, rigidity of the L5/S1 segment may transfer the stress to the vertebra above, leading to accelerated degenerative disease of the intervertebral disc and zygapophyseal joints (Elster 1989). In younger patients with a transitional vertebra, SPECT with either CT or MRI correlation has shown that increased uptake may occur in the majority of cases (39/48) (Connolly et al. 2003). In this series, ~60 % of these abnormalities were only apparent by SPECT and not evident on planar imaging. The potential for SPECT/CT is obvious as it allows evaluation of the anatomy of the joint in addition to showing a potential pseudoarthrosis. There are references to its potential utility (Scharf 2009), but no critical analysis to provide a foundation for routine use of the technique.

6.13 Shoulder and Upper Limb

6.13.1 The Shoulder

The shoulder is a difficult joint to study with scintigraphy due to its size and the dominance of soft-tissue injuries and the clear advantages of MRI in routine use. A systematic study was undertaken by Clunie et al. (1997). Using a number of positioning techniques, they were able to identify a cause of the painful shoulder in 79 % of patients. Distinct patterns of 99mTc-MDP image abnormality were identified. Increased uptake in the coracoid, acromion and medial humeral head on anterior planar images, together with an absence of posterior planar image abnormality, frequently occurred in association with a sub-acromial lesion. Posterior image abnormalities always occurred in patients with clinical features consistent with a diagnosis of adhesive capsulitis.

Systematic application of SPECT to suspected shoulder impingement with or without rotator cuff tears was assessed by Park et al. in 73 patients with operative confirmation of the findings (Park et al. 2009). Uptake was semi-quantitatively expressed as a ratio compared with the same site in the normal shoulder. The sites chosen for comparison were the anterior acromion, distal clavicle, coracoid process and greater and lesser tuberosities of the humerus. The greater tuberosity showed an average 164 % increase in uptake over the normal side followed by the distal clavicle and anterior acromion with a 150 % increase in uptake. This group concluded that impingement is best reflected by uptake in the greater tuberosity of the humerus, regardless of whether or not there is a rotator cuff tear: the higher the relative uptake at this site, the better the reported clinical response after surgical intervention. SPECT/CT can only enhance this type of imaging. Clearly, MRI is going to be the best and preferred imaging modality for soft-tissue pathology, but there is evidence that it does not perform as well for sub-acromial lesions in the shoulder (Clunie et al. 1997).

6.13.2 Arm and Forearm

Injuries other than acute fractures are infrequently reported in the humerus, with occasional reports of muscle insertion splints at the proximal insertion of the brachioradialis (Roach and Cooper 1993). Injuries around the elbow are more common, with scintigraphic reports of a number of soft-tissue manifestations such as triceps avulsion from the olecranon process, olecranon bursitis, medial and lateral epicondylitis and distal biceps avulsion injury (Van der Wall et al. 1999). The majority of forearm injuries are due to acute or chronic fractures. Distal radial fractures are reported to account for one sixth of all acute fractures presenting to the emergency room (Knirk and Jupiter 1986), with 50 % involving dislocation and over 60 % involving the radiocarpal or radioulnar joint. SPECT/CT can only enhance imaging of the elbow, as we have found in a number of complex injuries, where it has been possible to identify osteochondral injury and collateral ligament damage.

6.14 Wrist and Hand

6.14.1 Wrist and Hand: Soft-Tissue Injury

Scintigraphy can demonstrate evidence of soft-tissue and bone injury in the wrist. It can demonstrate tenosynovitis of the tendons of the wrist. De Quervain's tenosynovitis has been described as showing elongated hyperaemia in the distribution of the tendons in the radial compartment of the wrist with delayed uptake in the radial styloid (Sopov and Groshar 1999). Post-traumatic pain due to the complex regional pain syndrome I (reflex sympathetic dystrophy) may be diagnosed accurately.

6.14.2 Wrist and Hand: Bone Injury

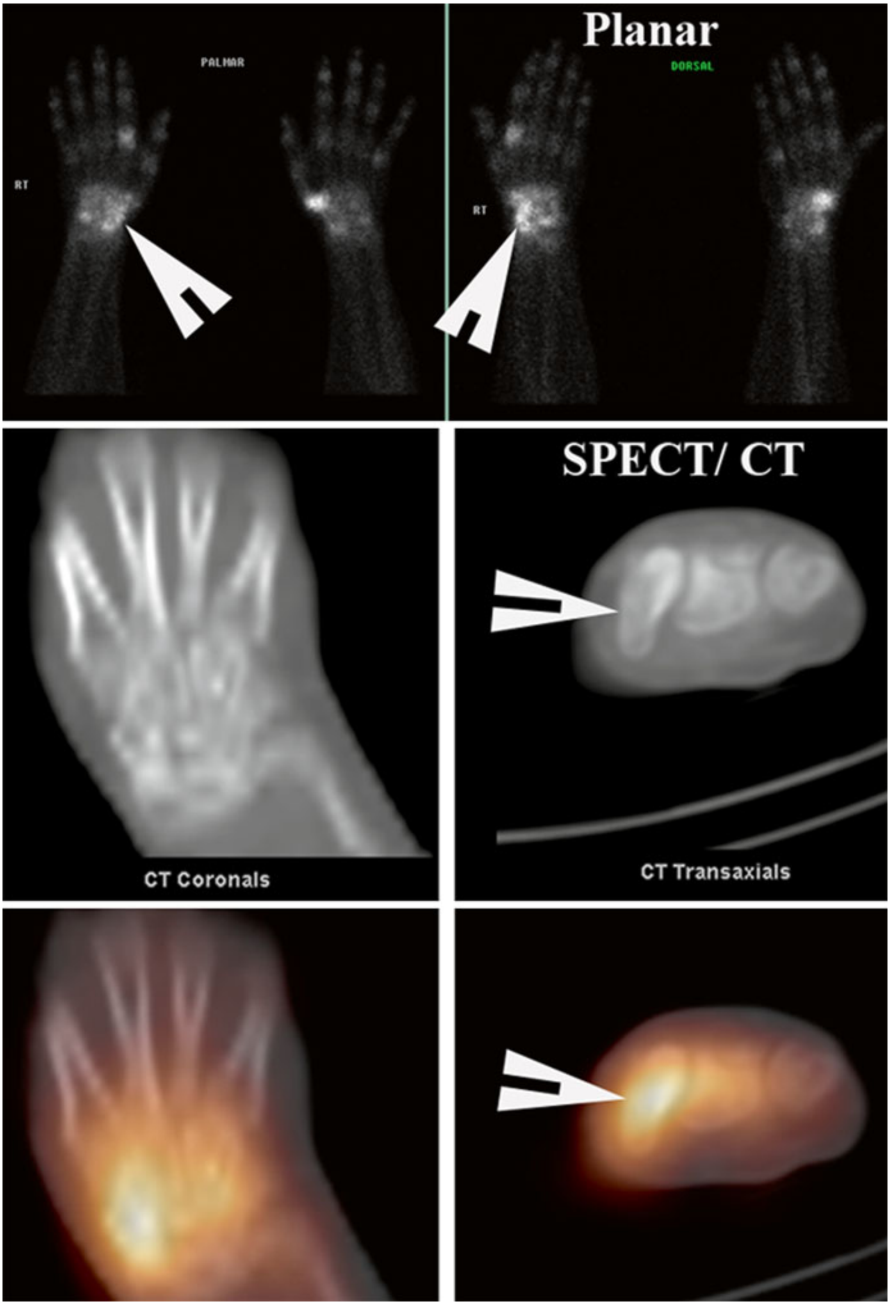
Reports of the scintigraphic detection of fractures of every bone in the carpus and hand have been made since the inception of the technique (Patel et al. 1992; Maurer 1991). Scaphoid fractures are the most common, accounting for 60–70 % of all carpal injuries (Sherman and Seitz 1999). Fractures of the lunate are rare but prone to avascular necrosis if not treated, as 20 % of the population have only a single blood supply to the bone (Sherman and Seitz 1999). Injuries to the hamate usually affect the hook, although any portion of the bone may be involved (Sherman and Seitz 1999). Fractures of the hook are usually seen in sports that involve bats, clubs or racquets. Fractures of the triquetrum, pisiform, capitate, trapezium and trapezoid may occur due to direct blows or compression of the wrist in falls. These are easily diagnosed by scintigraphy, with significant improvement in accuracy if the study is co-registered with the plain radiographs (Mohamed et al. 1997).

There are several reports of the feasibility and accuracy of wrist SPECT and SPECT/CT in the detection of fractures and other wrist injuries (Dubowitz and Miles 1994; Groves et al. 2005). Our experience has also been of much improved accuracy and ease of reporting with SPECT/CT, although technical attention to detail in positioning is critical. The technique is particularly important when there is degenerative disease of the first carpometacarpal joint which can obscure subtle uptake in the scaphoid (Fig. 6.26).

Conclusion

Bone scintigraphy has extensive applications in the diagnosis and monitoring of sporting injury. While the technology continues to improve with the addition of hybrid radiological instruments such as CT, the report must be tempered by the clinical history and examination. Appropriate positioning of the injured site based on history and examination is crucial in deriving an accurate report. The gamut of diagnostic possibilities encompasses soft-tissue and bone injuries, making the acquisition of high-quality blood pool phase studies mandatory. SPECT/CT will revolutionise the imaging of such injuries as there is currently a good body of evidence to confirm its incremental value in most instances. The fused images are also a powerful persuader for the referrer and will help increase the acceptability of the technique, especially for orthopaedic surgeons. When imaging children, special consideration needs to be given to positioning, anatomical variants and issues of radiation exposure.

Fig. 6.26 Scaphoid fracture. An elderly lawn bowler fell over, landing heavily on the right wrist while carrying the ball. He experienced severe pain in the radial side of the wrist. Plain films were reported as showing no fracture, but severe degenerative change in the right first carpometacarpal joint. The planar images were difficult to interpret because of increased uptake at the site of degenerative disease in the right first carpometacarpal joint, but more marked uptake was evident in the scaphoid (*arrowhead* in planar). This is more obvious in the SPECT/CT images with a subtle fracture line through the waist of the scaphoid (*arrowhead*)


Planar
PALMAR
DORSAL
RT
RT
SPECT/ CT
CT Coronals
CT Transaxials

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Part II

The Musculoskeletal System Topographically: Head and Face

Injuries of the Head and Face

7

Robert Jan de Vos and Andrew S. McIntosh

Contents

Abstract

Head and orofacial injuries in sports are common, but serious injuries are rare. At present, there is substantial interest in concussion and its management in sport. Many sports give rise to the potential for the athlete to be struck in the head or face,

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often by relatively rigid high-speed projectiles or body parts. The bony contours of the face combined with the soft tissue covering makes the face vulnerable to fractures and lacerations when it is exposed to impacts. The dimensions of many projectiles, e.g. squash balls and cricket balls, mean that they can impact the eye or damage the orbit. In the context of the range of normal impacts in team sports, skull fractures are not common. Head impacts against rigid pieces of infrastructure, e.g. posts, concrete footings and hard floors, can give rise to skull fractures. In powered sports or high-speed individual sports, e.g. cycling, skiing and horse racing, the unprotected head is exposed to a measurable risk of skull fracture and severe intracranial injury. The brain, however, is vulnerable to the range of head impact severities that athletes are exposed to in sport, with the most frequent manifestation being concussion. Consensus guidelines on the management of concussion indicate that athletes should not return to match play in the event in which they have been concussed and their future return to play must occur after resolution of symptoms and cognitive function. The application of risk management approaches to prevent head and facial injury is successful. The application of rules that prevent and limit head contact is important. Improving the infrastructure to remove hazards is another element. Personal protective equipment, such as helmets and mouthguards, has been shown in some sports to protect the head and mouth. Immediate medical management of injuries and evidence-based return-to-play processes are also essential.

Abbreviations

CT	Computerised tomography
d	Deformed
F	Force
FIFA	Fédération International de Football Association
KE	Kinetic energy
N	Newton
SCAT	Sport concussion assessment tool
W	Work

7.1 Introduction

Head and orofacial injuries are frequent in sports, though serious injuries are rare. The majority of head and orofacial injuries are soft tissue injuries, such as lacerations and contusions. Athletes rarely seek medical attention for these injuries and either self-treat or are attended to by trainers, first aid officers or allied health professionals. At the most severe end of the spectrum, fatal head injuries occur in high-energy sports, including powered sports. In recent years there has been a specific focus on concussion in sports. Only a small proportion of concussed athletes seek medical attention, although that issue is now being addressed.

The recognition by many sports that there is an inherent high risk of head injury has led to cultural changes in those sports, e.g. where once no athlete wore a helmet, now all athletes wear helmets (McIntosh et al. 2011). When one looks across the spectrum of sports, it is possible to see discussions and developments taking place in one sport that are already history in other sports. In the recent past, for example, recreational skiers rarely wore helmets. Now, there are widespread use of helmets in alpine sports and regular calls for helmet use to be made mandatory. There has been a long history of helmet use in American football, but it has been recognised that the helmets are not designed optimally to prevent concussion; the design focus has been to prevent skull fractures and traumatic brain injury. Helmets are also worn as much to provide a mechanism for protection of the face. In projectile sports, such as baseball and cricket, batters can suffer orofacial injuries, including fractures to the orbit, as a result of ball-to-face impacts.

In the past decade, there has been a great deal written on the incidence and prevalence of sporting injuries in specific sports, including head and facial injury. When reporting these metrics, researchers tend to use a variety of numerators for injury and denominators for exposure that limit the ability to compare sports or within a sport. Commonly used numerators are on-field treatment for an injury, missed-game injury (1 day to 7 days) or hospital separation. Commonly used denominators for exposure are athletic exposures (when an athlete competes there is one exposure), time of exposure (minutes played) or seasons. It would appear that because of the high speeds and propensity to crash, a large proportion of injuries in equestrian sports, in particular horse racing (19–48 %), and alpine sports (15–30 %) are to the head. Due to the variability in injury metrics, the proportion of injuries to the head in football codes is reported to cover a wide range, e.g. soccer 4–20 %, rugby union 14–25 % and American football 8–12 %. In cricket and baseball, the proportion of injuries to the head is between 3 and 25 %. In terms of traumatic brain injury, there are minimal risks in football (soccer), rugby union, baseball and cricket; medium risks in American football (approximately seven catastrophic head injuries per annum in US college and high school football) and cycling when helmets are worn; and high risks in alpine and equestrian sports. In terms of incidence, in rugby football the rate of head injury for youths is 8.1 per 1,000 h of game time and 6.6 per 1,000 h for professionals. In male youth baseball, for example, the incidence rate of concussion has been reported to be 1.6 per 1,000 athletic exposures. The numbers of athletes imaged or who require imaging as a result of head injury are unknown.

Functional anatomy, aetiology and injury mechanisms, as well as specific sports injuries, will be described.

7.2 Functional Anatomy

The anatomy of the skull and brain is complex due to its structure and functions. The skull can be divided into two main parts, the neurocranium which enfolds the brain and the viscerocranium which constitutes the face. Parts of the neurocranium are the ethmoid, frontal, occipital, sphenoid, parietal (paired) and temporal (paired) bones (Lohman and ten Donkelaar 1997).

The space in the skull that constitutes the brain is named the cranial cavity. The upper side is formed by the bones of the calvaria (skull roof), and the lower side is formed by the skull base. The skull has an important function in protection of the brain. Skull fractures can give rise to specific injuries, such as epidural/extradural haemorrhages because the fracture transects a blood vessel.

The brain plays a major role by receiving, interpreting and directing sensory information. The focus of recent research into concussion in sports has been to understand the relationships between symptomatic presentation, e.g. loss of consciousness or balance disturbance, with the underlying pathophysiology. Neuroimaging is playing a role in this research. The medulla oblongata in the hindbrain is responsible for controlling autonomic functions as breathing, heart rate and digestion (Lohman and ten Donkelaar 1997).

The bones of the face give shape to the eye sockets and the oral and nasal cavity. This viscerocranium constitutes the inferior nasal concha (paired), lacrimal bones (paired), mandible, maxilla (paired), nasal (paired), palatine (paired), vomer and zygomatic (paired) bones. The orbit is formed by a supraorbital ridge, infraorbital part, the nasal bone medially and zygomatic arc laterally. It is cone shaped and therefore protects the eyes for impact of larger objects. This makes other bones, especially the zygomatic bone, susceptible to be fractured in an impact because of its prominent location (Brukner and Khan 2012). The upper jaw is formed by the maxilla, which supports the orbital floor and hard palate. The lower jaw is formed by the mandibular bone which is also superficially located.

7.3 Aetiology and Injury Mechanisms

The vast majority of sports injuries to the head and face arise because of impacts. The key factors to consider in terms of the impact and the likelihood that it will result in an injury are the impact speeds and masses of the colliding objects; available methods to attenuate energy, such as helmets or padded surfaces; injury mechanisms; and human tolerance. A punch to the back of the head may deliver the same amount of energy to the head and be as forceful as a punch to the face but will not cause a fracture, whereas the same punch to the face may cause a nasal or zygomatic fracture. If the punch delivered a sufficiently high force and resultant head acceleration, then it may concuss the recipient, but the likelihood will depend on the direction of the impact because of human tolerance, and the actual symptomatic presentation may also be different.

The following is a brief biomechanical overview of the key concepts. When energy transfer is considered in this context, the principle of conservation of energy needs to be applied.

Example 1: In an uncomplicated impact, a baseball is thrown and strikes the batter's face. This can be considered simplistically with the total energy of the ball being transferred to the face. The energy being equivalent to ball's kinetic energy (KE), e.g. a 0.14 kg ball travelling at 19 m/s has a kinetic energy of 25 J ($KE = 1/2\ mv^2$). The impact force (*F*) will be determined by the amount of deformation that occurs in the impact, i.e. the work (*W*) performed. If the ball and face deformed (*d*) by 10 mm, then the average impact force would be 2,500 N ($W = F.d$). The impact force is around the range required to cause lacerations or fractures to the face. In a series of experiments replicating this impact, the head's peak resultant linear acceleration was measured to be 316 g, suggesting that brain injury is also highly likely (McIntosh and Janda 2003). When tested with a standard baseball helmet, there was an 80 % reduction in peak head acceleration, due to the greater amount of deformation enabled by the helmet.

Example 2: When the heads of two soccer players collide, the energy transfer will depend on their velocities (speed and direction). From the sideline, it can appear that because of the athletes' speeds, a severe impact has occurred, but that may not necessarily be the case:

(a) If both players were running in the same direction, jumped to head the ball and clashed heads, then the transfer of energy that occurs in that head impact will be largely associated with the heads' velocities relative to players' bodies, e.g. related to head lateral or forward flexion. It might be painful, and if a very rigid part of one player's head collides with a more flexible part of the other's, e.g. the nose, then a nasal fracture could arise.

(b) In contrast, when a player is running in one direction and his head collides with the head of a player running in the opposite direction, the energy transfer will be related to the running velocity of each player leading to a much higher energy transfer compared to example 2(a), even if the running speeds were the same in the two examples. The reason why one player is more severely injured than the other in these two cases is related to the injury mechanism and that individual's tolerance to impact. In these cases, the location and direction of the impact force is important, with impacts to the temporoparietal region being more likely to result in concussion due to the specific patterns of linear and angular acceleration that arise and their association with strains in selected parts of the brain, e.g. corpus callosum and brainstem (Patton et al. 2012).

Fracture causation tends to be seen through three factors – the magnitude of the force, the concentration of the force (pressure) and mechanics of loading (compression, tension, bending, shear and torsion). As force increases, so does the likelihood of fracture. Projectile impacts to the head and face cause a concentrated load resulting in localised bending of the bone and related deformation and failure. Individual variation in bone dimensions influences the fracture force and fracture pattern. In a more distributed impact, e.g. an unhelmeted cyclist falls onto the road, the patterns of tensile strain caused by the flattening of the calvaria and the variation in bone dimensions including buttresses may cause linear fractures that commence at the periphery of the impact site and extend some distance, including into the base.

7.4 Sports Injuries

7.4.1 Concussion and Its Complications Including Postconcussion Syndrome

According to the 4th International Conference on Concussion in Sport, concussion is defined as a 'complex patho-physiological process affecting the brain, induced by biomechanical forces' (McCrory et al. 2013). It is considered to be a functional injury, and as such 'no abnormality is seen on standard structural neuroimaging studies'. The cause of concussion may be due to direct head impact or 'impulsive' forces transmitted through the cervical spine, both resulting in head linear and angular acceleration. There are some important features of sports-related concussion. It may cause loss of neurological function which resolves spontaneously within a short time; it does not cause structural injury, and therefore conventional neuroimaging is normal, and it results in a broad spectrum of clinical signs and symptoms. Resolution of these symptoms follows a sequential course, but the timeframe may be very varying between patients. Loss of consciousness can be possible, but this sign is not needed for the diagnosis of concussion. According to the present literature, the pathophysiology of the neuronal dysfunction is a consequence of a complex bio- and neurochemical cascade (Marshall 2012).

The clinical diagnosis of concussion may be hard to establish within the constraints of on-field management. One reason for this may be that athletes can be misleading in their presentation because they try to hide symptoms in order to return to the game. Valuable information can be gained from an athlete's reaction after an impact; signs that may reveal a concussion include impaired balance and confusion. It is important to recognise that every athlete sustaining a head injury is at risk of having structural brain injury. Cervical injury should also be excluded or managed appropriately with immobilisation. Excluding structural brain injury on the sideline can be very difficult because some of these (subdural or epidural haematoma) need time to develop and the assessment can become more complex as a result of the cognitive impairment of the athlete.

The on-field management of concussion and head injury is ideally carried out by a physician, and the medical evaluation should start with control of airway, breathing, circulation and level of consciousness using the Glasgow Coma Scale. If possible, the player can be checked on the sideline for further medical assessment, including neurological examination. According to the validated 'Maddocks score', questions regarding the score, the current opponent and game rules contribute more to the diagnosis of concussion than simple orientation tests in time, person and location (Meehan and Bachur 2009). These questions can be combined with a simple Romberg balance test. An athlete with the diagnosis of concussion should not be allowed to return to play on the day of injury (Khurana and Kaye 2012). The physician may have to make a decision whether to refer to a hospital for additional neuroimaging. Table 7.1 does provide criteria that indicate the need for CT scanning whenever suspicion of an intracerebral structural lesion is present. It does not support the diagnosis of concussion, and it does not provide prognostic information

Table 7.1 Indications for urgent neuroimaging according to the New Orleans Criteria (NOC), based on patients with mild traumatic brain injury and a maximum Glasgow Coma Scale. There is an indication of computed tomography (CT) scanning if the patient meets one or more of the following criteria

Headache (any head pain)
Vomiting
Age older than 60 years
Intoxication
Deficit in short-term memory (persistent anterograde amnesia)
Physical evidence of trauma above the clavicle
Seizure

Table 7.2 Possible signs and symptoms of concussion

Cognitive	Somatic	Affective	Sleep disturbance
Confusion	Headache	Emotional lability	Trouble falling asleep
Amnesia	Dizziness	Irritability	Sleeping more than usual or sleeping less than usual
Disorientation	Balance disruption	Fatigue	
Feeling 'zoned out'	Nausea or vomiting	Anxiety	
Loss of consciousness	Visual disturbances	Sadness	
Vacant stare	Phonophobia		
Inability to focus			
Delayed verbal and motor responses			
Incoherent speech			
Excessive drowsiness			

after concussion. Absence of all seven findings has a very high negative predictive value of nearly 100 % (Jagoda 2010). However, the approach should always be 'when in doubt, refer' because of the potentially large consequences of intracerebral lesions.

The wide spectrum of concussion signs is divided in cognitive, affective, somatic and sleep disturbance (Table 7.2). As isolated variables, these factors are not specific for concussion. However, in case of a head trauma, these symptoms are susceptible for the diagnosis of concussion. In case of the presence of loss of consciousness or confusion, the diagnosis of concussion is obvious. When the diagnosis is less certain, a standardised assessment using the Sport Concussion Assessment Tool (SCAT) 2 can aid in the diagnosis (McCrory 2009). The SCAT2 evaluates symptoms, cognitive function and balance. A player with a disturbance of these functions after head trauma can be considered as a patient suffering from concussion. Ideally, it should be performed in the preseason and compared to the athlete's baseline value. The SCAT2 can be a very helpful tool which is easy to administer. However, it should not be used as a solitary test to diagnose concussion and measure recovery for return-to-play decision. At present there are no accepted grading systems to express concussion severity; the Cantu Scale is an example of a grading system with a long history of use. There is currently no single questionnaire, neuropsychological test, biomarker or additional neuroimaging modality (e.g. functional magnetic resonance brain scanning) to classify a concussion. However, studies in this field are ongoing.

Return to play is a challenging decision. The athlete has to be recovered fully, and symptom evaluation only is not adequate for this decision. A concussed athlete should be monitored multiple times by a physician to evaluate recovery of symptoms, cognitive function and balance. In general, a graduated return-to-play protocol is recommended with an initial brief period of cognitive and physical rest of 2–3 days. As symptoms resolve, a graduated increase in activities can be started with subsequently light aerobic exercise, sports-specific training, training drills without body contact and later on contact in a group and finally return to match playing. According to the Zurich consensus, statement players should be allowed to progress to the next stage when they remain asymptomatic for 24 h after training. If symptoms persist or recur, the player is advised to step back in the protocol. In case of a successful recovery, the player can return to sports within a week. In the majority of cases, full recovery occurs in 7–10 days.

There are several reasons for this conservative programme. It is known that an athlete is at greater risk for further injury when the recovery is not yet fully completed. This injury may be musculoskeletal or a second concussion, due to the decreased reaction time of the athlete. Another consequence of repeat concussions is the chance of developing 'postconcussion syndrome'. Associations have been postulated between repeat concussions and chronic traumatic encephalopathy and with depression, cognitive impairment and other mental health problems in a small number of athletes. The definition of this postconcussion syndrome is 'a prolonged symptom duration after concussion'. The exact timeframe for this diagnosis, however, remains unclear according to the variable definitions used in literature (Jotwani and Harmon 2010). The most frequently used cut-off is the presence of more than 3 months of symptoms (Prigatano and Gale 2011). Symptoms persisting from 1 to 6 weeks have been suggested as thresholds for the diagnosis of postconcussion syndrome in athletes. The pathophysiology is not well understood, and hypotheses range from poor coping mechanisms to the occurrence of biomechanical forces on the brainstem, forebrain and temporal lobe. The clinical features can be divided into physical symptoms, emotional changes and cognitive disorders and cover a wide gamut of signs and symptoms. In cases of suspected postconcussion syndrome, the standard additional imaging modalities are applied. Novel modalities, such as functional MRI, are promising and studies are upcoming. The mainstay of the management of this condition is observation and adjustment of activity. Currently, there are no other evidence-based treatments for the sports medicine physician to apply. In older athletes with a history of recurrent concussions, it is known that approximately 10 % will have persisting symptoms of postconcussion syndrome, which further emphasises the need for prevention of recurrent concussions (Prigatano and Gale 2011).

7.4.2 Facial Injuries

In contact sports there is a higher frequency of facial injuries. According to the literature, 3–29 % of facial injuries are due to sporting activities (Reehal 2010). The complex anatomy in this region and the high variability in types of injuries lead to a challenging diagnosis and treatment of these injuries.

Table 7.3 Practical steps in the evaluation of facial injuries

Evaluate airway, breathing, circulation, level of consciousness and possibility of cervical spine injuries
Discover trauma mechanism
Locate patient's pain
Evaluate eye injury symptoms, diplopia and blurred vision
Search for signs of skull base fractures, cerebrospinal fluid leakage from the nose or ear and 'battle sign' at the mastoid bone or 'raccoon eyes' which may not be present at the initial stages
Inspect for nasal haematomas and deviations of the nasal septum
Inspect the external auricle and ear for haematomas
Look for facial asymmetry, such as structural depressions or a sunken eye globe
Observe for wounds that can overly suspected fractures

The clinical assessment of facial injuries is similar in case of other acute on-field injuries and starts with control of airway, breathing, circulation, level of consciousness and cervical spine injuries. A practical series or steps in the evaluation of facial injuries are provided in Table 7.3 (Brukner and Khan 2012).

7.4.3 Soft Tissue Injuries

The most prevalent face injuries in sports are lacerations of the skin and contusions, which are easy to diagnose. However, thorough examination of the underlying bone and neurological examination in case of suspected skull fracture or concussion should be performed. Treatment of contusions generally starts with immediate ice application and compression of the affected area. Lacerations can be treated by applying adhesive strips, tissue adhesives, suturing or skin stapling. The role of antibiotic treatment as prophylactic management remains controversial. Tetanus prophylaxis should be considered if this is not up to date (Reehal 2010).

7.4.4 Nasal Injuries

The most prominent bones in the face are formed by the nose, which is the most frequently fractured bone in the adult face (Reehal 2010). There is an extensive vascularisation network around the nasal bones, and the clinically most relevant part is Kiesselbach's plexus, located in the nasal septum. A nasal fracture is therefore frequently accompanied by epistaxis. Other symptoms include pain, swelling, deformity, crepitations and increased mobility.

Additional imaging is usually not requested because undisplaced fractures do not require treatment, and displaced fractures are clinically easy to distinct.

Treatment consists of controlling the epistaxis. In most of the cases, this bleeding is originated from Kiesselbach's plexus on the anterior side, which can be treated by digital pressure through pinching the nose. If this measure fails, the physician can choose for nasal packing combined with a nasal decongestant spray. If these interventions do not lead to bleeding control, referral to a specialist is needed for arterial ligation or embolisation (Reehal 2010). Nasal fractures can be treated with a delayed closed reduction when swelling has settled (Higuera et al. 2007).

A complication of nasal bleeding may be the formation of a septal haematoma. This condition can be recognised as a purple area of swelling, and fever may be present. If a septal haematoma is present, it should be evacuated to prevent abscess formation and development of cartilage necrosis (Mondin et al. 2005).

7.4.5 Ear Injuries

Ear injuries are common in scuba diving and contact sports as judo, rugby and wrestling. Blunt or shearing forces can result in a haematoma around the perichondrium of the ear, and this auricular haematoma is also known as the 'cauliflower ear' (Khalili-Borna and Honsik 2005). It usually presents as a painful swelling in the antihelix, and the contours of the auricle are declined. Initial treatment is application of ice and firm compression. However, aspiration or even an incision may be needed (Lee and Sperling 1996).

A perforated eardrum is most commonly seen after large changes in pressure or after a direct hit to the ear. Symptoms that suggest this diagnosis are a sudden pain, loss of hearing and external ear bleeding. Management is expectative, and athletes participating in water sports can use earplugs. Scuba diving is prohibited in these cases because of the large pressure changes (Romeo et al. 2005).

7.4.6 Ocular Injuries

Sports-induced eye injuries can potentially result in a major loss of function, and therefore they require serious examination. Special attention should be given to high-velocity impact with ball sports or injuries induced by a sharp object with risk of a penetrating eye injury.

With a directional history taking and physical examination, the physician can manage most cases of eye injury, although referral to a specialised ophthalmologist may be required.

Among the most frequent eye injuries are corneal abrasions. This is a defect in the surface of the corneal epithelium as a result of direct trauma or drying eyes. A trauma is often directly induced by an opponent's finger or with a foreign body. Symptoms include pain and a foreign body sensation, as well as photophobia. An anaesthetic drop can be a helpful medicine for the examination, and fluorescence staining can detect abrasions or foreign bodies (Drolsum 1999). If the physician is experienced, a foreign body can be removed using a cotton-tip equipment, but with deeply located foreign bodies, a referral to an ophthalmologist is needed for removal.

Subconjunctival haemorrhage can occur as a result of a trauma to the conjunctiva or high blood pressure. It is recognised by a red area as a contrast to the white conjunctiva. If there are no symptoms of vision loss or photophobia, the management can be expectative with reassurance (Cass 2012). Less common eye injuries are a hyphaema, globe rupture and retinal tears. These conditions need referral to an ophthalmologist.

An increasing incidence of orbital fractures in sports is observed. In racket sports, an object with the same size as an eye socket can cause a blowout fracture. The orbital floor is affected in the majority of the cases. Signs of an orbital floor fracture include periorbital swelling, painful extraocular movements, a protruding or sunken eye and double vision on upward gaze (due to entrapment of the inferior rectus muscle within the fracture) (Cass 2012). Hypoesthesia or dysaesthesia can be found as a result of infraorbital nerve damage. On physical examination a step-off can be palpated if the orbital rim is fractured. Referral for additional imaging and treatment is needed. Treatment includes the advice to avoid blowing the nose for several weeks to prevent orbital emphysema, which could affect vision (Cass 2012). The role of surgery is controversial.

7.4.7 Dental Injuries

Injuries to the teeth are most frequently due to collision in sports, and evaluation of the oral status and extent of the dental injury is required (Ranalli 2005). For tooth fractures, luxations or avulsions, the proposed treatment is generally to replace the avulsed tooth in its socket (Saini 2011). If this is not possible, it is advised to keep the tooth or the tooth fragment in a solution (Brukner and Khan 2012). Fast reimplantation of a tooth by a dentist results in a much greater chance of saving the tooth (Reehal 2010).

7.4.8 Fractures of Facial Bones

Facial fractures account for 4–18 % of all sports-related injuries (Reehal 2010). Midface and mandibular fractures are important to recognise because they may result in a larger bleeding or threatened airway. Orbital fractures and zygomatic fractures can potentially result in threatened vision.

Maxillary fractures in sports are in the majority caused by a direct hit. The cheek and nasal bones may also be involved, and the extensiveness is described in the Le Fort classification. A Le Fort I fracture results in a separation of the tooth-bearing part of the maxilla from the rest of the maxilla. On examination it is important to palpate the palate for a step-off and to test the stability of the palate in an anterior to posterior direction. The posterior part of the palate can drop downward, leading to an open bite (Reehal 2010). A Le Fort II fracture can be tested through a wobbling movement while grasping the upper teeth, because the maxillar bone and nasal complex are moving as one complex. In cases of a Le Fort III fracture, manipulation of the palate will also result in displacement of the involved zygoma (Reehal 2010). Le Fort I fractures are less severe than type II or III fractures, which tend to cause airway obstruction. Rapid referral to a hospital is required in these circumstances, and it is advised to let the conscious patient sit forward to prevent an airway obstruction.

Fracture sites at the mandible are frequently located at the angle and mandibular condyle. The presence of one mandibular fracture should remind the physician to search for another fracture, as multiple fractures are common in these cases

(Brukner and Khan 2012). Undisplaced fractures are treated conservatively with rest and pain management. Displaced mandibular fractures are regarded as severe injuries. On examination, a malalignment of the teeth can be palpated. Other symptoms include pain, malocclusion and hypoesthesia or dysaesthesia below the lower lip when the inferior alveolar nerve is involved. Airway obstruction is possible due to profuse bleeding or dental injuries, but posterior displacement of the mandible may also result in an obstruction of the airway by the tongue. Therefore, the conscious patient is also advised to lean forward after diagnosing these fractures. These displaced fractures should be referred to an oral maxillofacial surgeon for reduction and fixation.

Fractures of the cheekbone, or zygomatic bone, can affect vision, jaw movement and the shape of the face. They are often a result from a direct blow, and the most common presenting signs are pain, swelling and flattening of the cheekbone. Other signs may be infraorbital hypoesthesia and a palpable step-off. Involvement of the orbital bone should be checked with examination of the eye movements as well. Treatment is generally surgical, and displaced fractures should be internally fixated within 2 weeks (Reehal 2010).

7.5 A Little Bit of Prevention

There are a number of areas in which sports injuries can be prevented: policies, rules and regulations, policing (refereeing and application of the rules), infrastructure, equipment, training and culture. A system approach to prevention needs to be adopted. The sports in its broad context needs to recognise that there is an injury issue that needs to be addressed, e.g. concussion. Policies around equipment and return to play need to be reviewed, standards organisations and equipment manufacturers need to be engaged on the topic, and programmes to change the culture are required. There are many reasons why good ideas are not successful: a manufacturer could design the perfect helmet, but there is no impetus for athletes to wear it; the sports culture at the grass roots can change so that there is a demand for safety, but there are no policies, equipment standards or equipment to fill that need. The processes are progressive and iterative, requiring research, translation, policy work, cultural change and engagement across the sports. New technologies, such as instrumented helmets, offer opportunities to monitor the 'hits' a player receives and to build this information into a holistic player management programme.

7.5.1 Protective Equipment

Protective equipment has been designed for athletes who are at increased risk for concussion and ocular and facial injuries. The use of a helmet has been shown to decrease head and/or brain injury risk among bicyclists, skiers and snowboarders (McIntosh et al. 2011). However, the effect of headgear use is not conclusive if concussion risk is evaluated specifically (Benson et al. 2009). Full facial protection in ice hockey players resulted in a decreased time loss from competition, thus possibly protecting athletes from more severe concussions. Some propose that headgear will have an opposing effect through more dangerous behaviour, but a systematic review could not demonstrate an association between mouthguard or face shield use and concussion risk (Benson et al. 2009). There is strong evidence that mouthguards prevent oral and dental injuries, but little evidence that they prevent concussion.

7.5.2 Rules and Player Behaviour

Focussed and conclusive research has shown how rules can be implemented to reduce the potential for accidental head contact. In football (soccer), the contest for the ball in the air is an important skill and one associated with head injury. Research by Andersen showed that head contact occurred when players raised their arms above shoulder level – hitting the opponent in the head with the elbow or forearm (Andersen et al. 2004). Rule changes to reduce this have been implemented by FIFA. Athletes can also decide to play noncontact versions of a sport, e.g. touch (rugby) football.

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Radiologic Imaging of Sports-Induced Brain Injuries

8

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Abstract

TBI can occur in a wide range of sports activities. Lesions are most commonly caused by impact (contact sports) or activities involving high velocity. Acute sports-related injuries are indistinguishable from head trauma sustained in other accidents. Recurring craniocerebral injuries, such as in sustained in contact sports, can lead to chronic traumatic encephalopathy (CTE). This condition is a tauopathy, which is caused by repetitive mild traumatic brain injury (mTBI). Players of contact sports, such as rugby, hockey, boxing, or American football, have an increased risk of acquiring this condition.

Imaging studies play an important role in the diagnosis, management, and follow-up of sports-related TBI. CT remains valuable for the detection of intracranial hemorrhage, skull fractures, and mass effect; unfortunately this technique is less sensitive for lesions such as diffuse axonal injury (DAI). Therefore, whenever there is a discrepancy between the clinical status of a patient and the CT findings, MRI should be used. MRI is becoming increasingly important for diagnosing parenchymal damage in sports-induced injuries. New sequences, such as susceptibility-weighted imaging (SWI), are very useful to detect microhemorrhagic foci. Diffusion-weighted imaging (DWI) and especially diffusion tensor imaging (DTI) provide quantitative measurements (such as FA, MD, ADC) which can be used as biomarkers for outcome prediction. Lower fractional anisotropy (FA) and high lesion count and volume have been related to poorer functional outcome. Other useful imaging modalities are ^{1}H-magnetic resonance spectroscopy (^{1}H-MRS), functional magnetic resonance imaging (fMRI), and positron emission tomography (PET).

8.1 Introduction

Given the increasing popularity of all kinds of sporting activities, it should not come as a surprise that the incidence of sports-related injuries is also rising.

Fortunately, injuries to the head and brain are not the most common lesions caused by playing sports, but they should be taken seriously, because they may lead to significant morbidity and/or mortality. In sports, injury to the head and brain is typically caused by physical contact with another person or with a stationary object. These sports may include activities involving high speeds (e.g., skiing, snowboarding, horse-riding, automobile or motorcycle racing, bicycling, roller blading, skateboarding, etc.) or contact sports (such as boxing, martial arts, rugby, American football, hockey, soccer, lacrosse, etc.).

In clinical terms, sports-related craniocerebral lesions can be subdivided into "acute injuries" and "chronic or repetitive injuries."

Acute craniocerebral injuries, such as collisions which can occur in high-speed sports, basically present the same imaging characteristics as other types of traumatic brain injury, unrelated to sports; therefore, acute craniocerebral injuries will not be discussed in detail.

Conversely, in this chapter, we shall focus our attention on chronic or repetitive craniocerebral injuries, which are typically encountered in contact sports.

8.2 Definitions

Injury to the brain, due to chronic or repetitive trauma, has first been described by H. S. Martland in 1928 (Martland 1928); he used the expression “punch drunk,” which refers to the neuropsychiatric impairment caused by repetitive blows to the jaw and head (mainly occurring in rather poor boxers). Pathophysiologically these changes were attributed to recurrent concussions (Martland 1928).

Guidelines by the American Association of Neurology define concussion as “a trauma-induced alteration in mental status that may or may not involve loss of consciousness” (Quality Standards Subcommittee 1997), with amnesia and confusion being the most prominent symptoms of concussion (Report of the Quality Standards Subcommittee 1997; Giza et al. 2013; Mendez et al. 2005).

Typically, in these patients, no structural changes of brain tissue can be identified on standard radiological studies performed in the acute setting (McCrory et al. 2013). However, recurrent concussions can cause various neuropsychiatric sequelae including postconcussion syndrome, chronic traumatic encephalopathy, and dementia pugilistica (Dashnaw et al. 2012). Despite the fact that some authors consider these conditions to be different entities, the terms are often used interchangeably. Persistent postconcussion syndrome, or sometimes simply postconcussion syndrome, is an elusive and only vaguely defined syndrome, which is characterized by mild post-traumatic mental impairment with no clear pathological correlate. It is usually a self-limiting condition, with 80–90 % of patients showing full recovery within the first 10 days, which distinguishes it from chronic traumatic encephalopathy. However, in some patients the transition to chronic traumatic encephalopathy does occur and is usually assumed if symptoms last longer than 3 months (Mendez et al. 2005; Gandy et al. 2014; Larrabee and Rohling 2013; Hung et al. 2014; Henry et al. 2011a, b; Erlanger et al. 1999; Ryan and Warden 2003). For reasons of clarity and consistency, in this chapter we will use exclusively the term chronic traumatic encephalopathy (CTE); this concept was formerly known as “dementia pugilistica” (from the Latin noun “pugil” or “pugilator” meaning “fistfighter, boxer”) (Erlanger et al. 1999; Saulle and Greenwald 2012).

CTE is a condition of insidious onset causing emotional lability, cognitive impairment, and Parkinson-like symptoms. It usually starts with mild cognitive impairment, such as irritability, poor memory, and attention deficit. As the disease progresses, aggression and confusion become more prevalent, leading in some cases to depression and suicide. Ultimately, Parkinsonian symptoms, loss of cerebellar function, and dementia become apparent. Two thirds of athletes, who retire from sports during a symptom-free interval, do not experience any symptoms until later in life. Typical onset of CTE is between 30 and 65 years of age. The severity of the disease appears to be linked to the number of concussions or traumatic brain injuries sustained throughout the sports career; however, the role of the severity of impact on disease progression has yet to be determined. Young age has been found to be a protective factor, possibly because of the brain’s higher plasticity in comparison to older populations. Other risk or protective factors, especially the presence of ApoE4 as a negative risk factor, remain controversial (Gandy et al. 2014; Saulle and Greenwald 2012; Gavett et al. 2011; Karantzoulis and Randolph 2013; Levin and Bhardwaj 2014; Mez et al. 2013).

8.3 Epidemiology of Traumatic Brain Injury and Concussion in Athletes

Traumatic brain injury (TBI) has been estimated to affect 1.7–2.7 million people annually in the United States of America (USA) (Coronado et al. 2012; Faul et al. 2010). Men are more commonly involved than women. Males are reported to be more prone to sustain TBI through all age groups, with an annual rate of TBI that is up to 2.7 times higher than for females (Faul et al. 2010). However, in a study among children aged 5–18 years in the USA, the authors could not find evidence of differences in odds to be admitted to hospital due to sports-related concussion between sexes, though increased age was associated with an increase in odds (Yang et al. 2008).

In the USA more than 300,000 people suffer sports-related mild-to-moderate TBIs in any given year (Sosin et al. 1996). The annual incidence of sports-related TBI has experienced a steep increase from 19.7/100,000 population in 1998 to 45.6/100,000 population in 2011, which might reflect an increase of people involved in playing sports (Selassie et al. 2013). It has been estimated that 2.5 concussions per 100,000 athletic exposures occur across all sports in US high school students, with athletic exposures being the participation in one competition or practice (Guerriero et al. 2012). In the Canadian National Population Health Survey, more than 54 % of all concussions were sports-related, with a peak in the age group 16–34, where more than 85 % of all concussions were sports-related (Gordon et al. 2006). Sports-related severe concussional head injury in children has been found to be six times more likely to have been caused during an organized sports event than being attributable to other leisure physical activities (Browne and Lam 2006).

In a large epidemiological study on the incidence of sports-related craniocerebral injuries in South Carolina (USA), TBI resulted most commonly from having been kicked in football, followed by injuries due to falls (Selassie et al. 2013). Noble et al. reviewed the incidence of concussions in different sports, demonstrating an incidence of 0.86–1.45 concussions per 100 games among professional American football players. At college level, 2.5 concussions per 1,000 competition athletic exposures occurred; at high school level, the incidence of head injuries is lower, ranging from 3.1 (during practice) to 22.9 (during competitions) per 10,000 athletic exposures. The lowest incidence was observed in youth leagues with "only" 1.76–2.53 concussions per 1,000 athletic exposures, with age being a risk factor. In ice hockey and field hockey, the incidence is 0.72–1.81 per 1,000 athletic exposures, with a slightly higher incidence for females than males. Among soccer and European football players, 0.06 concussions per 1,000 player hours in men and women at professional level; 0.3–0.6 per 1,000 athletic exposures for males and 0.4 per 1,000 athletic exposures for females at college level; and 2.1 (males) to 3.4 (females) per 10,000 athletic exposures at high school level have been reported (Noble and Hesdorffer 2013). To summarize, these epidemiological data show that there is an increasing incidence of concussion across all sports, with American football having the highest incidence of concussion, followed by hockey and soccer.

Accurate figures are hard to obtain, because sports-related concussions are frequently underreported. The most likely reason for this is that the great majority of concussions are mild and might not even be recognized by the athletes themselves (Langlois et al. 2006). One study among high school American football players in the USA revealed that only 47.3 % reported their injury. Concussions were not reported when the athlete considered the injury unimportant, did not want to be withheld from competition, or was not aware of the likelihood of concussion (McCrea et al. 2004). In another study, among athletes exercising contact sports, the authors compared the answers given during a concussion symptom survey (CSS) with occurrence of self-reported previous concussions; 71 % of athletes reported symptoms, which were consistent with those experienced with concussion, yet had not given a history of previous concussion (LaBotz et al. 2005). Estimates by the British Columbia Amateur Hockey Association (BCAHA) for concussions among both elite and non-elite youth players demonstrated an incidence of concussion in official reports between 0.25 and 0.61 concussions per 1,000 player game hours (PGH) for male players. However, volunteers estimated that the incidence is significantly higher, ranging from 4.44 to 7.94 per 1,000 PGH, with actual players reporting an incidence between 6.65 and 8.32 (elite) and 9.72–24.30 (non-elite) per 1,000 PGH (Williamson and Goodman 2006). Additionally, many athletes continue to compete even when experiencing symptoms consistent with concussion (Kaut et al. 2003).

8.4 Pathophysiology of Sports-Induced Chronic Traumatic Encephalopathy

It is generally accepted that chronic traumatic encephalopathy (CTE) is caused by repetitive acceleration/deceleration injuries, more commonly by their milder forms and in particular without any open-head injuries. CTE is currently assumed to be a progressive tauopathy (Gandy et al. 2014; Saulle and Greenwald 2012; Gavett et al. 2011; Karantzoulis and Randolph 2013; Levin and Bhardwaj 2014; Mez et al. 2013; Bramlett and Dietrich 2014; Costanza et al. 2011; McKee et al. 2009, 2013; Omalu et al. 2011).

The modern concept of CTE was first described by the Boston (Massachusetts, USA) research group headed by A. C. McKee in 2009 (McKee et al. 2009). Since then, these authors have proposed a four-stage histopathological classification system (McKee et al. 2013). A similar, though not identical, classification was published by a Sacramento (California, USA) research group in 2011 (Omalu et al. 2011). While both classifications involve a four-stage grading system of disease severity, they mainly differ in the description of the extent and importance of the presence of neurofibrillary tangles, Aβ amyloid plaques, and brain atrophy (Gandy et al. 2014; Saulle and Greenwald 2012; Karantzoulis and Randolph 2013; McKee et al. 2013; Omalu et al. 2011). Unfortunately, these histopathological models remain under discussion and are not yet perfect. Most patients, in whom the diagnosis of CTE was established postmortem, did not die of the disease itself but of other causes, an observation which is very uncommon in other neurodegenerative diseases. At the same time, many patients met the pathological criteria for Alzheimer's disease, which raises the issue if these changes are related to (ab)normal aging or if they are really caused by CTE. Inconsistent histological findings and a selection bias negatively influence its scientific value also (Gandy et al. 2014; Saulle and Greenwald 2012; Levin and Bhardwaj 2014; Bramlett and Dietrich 2014; McKee et al. 2013).

On a cellular level, mild traumatic brain injuries cause diffuse axonal injury (DAI), white matter loss, and microhemorrhages due to coup/contrecoup injuries and increase of traction and shearing forces on nerve fibers. The extent of DAI after traumatic brain injury is an important predictor of prognosis of post-traumatic cognitive impairment (Gandy et al. 2014; Saulle and Greenwald 2012; Levin and Bhardwaj 2014; Bramlett and Dietrich 2014; Sharp et al. 2014). Microtrauma to the brain has been postulated to lead to neurotoxicity from increased extracellular glutamate levels, causing subsequent demyelination. At the same time generation of reactive oxygen and nitrogen species can cause oxidative stress to neuronal membranes and irreversible damage of membranes (Gandy et al. 2014; Saulle and Greenwald 2012; Bramlett and Dietrich 2014; Byrnes et al. 2014; Henry et al. 2011a, b). Other factors that could further damage the brain include post-traumatic inflammation and apoptosis, though they could also be part of (benign) physiological repair mechanisms. Microglia cells, in particular, have the ability to switch between neuroreparative and neurodestructive states, even though this may be just another interpretation of the same process. Increased levels of inflammatory peptides and of proteins of neuroglial origin are frequently observed and might be used as biomarkers to assess severity of neurotrauma. However, at the current stage, scientific evidence is insufficient to support usage of biomarkers in clinical practice (Gandy et al. 2014; Saulle and Greenwald 2012; Bramlett and Dietrich 2014; Byrnes et al. 2014; Papa et al. 2013; Yokobori et al. 2013).

Histologically, areas of focal DAI and inflammation correspond to which has been described as progressive tauopathy. Currently, attempts are made to diagnose chronic traumatic encephalopathy, and its predecessors DAI and microhemorrhages in particular, by means of neuroimaging to possibly prevent further damage to the brain (Gandy et al. 2014; Saulle and Greenwald 2012; Gavett et al. 2011; Karantzoulis and Randolph 2013; Levin and Bhardwaj 2014; Mez et al. 2013; Bramlett and Dietrich 2014; Costanza et al. 2011; McKee et al. 2009, 2013; Omalu et al. 2011; Sharp et al. 2014; Papa et al. 2013; Yokobori et al. 2013).

John Grimsley – The man who brought us CTE (Boston University CTE Center John Grimsley; NFL Enterprises LLC John Grimsley; Schwarz 2008)

John Grimsley, a professional National Football League (NFL) player died at the age of 45 after he shot himself accidentally. During his career, from 1984 to 1993, he played a total of 133 games for the Houston Oilers and later for the Miami Dolphins. He donated his brain to the Center for the Study of Traumatic Encephalopathy (CSTE) at Boston University, where it *was examined postmortem. Evidence of excessive CTE was found, and in particular there were large areas with tau protein depositions. His brain was the first being examined at CSTE in Boston. Ann C. McKee, MD, codirector of the CSTE and one of the key figures of the Boston CTE research group, publicly commented that the changes seen in Grimsley's brain were consistent with dementia pugilistica. The last 4–5 years before his tragic death Grimsley had exhibited irritability and impairment of his short-term memory, according to his wife. He also admitted to her that he had sustained eight to nine concussions during his professional career.*

8.5 What Is the Role of CT for Visualizing Chronic Traumatic Encephalopathy?

Computed tomography (CT) is known to underestimate the amount of traumatic brain damage, because of its low sensitivity in detecting subtle parenchymal changes. Since many years, we know that CT tends to severely underestimate the cerebral damage which occurs in diffuse axonal injury (DAI), white matter changes, and microhemorrhages (Parizel et al. 1998; Byrnes et al. 2014; Gonzalez and Walker 2011; Iverson et al. 2000; Lee et al. 2008; Mittl et al. 1994; Suskauer and Huisman 2009; Toledo et al. 2012). This was confirmed in the TRACK-TBI Pilot Study, where 27 % of all patients with mild TBI and an initially normal CT scan on admission later showed an abnormal magnetic resonance imaging (MRI) scan at an average of 12 days post-injury (Yuh et al. 2013).

Despite these important limitations, its wide availability and short acquisition time still make that CT remains the most frequently used imaging technique in the assessment of craniocerebral injuries. CT provides very accurate information on skeletal abnormalities (such as fractures), macroscopic hemorrhages, and other space-occupying lesions. The main role of CT in the emergency department is therefore to rule out major injuries, which require immediate attention (Byrnes et al. 2014; Gonzalez and Walker 2011; Lee et al. 2008; Suskauer and Huisman 2009; Toledo et al. 2012; Coles 2007; Dimou and Lagopoulos 2014; Johnston et al. 2001; Le and Gean 2009). In short, CT is extremely valuable for detecting skull fractures, macroscopic hemorrhage, and soft tissue injuries, but the method severely underestimates the true extent of parenchymal damage.

8.6 Magnetic Resonance Imaging Is Superior in Detecting Microhemorrhages

For imaging patients with TBI, T1-weighted, T2-weighted, gradient echo T2*-weighted, and/or susceptibility-weighted imaging (SWI) and fluid-attenuated inversion recovery (FLAIR) sequences are frequently employed (Aquino et al. 2015).

Susceptibility-weighted imaging (SWI) has been found to be a very sensitive MRI sequence to find microhemorrhages. It is well known that, intracranial hemorrhages present a variable signal intensity on T1- and T2-weighted images, depending on the time after injury (Parizel et al. 2001). In the chronic stage, hemosiderin deposits remain as the end product of the hemoglobin degradation process. Hemosiderin appears hypointense on gradient echo T2* and SWI (Kang et al. 2001; Liu et al. 2014; Moritani et al. 2009; Zhu et al. 2008). SWI is superior to T2-weighted, gradient echo T2*-weighted, and FLAIR imaging in detecting microhemorrhages, with gradient echo T2* being superior to T2-weighted and FLAIR sequences (Zhu et al. 2008; Geurts et al. 2012; Spitz et al. 2013). Especially in individuals with a history of high-speed acceleration/deceleration trauma and suspected DAI, SWI has a very high yield in detecting punctate microhemorrhages, which is the hallmark of DAI. The diagnostic yield for microhemorrhages is estimated to be 3–6 times higher than T2- or T2*-weighted imaging (Babikian et al. 2005; Mittal et al. 2009; Tong et al. 2004, 2008). However, it has yet to be determined if this increase in sensitivity alters clinical outcome (Yates et al. 2013).

Detection of microhemorrhages is important in sports-related TBI. Hasiloglu et al. demonstrated an increased lesion count in boxers on SWI in comparison to T2- and T2*-weighted imaging, confirming its superiority in sports-related mild TBI (Hasiloglu et al. 2011). In one study among university-level ice-hockey players over a season, SWI demonstrated an increase of the number of hypointensities, suggesting multiple microhemorrhages due to (sub)concussions (Helmer et al. 2014).

8.7 Proton (^{1}H) Magnetic Resonance Spectroscopy in Head Trauma

Proton magnetic resonance spectroscopy (^{1}H-MRS) is the most widely used form of MRS, though other nuclei, such as ^{13}C and ^{31}, have been studied and used as well. ^{1}H-MRS is more easily performed than spectroscopy with other nuclei due to the prevalence of protons in biological tissues and in the human body. Currently, ^{1}H-MRS can measure more than 20 different metabolites. Aspartate, choline, creatine, glutamate and glutamine, lactate, myoinositol, and N-acetyl-aspartate (NAA) are currently the most important metabolites used in the study of traumatic brain injury (TBI). In the absence of pathology, the concentration of these metabolites has been found to be very stable across individuals (Suskauer and Huisman 2009; Burtscher and Holtås 2001; Danielsen and Ross 1999; Lin and Rothman 2014; Mountford et al. 2010). ^{1}H-MRS is a robust technique, and it appears likely that, in the future, it will be possible to broaden the neurobiochemical profile by using shorter echo times (Duarte et al. 2012). No significant differences in the results of biomarker levels have been found between 1.5 T and 3.0 T scanners (Kantarci et al. 2003).

N-acetyl-aspartate (NAA) is considered to be a marker of neural integrity and viability. Since it is found almost exclusively in neurons, it is a very sensitive marker for neuronal injury or loss (Suskauer and Huisman 2009; Burtscher and Holtås 2001; Lin and Rothman 2014; Gardner et al. 2014; Mountford et al. 2010). Choline

(Cho), an umbrella term for different molecular components of fluid-mosaic cell membranes, can be used as marker for synthesis and degradation of membranes. Choline levels are positively related to cell membrane turnover and increase when neuroglial injury is present (Suskauer and Huisman 2009; Burtscher and Holtås 2001; Danielsen and Ross 1999; Lin and Rothman 2014). Phosphocreatine (Pcr) is a crucial component of ATP synthesis and is used together with creatine (Cr) as marker for brain metabolism and energy levels. Creatine is produced in the kidney and liver; it is transported through the bloodstream and is taken up by tissues with high metabolic rates, such as the brain and skeletal muscle. Metabolite/creatine ratios have been widely used to describe pathological conditions because of their relatively stable reproducibility (Suskauer and Huisman 2009; Danielsen and Ross 1999). Lactate (Lact) levels are increased in any condition that stimulates anaerobic metabolism and can therefore be used to determine if inflammation or tissue injury is present. Lactate is not found in the spectrum of healthy individuals (Byrnes et al. 2014; Suskauer and Huisman 2009; Burtscher and Holtås 2001; Danielsen and Ross 1999; 77). Myoinositol (mI) has been shown to be a marker for astrocytes; this metabolite tends to be increased in low-grade astrocytomas (Burtscher and Holtås 2001; Danielsen and Ross 1999; 77). Glutamate and glutamine are essential metabolites of the citric acid cycle and therefore their concentration can change in metabolic disorders (Burtscher and Holtås 2001; Danielsen and Ross 1999). It is important to know that, with the exception of creatine, the concentrations of these metabolites vary across different brain areas (Burtscher and Holtås 2001; Danielsen and Ross 1999; Baker et al. 2008).

Some distinct changes can be observed in the healthy aging brain. With aging, as the number and diameter of large neurons decreases, levels of NAA fall concordantly. At the same time mitochondrial metabolism increases by up to 30 %, causing a rise of mI (Lin and Rothman 2014; Esopenko and Levine 2015). Levels of NAA and NAA/Cr ratio also decrease in patients with Alzheimer's disease (AD) and other dementias, faster than in elderly individuals without any cognitive impairment. Changes in biomarker levels can be related to clinical changes. This is an important finding, since chronic traumatic encephalopathy (CTE) shares some features with AD, as discussed above (Burtscher and Holtås 2001; Haga et al. 2009; Kantarci et al. 2007; Lin et al. 2003; Zhang et al. 2014). However, antipodal changes of Cho/Cr ratios in individuals who suffer from AD have been reported also (Burtscher and Holtås 2001; Haga et al. 2009; Kantarci et al. 2007; Zhang et al. 2014). Also, the NAA/mI ratio has been shown to decrease in patients with mild cognitive impairment (Burtscher and Holtås 2001; Haga et al. 2009; Kantarci et al. 2007; Lin et al. 2003; Zhang et al. 2014).

Several studies have shown that, in patients with mild traumatic brain injury (mTBI) or concussion, NAA concentrations are lower (in the acute phase) than in healthy controls (Chamard et al. 2012; Cimatti 2006; Davie et al. 1995; Henry et al. 2010, 2011a, b; Johnson et al. 2012a, b; Kirov et al. 2013; Vagnozzi et al. 2008, 2010, 2013). However, in one study among children aged 11 to 15 with sports-related concussion, the authors could not find any metabolic changes on ^{1}H-MRS (Maugans et al. 2012). Also, other investigators have reported equivocal findings

(Cimatti 2006). Additional changes observed in patients post-mTBI or postconcussion included decrease of glutamate levels, decrease of AA/CR ratio, decrease of NAA/Cho ratio, increase in the Cho/Cr ratio, and increase of mI/Cr ratio in the chronic phase (Henry et al. 2010, 2011a, b; Vagnozzi et al. 2010, 2013). Two studies (from the same group of authors) found that increased NAA/Cho and NAA/Cr ratios correlated with the number of mTBIs (Johnson et al. 2012a, b). In one study with concussed athletes, correlation between metabolic changes and self-reported symptom severity was documented, though neuropsychiatric assessment could not replicate these findings (Henry et al. 2010). These different and conflicting study results may be explained by the use of various echo times, low spectral resolution, the generally small number of subjects in many studies, and the variability of time that had elapsed between injury and scan (Duarte et al. 2012).

Metabolic abnormalities seem to outlast clinical symptoms. A longitudinal follow-up study on female ice-hockey players found remaining post-seasonal decrease of NAA/Cr ratio postconcussion; however, male players who had sustained a concussion during the season did not show any lasting changes of the metabolic spectrum (Chamard et al. 2012). One study performed diffusion tensor imaging (DTI) and ^{1}H-MRS in healthy individuals, demonstrating a positive correlation between fractional anisotropy (FA) and concentrations of NAA (Cheng et al. 2014).

In summary, a decrease of NAA and the NAA/Cr ratio has been observed postconcussion in sports-induced injuries. These changes appear to be similar to those seen in individuals with AD.

8.8 Diffusion Tensor Imaging (DTI) Opens a Window on the Microstructural Environment of the Brain

In the middle 1980s, visionary MRI scientists predicted that magnetic resonance imaging (MRI) could be used to provide information about molecular diffusion in tissues. The practical implementation was initially hampered by hardware limitations, but by the late 1990s a workable diffusion-weighted imaging (DWI) sequence became available for routine brain imaging. In DWI images, the intensity of each voxel reflects the magnitude (or rate) of water diffusion in that specific location. Diffusion-weighted sequences measure the magnitude of free water diffusion in tissues, but do not yield directional information.

However, these images not only represent "true" diffusion, but also include other confounders such as perfusion effects or T2 shine-through phenomena. To eliminate such influences, the concept of the apparent diffusion coefficient (ADC) was introduced. This parameter can be expressed in parametric ADC maps, representing the observed ("apparent") diffusion in a particular voxel. The degree to which a sequence is sensitive to diffusion is expressed by the "*b*-value," expressed in s/mm^2. The higher the "*b*-value," the more the signal intensity reflects "true" tissue water diffusion changes. In DWI, the diffusion gradients are applied in three orthogonal directions; this allows an estimation of the "trace," which is an indicator of the average diffusivity. Trace-weighted diffusion images initially found their main area of application in neurological disorders, especially for the early detection of the cytotoxic edema associated with acute ischemic stroke. Since about 15 years ago, DWI has become a crucial part of routine clinical MRI examinations of the brain and, increasingly, also other organs.

However, diffusion in white matter of the brain is known to be anisotropic and depends on the orientation of axonal fibers. This observation led to the development of a sequence that could measure, at a microstructural level, not only the magnitude of diffusion, but also the direction or path of diffusion. In this way diffusion tensor imaging (DTI) was born. In order to obtain the directional information, which is essential for DTI, diffusion gradients need to be applied in at least six directions and preferably more. This technique provides an insight into the internal microstructural organization of the brain. From the acquired DTI data, metrics such as fractional anisotropy (FA) and mean diffusivity (MD) can be derived; parametric images can be reconstructed which reflect the fraction of the diffusion tensor that is attributable to anisotropic diffusion. FA values are between zero and one, with higher values standing for a more uniform directionality of diffusion.

FA and ADC can be assessed using different analyzing methods. In a whole-brain distributional analysis, DTI parameters are created for every voxel of the brain. This approach calculates averaged values of changes in FA and ADC across the brain which might blur the overall picture, since spatial information might be lost. A second possibility is the employment of whole-brain voxel-based analysis. Hereby data sets are aligned to anatomical structures to increase spatial resolution. In region-of-interest (ROI)-based analysis, groups of voxels in specific regions are averaged and checked against each other. This allows an even better spatial resolution; however, it is a rather work-intensive process which might be confounded by preferences of the examiner. In vivo tractography allows to obtain data sets for specific white matter tracts, thereby raising specificity, validity, and spatial resolution of results (Dimou and Lagopoulos 2014; Moritani et al. 2009; Gardner et al. 2012).

In patients with TBI, it has been hypothesized that a decrease of FA represents anterograde degeneration, axonal injury, and demyelinization, whereas an increase is anticipated in the presence of cytotoxic edema. ADC values usually change in negative concordance with FA.

TBI has been associated with DAI and traumatic axonal injury, respectively, which can be visualized using DTI (Henry et al. 2011a, b; Moritani et al. 2009; Meythaler et al. 2001; Xu et al. 2007). These cellular injuries occur when shearing forces are applied to neurons as it occurs during concussion (Moritani et al. 2009; Meythaler et al. 2001; Slobounov et al. 2012). Trauma to axons causes disruption of axonal transport and therefore accumulation of metabolites leading to axonal edema. However, primary axostomy is rarely seen, though the subsequent swelling of axons can cause secondary axostomy which is much more common than primary anatomical disruption. It is therefore assumed that most of the damage occurs intra-axonal to the cytoskeleton while the outer membrane may still be intact. Later ionic imbalance, uncontrolled glutamate release, and oxidative stress are detrimental and may aggravate cytotoxic edema. Post-injury amyloid precursors accumulate which may be released in case of axonal lysis or apoptosis, having a theoretical potential to contribute to neurodegenerative diseases (Moritani et al. 2009; Meythaler et al. 2001; Johnson et al. 2013).

In the early stages after TBI, the most prominent findings are decreased FA and increased ADC values, representing damage to axons and mixed intra- and extracellular edema (Moritani et al. 2009; Xu et al. 2007). However, more recently those findings have been challenged suggesting there could be an increase of FA in the acute phase (Eierud et al. 2014). A decrease of ADC without any change of FA may be caused by edema without any physical disruption of axons. In the subacute phase a decrease of FA and increase of ADC represent progressive repair of nerve fibers (Slobounov et al. 2012; Inglese et al. 2005; Kumar et al. 2009a, b; Niogi and Mukherjee 2010; Sidaros et al. 2008). In mouse models, demyelination (which can be a feature of TBI as described above) presents as increased radial diffusion (RD) (Song et al. 2002). In humans decrease in FA and increase in mean diffusivity (MD) represent post-traumatic demyelination and gliosis (Kumar et al. 2009a, b). However, the differences in reported FA, ADC, and MD values could also be explained by the variability in research protocols across different studies and the disregard of the factor time in the healing process and its implication on repair-induced changes of diffusity. Other technical factors in the acquisition (number of DTI images, spatial resolution) may influence the validity of results and could explain the great variety of findings (Eierud et al. 2014; Dodd et al. 2014; Farbota et al. 2012; Shenton et al. 2012; Xiong et al. 2014).

Since the late 1990s a huge increase in interest on TBI has occurred and several meta-analysis and reviews have attempted to find a common spatial pattern of diffusivity alteration post-(m)TBI across all published studies. (Pre)frontal areas seem to be more vulnerable to TBI; however, the mechanism of injury might be a huge determinant of location of injury. Injury to the corpus callosum and in particular its anterior parts, rostrum and genu, have been reported frequently. Minor and less frequently reported injuries post-TBI have been demonstrated almost all over the brain. Though those data might appear to be random, they all support the presence of subtle post-TBI alterations (Eierud et al. 2014; Dodd et al. 2014; Shenton et al. 2012; Xiong et al. 2014).

Gardner et al. conducted a review of literature focusing specifically on postconcussional DTI findings in athletes (mostly boxers) (Gardner et al. 2012). In sports-related concussion (SRC) a tendency of increased ADC was observed with anatomical foci in the corpus callosum, internal capsule, and inferior and superior fasciculus. Nevertheless, not all studies included in this review supported these observations, and therefore, overly enthusiastic interpretation should be avoided (Gardner et al. 2012). However, increases in FA in the corpus callosum post-SRC have been reported also (Henry et al. 2011a, b). In soccer players increased axial diffusity (AD) in the corpus callosum and diffuse increase of radial diffusity (RD) in various brain regions have been shown (Koerte et al. 2012). Moreover, DTI has been proven to be more sensitive than MRI in diagnosing sports-related mTBI. Especially, in clinically asymptomatic patients post-mTBI with normal MRI or aspecific MRI findings, changes suggestive for mTBI can be demonstrated on

DTI (Mendez et al. 2005; Henry et al. 2011a, b; Chappell et al. 2006; Green et al. 2010; Zhang et al. 2003, 2006, 2010a, b).

Looking at the prognosis of TBI, higher FA values have been associated with better functional outcome, whereas low MD predicted rather poor outcome (Bazarian et al. 2007; Betz et al. 2012; Ewing-Cobbs et al. 2008; Irimia et al. 2012; Kumar et al. 2009a, b; Ljungqvist et al. 2011; Messé et al. 2011; Sidaros et al. 2008; Strangman et al. 2012; Wilde et al. 2006; Yuh et al. 2014). However, no evidence has been found linking FA, ADC, or MD to the common phenomenon of post-TBI depression (Maller et al. 2010). In the future, diffusion kurtosis imaging (DKI) might supplement DTI, allowing even more precise outcome prediction. Mean kurtosis (MK) in particular has been related to chronic cerebral damage and permanent cognitive sequelae (Grossman et al. 2012).

8.9 Functional Magnetic Resonance Imaging (fMRI)

Blood oxygen level-dependent functional magnetic resonance imaging (BOLD fMRI) is used to visualize local distribution of oxyhemoglobin and deoxyhemoglobin levels in the brain, with oxyhemoglobin leading to higher signal intensity. Increase in neuronal activity requires more oxygen, and through the mechanism of neurovascular coupling, a higher BOLD signal represents areas of increased metabolism and therefore areas of increased neuronal activity (Slobounov et al. 2012). In postconcussion test subjects, who were asked to perform cognitive tasks, some authors have observed an increased BOLD signal, primarily in the frontal cortex, with the most reproducible results being seen in the dorsolateral prefrontal cortex, which plays an important role in activation and modulation of working memory (McAllister et al. 1999). Similar changes have been observed in retired professional football players of the National Football League (Hampshire et al. 2013). Longitudinal studies of high school football players have revealed increased activation of the dorsolateral prefrontal cortex in those without clinical symptoms in contrast to those players with clinically confirmed impairment, who showed an increased activation of the temporal lobe (Breedlove et al. 2012; Talavage et al. 2014). Generally, across several studies, the frontal areas of the brain appear to be more vulnerable to concussion than others (Slobounov et al. 2012; Eierud et al. 2014). These changes might be due to concussional damage, requiring increased activation to perform normal tasks, a theory termed neural insufficiency (Chang et al. 2004; Chiaravalloti et al. 2005; Hillary et al. 2003; Perlstein et al. 2004). Different explanations for the increased recruitment have been proposed, from brain reorganization, over neural compensation, to the latent support hypothesis (Slobounov et al. 2012; Eierud et al. 2014). However, contradicting results of decreased activation have been reported also, first by a research group around Chen et al. (Chen et al. 2007, 2008; Mayer et al. 2009).

Additionally, resting state fMRI has been used to map activity in the resting brain when no cognitive tasks were performed (Slobounov et al. 2012). Decreases in interhemispheric cross-talk and hippocampal and frontal activation (including the dorsolateral prefrontal cortex) have been reported (Marquez de la Plata et al. 2011; Nakamura et al. 2009; Slobounov et al. 2011). Other studies have attempted to demonstrate changes of the default mode network, an intracerebral, both functional and structural, network of highly activated neural connections, which probably represents brain activity at rest. So far several studies have shown postconcussional changes, though no distinct pattern has emerged yet (Slobounov et al. 2012; Abbas et al. 2015; Borich et al. 2014; Kapoor et al. 2004).

8.10 Can Imaging Techniques Serve as "Surrogate Endpoints" for Outcome Prediction?

Significant research efforts have focused on the identification of reliable imaging biomarkers (e.g., lesion count, cerebral atrophy, decrease of cortical thickness, decrease in whole-brain FA), which could serve as outcome predictors in patients with TBI. In children post-TBI, a decrease in hippocampal, corpus callosum, thalamic, periventricular white matter, cerebellar, and midbrain volumes and an increase of cerebrospinal fluid (CSF) has been found, in comparison to age-adjusted control individuals (Fearing et al. 2008; Keightley et al. 2014; Serra-Grabulosa et al. 2005; Spanos et al. 2007; Tasker et al. 2005, 2010; Wilde et al. 2005, 2007). Decreased volume of corpus callosum was related with poorer functional outcomes, in particular performance during memory assessment (Serra-Grabulosa et al. 2005; Levin et al. 2000; Verger et al. 2001). Decrease of hippocampal volume in adults has been related to severity of TBI (Green et al. 2014; Ng et al. 2008). Merkley et al. have reported an association of post-moderate-to-severe-TBI cortical thickness with alteration of working memory in a pediatric population. No correlation with the Glasgow Outcome Scale (GOS) could be found (Merkley et al. 2008). Decrease of brain volume has been demonstrated in patients with TBI, being related to prolonged post-injury coma and premature mental decline (Fox et al. 1999; Trivedi et al. 2007). In former university-level rugby players, increased ventricular volume related to cognitive decline has been observed (Tremblay et al. 2013). It is of note that similar patterns of brain atrophy can be found in patients with Alzheimer's disease (AD). In particular, atrophy of fusiform gyrus and middle and inferior gyri of the temporal lobe is associated with cognitive decline leading to AD (Convit et al. 2000). Other investigators found decreased hippocampal and entorhinal cortex volumes and increased ventricular volumes to be predictive for AD (Csernansky et al. 2005; de Leon et al. 1993; Devanand et al. 2007; Fleisher et al. 2008; Jack et al. 1999; Stoub et al. 2005). There are similar patterns of brain atrophy between patients after TBI and patients with AD; this could explain clinical observations of premature onset of AD, among other neuropsychiatric disorders, post-TBI (Bigler 2013; Kiraly and Kiraly 2007).

Much attention has been focused on the use of DTI with FA mapping as a biomarker in TBI. It has been reported that white matter assessment with quantitative DTI increases the accuracy of long-term outcome prediction compared with the available clinical-radiographic score (Galanaud et al. 2012). FA values have been related to GOS scores and neuropsychiatric outcome, with lower FA values being related to worse outcomes (Bazarian et al. 2007; Betz et al. 2012; Ewing-Cobbs et al. 2008; Irimia et al. 2012; Kumar et al. 2009a, b; Ljungqvist et al. 2011; Messé et al. 2011; Sidaros et al. 2008; Strangman et al. 2012; Wilde et al. 2006; Yuh et al. 2014). In adult long-term post-TBI survivors, no changes in FA were reported though there was a significant increase of mean diffusity (MD) (Porto et al. 2011). This suggests that FA should be measured as soon as possible after the injury to maintain its predictive value. However, these results should be treated with caution since different studies used different outcome measurements and performed DTI at different times post-injury (Hulkower et al. 2013).

The number of lesions on SWI and FLAIR can be used to predict functional outcome on Glasgow Outcome Scale Extended in TBI patients (Marquez de la Plata et al. 2007; Moen et al. 2012; Pierallini et al. 2000). It is important to note disappearance of brainstem lesions from 3 months post-injury onwards, which demands early MRI scans (Moen et al. 2012). Similar observations have been made using computed tomography (CT) (Jacobs et al. 2011). These results have been confirmed in National Football League players, in whom total and deep white matter lesion volumes were related to cognitive impairment (Hart et al. 2013). SWI has been shown to be more sensitive than FLAIR and lesion volume found on SWI was related to severity of TBI, opposed to FLAIR where no correlation was found between lesion volume and injury severity (Spitz et al. 2013). This observation, however, stands in contrast to a (older) study by Chastain et al. which favored FLAIR and T2 sequences over SWI. Back then it was hypothesized that SWI is too sensitive and detects too many too small lesions, which have no significant impact on outcome (Chastain et al. 2009). Up to now, this issue remains unsolved.

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Nuclear Medicine Imaging of Head and Face Injuries

9

K.P. Koopmans

Contents

Abstract

Head injuries, which form approximately 10 % of all sports-related trauma in high school sports activities, can have devastating effects on the individual and society.

Nuclear medicine has thus far not been playing an important role in trauma to the bony structures of the head, but this might change due to the higher resolution and sensitivity of ^{18}F-NaF PET for ossal pathology. Especially in the follow-up, ^{18}F-NaF may become more important, but research is warranted.

Concussion is mainly a clinical diagnosis, and imaging techniques do not play an important role. However, new techniques in both cerebral blood flow measurements with SPECT and cerebral metabolism with PET are emerging. These techniques not only give a better insight in the underlying pathological mechanisms of concussion but can also aid in the diagnosis and follow-up of patients suspected of concussion. Actually, the position of nuclear medicine techniques in the diagnosis of concussion has not been determined, so more research is warranted.

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9.1 Introduction

Participating in sports has many advantages, since it can increase one's strength, endurance, and flexibility. Furthermore, it has a beneficial effect on weight management and on self-esteem (Darrow et al. 2009). In the USA, approximately 50 % of all children participate in organized sports programs (Adirim and Cheng 2003). However, the downside of the participation in sports is the potential risks caused by sports trauma. Generally, patients with sports-related injuries tend to be younger than the average population (Bensch et al. 2011). Children seem to be more vulnerable to sports-related injuries due to both physical and psychological factors (Adirim and Cheng 2003). It has been calculated that in young athletes, approximately 10 % of all high school sports-related trauma was inflicted to the head (Rechel et al. 2011). Conversely, in 3–25 % of all patients, head and neck trauma was caused by accidents occurring during sports activities (Kraus 1991). The majority of these injuries consist of fractures of maxillofacial structures and brain concussions. Moreover, the incidence of head and neck injuries is related to the violence and aggression related to the type of sport practiced (Proctor and Cantu 2000).

The potential consequences, both economical and personal, of potentially disabling injuries to the head have a very high impact on the individual and the society (Bensch et al. 2011). Since concussions and repeated concussions may have long-term neuropsychological effects, correct understanding, diagnosing, and imaging are essential (Broglio et al. 2011; Marshall 2012; Su and Ramirez 2012).

9.2 Bone Injuries to the Skull in Sports Medicine

In contrary to the other skeletal structures, athletes almost never sustain stress fractures of the skull due to sports-related activities. The most common sports-related traumata to the skull are caused by blunt trauma in an acute setting. In patients with suspected fractures of the skull and maxillofacial structures, it is essential to perform radiological imaging to assess the extent of the damage and evaluate treatment options (Darrow et al. 2009; Kaur and Chopra 2010; Zemper 2010). In most cases, nuclear medicine has no role for the diagnosis of fractures of the skull and maxillofacial structures. However, when radiological imaging shows no abnormalities, but fractures are still suspected based on trauma mechanism and patient complaints, bone scintigraphy and ^{18}F sodium fluoride (^{18}F-NaF) PET scanning may be used to rule out fractures since these techniques are able to detect minimal changes in osteoblastic activity, before radiographic changes become evident (Even-Sapir et al. 2007; Zukotynski et al. 2010).

In the follow-up period after the diagnosis of maxillofacial and skull trauma, nuclear medicine may have added value, especially to assess the fracture healing. Only few studies have thus far been published on fracture healing in the skull. Bone scintigraphy with SPECT has been proven useful for the follow-up of complex midfacial fractures, in particular for the diagnosis of complications after initial repositioning of the midfacial ossal structures (Top et al. 2004). PET/CT scanning with

^{18}F-NaF PET could theoretically be more useful in the follow-up period, since it has a higher resolution compared to SPECT. ^{18}F-NaF uptake corresponds to osteoblastic activity and also for accompanying reactive osteoblastic changes, even when minimal (Even-Sapir et al. 2007). For example, in studies concerning child abuse, ^{18}F-NaF PET was shown to have a potential advantage over ^{99m}Tc-labeled methylene diphosphonate (MDP) based upon superior image contrast and spatial resolution (Drubach et al. 2008, 2010; Grant et al. 2008).

The process of fracture healing can be evaluated using plain radiography, CT, ultrasonography, fluoroscopy, bone scan, and MRI (Bishop et al. 2012). Although the role these different imaging techniques have in the diagnostic process of evaluating fracture healing is not yet clear, ^{18}F-NaF PET could become an important tool for this purpose based on animal experiments. In a study in rats, ^{18}F-NaF PET was able to identify fracture nonunions already at early time points and may therefore have a major role in the assessment of fracture healing (Hsu et al. 2007).

9.2.1 Contusions of the Maxillofacial Ossal Structures

Bone bruises arise together with soft tissue injuries after physical trauma and are usually presented as bleedings, edemas, or infarctions. Bone bruises are characterized by micro-trabecular fractures which leave the bone itself macroscopically intact (Rangger et al. 1998). MRI has, already early after recognition of this disease entity, an important role in diagnosis of bone bruises since it provides the clinician with a clear insight into the extent and severity of the bone lesion (Ucar et al. 2012). Historically, nuclear medicine has not played an important role in the detection of bone bruises. Bone scintigraphy is able to detect bone lesions but with a lower sensitivity and specificity than MRI (Soudry and Mannting 1995; Even-Sapir et al. 2002). In bone scintigraphy, bone bruises are characterized by focal increased osseous uptake. The intensity of uptake might relate to the extent of microfractures, i.e., more microfractures lead to an increased uptake. In combination with SPECT/CT or with ^{18}F-NaF PET, bone scintigraphy may possibly be used as a total body screening method for bone bruises.

9.3 Concussion

Concussion is defined as “a traumatically induced transient disturbance of brain function” and involves a complex pathophysiological process. Concussion is a subset of mild traumatic brain injury (MTBI) which is generally self-limited and at the less severe end of the brain injury spectrum (Harmon et al. 2013; McCrory et al. 2013). In the United States, each year, an estimated 1.6–3.8 million sports-related concussions occur (Langlois et al. 2006). These brain injuries may lead to immediate (headaches, dizziness) problems and to long-term changes (i.e., behavioral changes, problems with attention) (Iverson et al. 2004). Imaging is essential in gaining insight in the extent of the occurring changes in concussion.

Concussion results from rotational or angular brain accelerations. These accelerations result in shear strains on the soft tissues of the brain, which results in disruption of membrane potentials, followed by an efflux of potassium into the extracellular space. Glutamate and other excitatory amino acids are then released, leading to a further depolarization of neuronal cells. This in turn leads to a widespread potential depression in the brain. To restore homeostasis, energy is needed in the form of ATP. ATP is formed by an increased glycolysis, which in turn leads to intracellular lactate accumulation (Bigler and Maxwell 2012; Lin et al. 2012). These metabolic changes occur before morphologic changes can be seen on CT or MRI. Therefore, early after sustaining a concussion, CT and MRI often show a normal brain structure. To evaluate the underlying metabolic changes, MRI spectroscopy and nuclear medicine techniques can be used. MRI and functional MRI can be used to show activation patterns which can be related to extend and severity of concussion, but these techniques have been described in Chap. 8 (Harmon et al. 2013; Virji-Babul et al. 2013). Nuclear medicine techniques (SPECT and PET) for evaluating concussion have mainly been used in a clinical setting. Generally, in concussion, nuclear medicine imaging is to this time point restricted to athletes who sustained serious injuries and in whom possible structural anomalies are expected.

9.3.1 SPECT

The metabolic changes occurring after brain injury have lead to the assumption that cerebral blood flow changes must take place. To evaluate this, several tracers for SPECT imaging are readily available. The most commonly used tracer is ^{99m}Tc-hexamethylpropyleneamine oxime (^{99m}Tc-HMPAO) (Lin et al. 2012). ^{99m}Tc-HMPAO crosses the blood-brain-barrier easily and is distributed in the brain proportional to the regional blood flow. The rapid brain uptake and prolonged retention of ^{99m}Tc-HMPAO in brain structures makes this tracer very suitable for evaluation of regional blood flow changes in the brain (Leonard et al. 1986). Detectable concentrations can be measured for up to 24 h after injection. Image analysis requires selecting different regions of interest (ROI) within the brain, and comparing these with a reference region, preferably the cerebellum, to determine the existence of regions with abnormal blood flow (Abdel-Dayem et al. 1998; Lin et al. 2012).

Other tracers which have been used for the evaluation of contusion are, for example, ^{99m}Tc -ethyl cysteinate dimer (^{99m}Tc-ECD) (Catafau 2001), ^{123}I-iomazenil (^{123}I-IMZ), ^{123}I-N-isopropyl-p-iodoaphetamine (^{123}I-IMP) (Leonard et al. 1986; Hashimoto and Abo 2009), and ^{57}cobalt-chloride (^{57}CoCl^2) (Audenaert et al. 2003). However, ^{99m}Tc-HMPAO SPECT has been used most extensively.

Studies have been performed within 24 h after injury (acute phase), within 72 h (subacute phase) and in patients with chronic concussions (Lin et al. 2012). However, studies relating to sports-induced concussions are rare.

Only one case report described regional blood flow changes in the acute phase of concussion. In this case study, ^{99m}Tc-HMPAO was used to assess regional blood flow changes in a patient with a concussion after a motor vehicle accident. Within

24 h ^{99m}Tc-HMPAO SPECT scan was performed, showing hypoperfusion of the frontal and bilateral parietal lobes (Abu-Judeh et al. 1998).

SPECT studies for changes in regional blood flow in the subacute (<72 h) phase of concussion has been performed in larger patient groups. In a study using ^{99m}Tc-ECD SPECT in a patient group of 92 patients (28 adults and 64 children), the most commonly found perfusion abnormality was hypoperfusion in the frontal lobe(s) in adults and the temporal lobes in children. Furthermore, in patients with posttraumatic amnesia, postconcussion syndrome, and loss of consciousness, a significantly higher number of perfusion abnormalities were seen than in patients without these symptoms. Compared to CT, SPECT had a higher sensitivity for detecting an organic basis in patients with posttraumatic amnesia, postconcussion syndrome, and loss of consciousness (Gowda et al. 2006). Another study compared ^{99m}Tc-HMPAO SPECT with $^{57}CoCl^2$ SPECT in 8 patients. $^{57}CoCl^2$ was used as a marker for calcium accumulation. This study found a similar pattern of hypoperfusion in the frontal lobes for ^{99m}Tc-HMPAO SPECT with additional accumulation of $^{57}CoCl^2$ in these areas, but also additional accumulation of $^{57}CoCl^2$ was found in the parietal lobes. This may indicate that additional brain regions show dysfunctioning, which are not detected by blood flow changes only (Audenaert et al. 2003).

Two studies have been performed by Amen et al. (2011a, b) in which the effects of repetitive sports-induced head injury were evaluated with SPECT. In the first study, a group of 100 retired NFL players was evaluated in the chronic stage of their head injury. A significant decrease in regional cerebral blood flow was found in the whole brain, especially in the prefrontal lobes, temporal lobes, occipital lobes, anterior cingulate gyrus, and cerebellum. Furthermore, they found significant decreases in the posterior cingulate gyrus and hippocampus, areas which are also involved in dementia. The second group consisted of 30 retired NFL players with brain damage and cognitive impairment. Rehabilitation methods included weight loss (if appropriate), fish oil, a high-potency multiple vitamin, and a brain enhancement supplement that included nutrients to enhance blood flow, acetylcholine, and antioxidant activity. They were evaluated before and after six months of rehabilitation methods. After therapy, an increased perfusion in the prefrontal cortex, anterior cingulate gyrus, parietal and occipital lobes, and cerebellum was found, thereby demonstrating that cognitive and cerebral blood flow improvements are possible in this group with multiple interventions. Unfortunately, this study was not randomized, all patients received all interventional methods, and SPECT results were taken all together. Therefore, no conclusions can be made whether this was a real improvement or a medication effect on blood flow.

In conclusion, SPECT imaging of regional blood flow changes in concussion may have added value. However, the described SPECT changes in regional blood flow are not specific for concussion and may be seen in other cerebral abnormalities as well. SPECT imaging can be used in clinical practice to rule out abnormalities; in a study in 136 patients, Jacobs et al. showed that patients with concussion showing a normal regional blood flow SPECT developed no clinical sequelae when compared to patients that had changes in cerebral blood flow SPECT (Jacobs et al. 1996).

9.3.2 PET

In PET imaging, ^{18}F-FDG is commonly used to evaluate the brain metabolism. Since ^{18}F-FDG is analogous to endogenous glucose, it rapidly crosses the blood-brain barrier and is thereafter being taken up in cells. Contrary to glucose, ^{18}F-FDG is not further metabolized; therefore, it is trapped in the cells (Lin et al. 2012).

^{18}F-FDG has been used in most studies evaluating PET for concussion. Other tracers to evaluate concussion are scarce, and only a few studies used ^{18}F-FDG PET in the acute setting of concussion.

In one case report, ^{18}F-FDG PET was compared to ^{99m}Tc-HMPAO for the evaluation of a patient in the acute phase with a concussion after a motor vehicle accident. Within 24 h, both ^{18}F-FDG PET and ^{99m}Tc-HMPAO SPECT were performed. However, ^{18}F-FDG PET showed no abnormal findings (Abu-Judeh et al. 1998).

Unfortunately, ^{18}F-FDG PET findings in different studies were discordant. In one study, ^{18}F-FDG PET showed hypometabolism in frontal and anterior temporofrontal regions (Ruff et al. 1994); in another study, ^{18}F-FDG PET showed hypometabolism in medial temporal, posterior temporal, and posterior frontal cortices, as well as in the left caudate nucleus. In this study, ^{18}F-FDG PET uptake was significantly increased, compared to controls, in anterior temporal and anterior frontal cortices (Humayun et al. 1989). And finally, in the largest study with 20 concussion patients, abnormal local cerebral metabolic uptake ratios were found more prominent in mid-temporal, anterior cingulate, precuneus, anterior temporal, frontal white, and corpus callosum brain regions (Gross et al. 1996). In this study, 12 out of the 20 patients showed an increased ^{18}F-FDG uptake in the midtemporal lobes, opposed to a decreased cerebral ^{18}F-FDG uptake.

In a recent study in 19 boxers who had sustained multiple head injuries, ^{18}F-FDG PET uptake was compared to 7 controls. Compared to these normal controls, boxers showed decreased ^{18}F-FDG uptake by 8–15 % in the posterior cingulate cortex, parietooccipital and frontal lobes (Broca’s area) bilaterally, and the cerebellum.

The authors claimed that these areas of hypometabolism could be characteristic for boxers, which is questionable, given the heterogeneity of results in other studies (Provenzano et al. 2010; Lin et al. 2012).

Peskin et al. studied 12 Iraqi war veterans, who had experienced several blast exposures with concussion. They compared regional brain ^{18}F-FDG uptake in these veterans with regional brain uptake of 12 normal controls. Compared to normal controls, veterans with MTBI (with or without posttraumatic stress disorders) exhibited decreased cerebral metabolic rate of glucose in the cerebellum, vermis, pons, and medial temporal lobes (Peskind et al. 2011).

In a study with five retired NFL players, Small et al. evaluated whether brain tau deposits can be detected in living retired athletes, who had a history of mood and cognitive symptoms due to repetitive brain injury. These players were injected with 2-(1-{6-[(2-[^{18}F]fluoroethyl)(methyl)amino]-2-naphthyl}ethylidene)malononitrile (^{18}F-FDDNP). A control group of five patients was used. In this study, an increased uptake was found in players compared with controls in all subcortical regions and the amygdala, areas that produce tau deposits following trauma. Therefore, they postulate that ^{18}F-FDDNP may be used to evaluate identification of neurodegeneration in contact sports athletes (Small et al. 2013).

These results suggest that there is overlap in ^{18}F-FDG PET findings in patients who have experienced a concussion. However, due to the discongruence in available data, further research, especially in sports-related (repetitive) concussion, is warranted. Other tracers, such as (R)-^{11}C-PK11195 which has been used as an indirect marker of neuronal damage after traumatic brain injury (Folkersma et al. 2011) and ^{18}F-FDDNP, may be able to give more insights in the pathologic mechanisms underlying concussion.

Conclusion

So far, nuclear medicine techniques have not played a clinical role in the evaluation of trauma to the bony structures of the skull in the athlete. However, ^{18}F-NaF PET will likely gain a more important role in the future, thanks to its higher resolution compared to SPECT and the combination with CT. Although research on this topic is warranted, ^{18}F-NaF PET will be of value in the assessment of athletes with skull pain and in the follow-up of athletes after sustaining fractures.

Nuclear medicine techniques show great promise for the evaluation of concussion. However, the sensitivity and specificity for both SPECT and PET for concussion need to be determined. Also, (international) imaging protocols, on patient preparation, image acquisition, and image interpretation, have to be developed to facilitate evaluation of different techniques. At this point, however, it can already be concluded that these metabolic imaging techniques are complementary to morphologic imaging techniques, such as CT and MRI. The development of new therapies for concussion will need good imaging techniques to assess treatment response.

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Part III

The Musculoskeletal System Topographically: The Spine

Spine Injuries

10

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Abstract

When participating in sport and exercise activities, various – often age-dependent – injuries to any part of the spine are possible. The neck is most commonly injured in sports that involve contact, which place the cervical spine at risk of injury, in some cases with catastrophic consequences. The thoracic spine is less likely to be injured because it is relatively immobile and has extra support, but M. Scheuermann can lead to symptoms. The lower back is subject to a great deal of repetitive strain in many sports, which can result in nonspecific lumbago or more specific lumbar spine conditions, like spondylolysis and spondylolisthesis, disk disease, and lumbar stenosis which need further clinical and radiological investigation. This chapter describes the most common acute and chronic sports-related injuries of the spine.

10.1 Introduction

It can be challenging to make a precise diagnosis in athletes with pain in the neck or back, not least because demonstrable pathology is not always present and psychosocial factors often play a role. Low back pain has a lifetime incidence of up to 70 % in the general population (Sarwark et al. 2010). Therefore, it is not surprising that LBP is also a common condition in athletes. In fact, the incidence of LBP in athletes has been suggested to be as high as 30 % (Dreisinger and Nelson 1996).

Cervical pain is also a common complaint in the athletic population. Some injuries are mild in nature; however, more serious injuries, especially those involving the cervical spine, can have devastating consequences (Krabak and Kanarek 2011). Pain originating from the thoracic spine is less common.

Causes of pain in these anatomical regions are rather age specific (Table 10.1). Some sports are associated with a higher than normal percentage of spine injuries.

It is important for physicians dealing with athletes suffering from back or neck pain to understand the differences between serious and mild spinal injuries. In order to make a precise diagnosis, a good knowledge of the basic anatomy of the spine and its related structures, familiarity with mechanisms of injury and common causes of back and neck pain, and a thorough understanding of the clinical presentation of the disorders in these areas is necessary.

Table 10.1 Etiology of spine-related pain by age

Age	Condition
<18 years	Spondylolysis/spondylolisthesis
	Scheuermann disease
18–50 years	Acute lumbago/acute cervicalgia
	Internal disk disruption
>50 years	Chronic lumbago/facet osteoarthopathy
	Lumbar stenosis
	Osteoporosis and compression fracture

10.2 Functional Anatomy

The spine can be divided in five sections: cervical (7 vertebrae), thoracic (12 vertebrae), lumbar (5 vertebrae), sacral, and coccygeal. Special units exist for the "start-"(craniocervical junction) and "end-connections" (sacroiliac junction), articulating the spine respectively with the head and with the pelvis.

Normally the cervical and lumbar spine have a lordotic curve, whereas the thoracic spine is kyphotic. The main functions of the spine are to support the head, pelvic girdle, and abdominal organs, attachment of the thorax, protection of the spinal cord, and transfer of weight and bending movements of the head, trunk, and pelvis.

The spine consists of bones, joints, ligaments, and muscles. The vertebrae are joined by joints between the bodies (disks) and the neural arches (facets). The anterior column consists of the vertebral bodies, intervertebral disks, and the anterior and posterior ligaments. Other ligaments are the inter- and supraspinous ligaments and the ligamentum flavum. The posterior column includes the neural arch, facet (zygapophyseal) joints, spinal process, and pars interarticularis (the area between the upper and lower facet joints). Important neural structures (spinal cord, conus medullaris, and cauda equine) lie within the spinal canal that runs through the vertebral foramen.

The intervertebral disks are fibrocartilaginous structures located between the vertebral bodies. It has three components: (1) the annulus fibrosus, the outer circumferential ring with collagen layers arranged in a "criss-cross" type pattern to resist torsional, axial, and tensile loads; (2) the nucleus pulposus, the central core which is composed of 70 % water, determines the disk height and provides resistance to axial compression; and (3) cartilaginous vertebral endplates.

Different muscle groups act on the spine which can be divided into (1) the anterior muscle group (interspinal, intertransverse); (2) the middle muscle group semispinalis, multifidus, and rotators; (3) the posterior muscle group (erector spinae, iliocostal thoracis, longissimus thoracis, and iliocostal lumborum); and (4) the accessory muscle group (latissimus dorsi and trapezius). The anatomy of the neck is also complex; however, it is beyond the scope of this book to give a detailed description.

10.3 Etiology and Injury Mechanism

Acute muscle strains, ligament sprains, and soft tissue contusions are a very common cause of back and neck pain in athletes (Mautner and Huggins 2012). However, most low back injuries are not the result of a single exposure to a high-magnitude load, but instead a cumulative trauma from sub-failure magnitude loads: for instance, repeated small loads (e.g., bending) or a sustained load (e.g., sitting). In particular, low back injury has been shown to result from repetitive motion at end range. Sports that use repetitive impact (e.g., running), a twisting motion (e.g., golf), or weight loading at the end of a range of motion (e.g., weightlifting), commonly cause damage to the lower back (Alexander 1985). For example, repetitive hyperextension of the low back (gymnastics, figure skating, diving) is a risk factor for the development of spondylolysis.

Contact sports such as football and ice hockey carry an inherent risk of cervical spine injury. The major mechanism of serious cervical injury is an axial load or a large compressive force applied to the top of the head (Chao et al. 2010). This mechanism is more dangerous when the neck is slightly flexed, because the spine is brought out of its normal lordotic alignment, which does not allow for proper distribution of force to the thorax. Flexion puts the cervical spine in a straight line; thus, the musculature cannot assist in absorbing the force. Injury to the cervical spine occurs when it is compressed between the body and the rapidly decelerating head. When a fracture results, if the bone fragments or herniated disk materials encroach on the spinal cord, neurologic damage will occur. This mechanism is the primary cause of cervical fracture, dislocation, and quadriplegia.

10.4 Sports Injuries

10.4.1 Sprains, Strains, and Muscle Contusions

The vast majority of back pain in the athlete occurs as a result of soft tissue sprain, strain, or contusion, and these are often a diagnosis of exclusion (Mautner and Huggins 2012). Sprain represents stretching of a ligament beyond its elastic limit. Strain is tearing of a muscle during concentric or eccentric loading. Contusion occurs after blunt trauma to the soft tissue and often leads to formation of a hematoma. These injuries are readily diagnosed based on history and clinical examination. Initially sprains, strains, and contusions can be very debilitating, but most respond to conservative management with rest, NSAIDS, and massage. Activities can be resumed when pain resolves. In case the pain does not disappear or neurological symptoms develop, further examinations should be considered.

10.4.2 Cervicalgia and Cervicobrachialgia

Most neck pain is regarded as nonspecific in the absence of radiological evidence of relevant pathoanatomy. Acute cervicalgia is characterized by a sudden onset of sharp neck pain with protective deformity and limitation of movement. It typically occurs either after a sudden, quick movement or on waking. There may have been unusual movements or prolonged abnormal postures prior to the onset of pain (Hutson and Speed 2010).

The "stinger" or "burner" phenomenon is seen frequently in American football and rugby and less often in other contact sports (Standaert and Herring 2009). The player experiences transient upper extremity burning-type pain that may also be accompanied by paresthesia and/or weakness. Traction or compression of the cervical nerve root and/or plexus brachialis is considered to be the underlying mechanism. Symptoms may be localized to the neck or may radiate to the arm and hand. The symptoms are usually transient, but persistent neurological dysfunction and recurrent stingers may occur.

10.4.3 Acute and Chronic Lumbago

Lumbago can be defined as mild to severe pain or discomfort in the area of the lower back (Patrick et al. 2014). The pain can be acute (sudden and severe) or chronic if it has lasted more than 3 months. Most people will experience lumbago at some point in their life and so do athletes. It can occur at any age but is a particular problem in younger people whose work involves physical effort and much later in life in the elderly. Athletes present with pain across the lower part of the back that sometimes radiates into the buttocks, the back of the thigh, or to the groin. The pain is usually worse on movement. There can be a tense spasm of the muscles surrounding the spine, which causes a stiff back with limitation of flexion and extension of the spine. In some severe cases, the back may tilt to one side causing a change in posture or a limp. If the pain is accompanied by a tingling sensation or numbness in the back or buttocks or leg, which may pass right down into the foot, this is called sciatica, and it indicates irritation of the sciatic nerve, which passes down from each side of the spine to the feet. In most cases it settles in a few days to weeks, but for some it is a persistent problem. In the majority of cases, it is impossible to identify the exact cause of low back pain. Due to a forceful sports-related movement, there may, for example, have been tiny strains or tears of some of the small muscles and ligaments, which can be difficult to pinpoint within the complex structure that is the human back. In most cases of lumbago, no imaging is necessary. However, in about a quarter of cases, a specific problem can be found. Often, these athletes are suffering from conditions like osteoarthritis of the facet joints, a slipped disk (prolapse of an intervertebral disk), a collapse or fracture of one or more vertebrae (especially in the elderly athletes, when they have fallen or there is a deformation of natural spine curvature (scoliosis) or more rarely, skeletal damage due to tumors or infection.

10.4.4 Intervertebral Disk Injuries With(out) Radiculopathy

Discogenic pathology is the primary cause in almost 50 % of young to middle-aged adults that complain of low back pain (LBP), whereas it is the cause of only a minority of cases in young inactive adolescents. Adolescent athletes, however, have a higher risk for internal disk disruption (IDD) than their inactive peers with back pain due to a discogenic cause in 11 % of cases (Haus and Micheli 2012; Mautner and Huggins 2012). The adolescent growth spurt appears to be the most vulnerable time for injuries to the lumbar intervertebral disk. Repetitive hyperflexion and extension loading on the lumbar disk during sports can lead to endplate irregularities, Schmörl nodes, annular tears, disk protrusions, and endplate fractures. Competitive sports and sports with more frequent trunk rotation, as, for example, gymnastics, soccer, tennis, and golf, are associated with early lumbar disk degeneration. Discogenic pain is often nonspecific. Some findings may suggest a discogenic nature of the pain: midline pain, pain with periods of unsupported sitting, and pain worsening with forward flexion. Posterior annular tears without nerve root compression can cause radicular type buttock, groin, and leg pain. On examination often there is a decreased flexibility. Neurologic deficits are absent.

In case of herniation of the nucleus pulposus with nerve root compression patients typically present with low back, buttock, or hip pain and radicular symptoms including numbness, tingling, and sharp radiating pain in the lower extremity. Pain can be made worse by coughing or sneezing. Besides a full examination of the spine, a careful neurologic examination has to be performed, looking for (subtle) deficits in strength, sensation, or reflexes. Special test like the straight leg raise and slump test can be helpful. One should realize that this classical radicular pattern might be absent in younger patients.

MRI allows excellent evaluation of the intervertebral disk and may show early degenerative changes including disk signal reduction, loss of height, bulging, apophyseal abnormalities, and Modic changes and its interaction with nearby structures like nerve roots (see Chap. 11). However, many asymptomatic patients will have abnormal MRI studies and this should be kept in mind. The natural history of low back pain is often favorable and the mainstay of treatment is nonsurgical. Athletes should be encouraged to remain active (activity modification), and the use of nonsteroidal anti-inflammatory drugs (NSAIDs) as a first-line medication should be considered. Physical therapy to retrain the stabilizing spinal musculature results in less LBP recurrence.

10.4.5 Scheuermann Disease

The prevalence of Scheuermann disease is approximately 1–8 % (Haus and Micheli 2012; Lowe and Line 2007). The typical presentation is in the late juvenile age period (8–12 years). Cosmetic deformity caused by increased thoracal kyphosis is the most common complaint of patients with Scheuermann disease and is typically the primary reason for young patients to seek medical attention. The natural history remains controversial. Scheuermann disease tends to be symptomatic in the acute phase (during the teenage years) with thoracic pain worsening by activity and diminishing later in life. Patients with Scheuermann have more back pain than their healthy peers. This pain is believed not to interfere with daily activities. A recent study, however, reports a lower quality of life and more risk for disability in the activities of the daily living (Ristolainen et al. 2012).

The specific etiology remains unknown but is probably multifactorial. Genetic factors, failure in endplate ossification, chronic trauma (sports, hard labor), and hormonal factors are mentioned. Besides the most frequent "classic" Scheuermann found at the mid-thoracic spine, there also is a “lumbar” type (type II) localized at the thoracolumbar junction. This type II is typically seen in athletically active adolescent males or those involved in heavy lifting. There is a strong association with repetitive activities involving axial loading of the immature spine. In lumbar Scheuermann typically there is no kyphosis. Endplate irregularities can be more severe and can be confused with tumor, infection, or other conditions.

Imaging plays an important role in defining this condition. Radiological findings, including the typical Schmörl nodes, are discussed in Chaps. 11 and 12. Treatment of classic Scheuermann is controversial. Physical therapy is recommended and patients that are skeletally immature with a kyphosis between 45° and 65° are candidates for bracing. Surgery is generally considered if kyphosis is more than 65° and is associated with pain not alleviated by other methods. Unlike the classic type, the treatment of lumbar Scheuermann is more straightforward as its course is non-progressive. Symptoms generally resolve with rest, activity modification, and time (Afshani and Kuhn 1991; Lowe and Line 2007; Ristolainen et al. 2012).

10.4.6 Spondylolysis and Spondylolisthesis

Spondylolysis is defined as a unilateral or bilateral bony defect in the pars interarticularis (also known as the isthmus) of the vertebral posterior elements. In the general population, the incidence of spondylolysis is around 6–8 % (McTimoney and Micheli 2003). In the athletic population, however, the incidence of spondylolysis is much higher, up to 63 % (Rossi 1978). Spondylolysis is the primary cause of back pain in athletes and responsible for approximately 47 % of low back pain in this population (Micheli and Wood 1995). Spondylolysis is rarely seen in children younger than 5 years, which makes a congenital pathogenesis not very likely. The incidence increases with age until about 20, after which the incidence stabilizes (Brooks et al. 2010). Spondylolysis is more frequent in boys than in girls and more frequent in whites than in blacks (Leone et al. 2011). More recent studies suggest an equal prevalence between boys and girls (Haus and Micheli 2012). This might be due to a general increase in the number of female athletes, especially in sports such as ballet and gymnastics. Spondylolisthesis appears to be more frequent in girls (Loud and Micheli 2001).

The pathogenesis remains controversial. Most likely spondylolysis is a multifactorial condition in which a stress fracture occurs in a congenitally weak or dysplastic pars interarticularis (Leone et al. 2011). The mechanism of injury is often a combination of repetitive forces like flexion, extension, and rotation of the lumbar spine. Sports associated with an increased frequency of spondylolysis are typically sports requiring hyperextension motions such as gymnastics and diving. Contact sports such as football, soccer, hockey, and lacrosse also have an increased risk of spondylolysis (Afshani and Kuhn 1991). The injury may be unilateral or bilateral and occurs most commonly (in 95 % of cases) at the L5 vertebra. When the injury is bilateral, spondylolisthesis may occur. Spondylolisthesis generally refers to the forward translation of one vertebra relatively to the next more caudal vertebra. It mostly involves the L5–S1 segment. It has different etiologies (cfr. Wiltse classification) with isthmic spondylolisthesis being the most common subtype (Haus and Micheli 2012).

Spondylolysis may be completely asymptomatic. If there are symptoms, the athlete typically complains of a mechanical-type low back pain, typically getting worse with hyperextension and improving with rest. The pain may radiate to the buttocks or posterior thigh. The onset is often insidious, but can be precipitated by an acute injury. Common findings on physical examinations are a hyperlordotic posture and bilateral hamstring tightness. Hyperextension with a one-leg stance exacerbates the pain. Radicular signs are less common, but may occur in the presence of spondylolisthesis (Haus and Micheli 2012; Leone et al. 2011). The role of imaging is discussed in Chaps. 11 and 12.

The treatment of spondylolysis is initially conservative with cessation of sporting activities and spinal bracing for 3–6 months. The aim is to reduce pain and to facilitate healing. Surgical treatment is typically reserved for patients who do not respond to conservative treatment after 6 months. Surgery is necessary in 9–15 % of patients with spondylolysis and/or low-grade spondylolisthesis. Surgery should not be considered lightly as it often concerns young patients (Leone et al. 2011).

10.4.7 Lumbar Stenosis

Degenerative lumbar spinal stenosis is caused by mechanical factors and/or biochemical alterations within the intervertebral disk that lead to disk space collapse, facet joint hypertrophy, soft tissue infolding, and osteophyte formation, which narrows the space available for the thecal sac and exiting nerve roots (Lee et al. 2013; Issack et al. 2012). The clinical consequence of this compression is neurogenic claudication and varying degrees of leg and back pain. Symptoms include radicular pain, numbness, tingling, and weakness. It is a common diagnosis that is occurring with increased frequency in sports medicine clinics (Borg-Stein et al. 2012). Degenerative lumbar spinal stenosis is a major cause of pain and impaired quality of life in the elderly. The natural history of this condition varies; peripheral vascular disease presents similarly and must be considered in the differential diagnosis.

10.4.8 Sacroiliac Joint Injury/Inflammation

The sacroiliac (SI) joint may also give rise to low back pain. Symptoms usually develop insidiously and are worsened by sports activities (Brolinson et al. 2003). There is palpation tenderness over the SI-joint. Spine extension is often painful and the FABER test reproduces pain in the affected SI-joint. Straight leg raise testing is negative. Symptoms may be quite similar to those found in patients with spondylolysis. Inflammation of the SI-joint can be associated with several other conditions like Crohn's disease, psoriasis, and ankylosing spondylitis (seronegative spondyloarthropathies) and Reiter's syndrome. Serological screening and imaging (Chaps. 11 and 12) should be performed in case of doubt with regard to the diagnosis.

10.4.9 Fractures and Dislocations

Flexion injuries of the cervical spine can cause compression fractures of the vertebral bodies (McRae and Esser 2008). Flexion fractures occur most frequent at the level C5 and C6 in adolescents. When combined with significant axial loading, flexion injuries can result in burst fractures of the vertebral bodies with retropulsion of bony fragments into the spinal canal (Maxfield 2010). The spine is particularly vulnerable for rotational forces; combined rotational forces can result in more severe subluxation due to increased disruption of supporting tissue. Because of the small, flat, almost horizontal configuration of the articular processes of the cervical spine, dislocation can occur relatively easy in case of trauma (Boran et al. 2011).

Acute fractures of the thoracolumbar spine are less frequent than cervical injuries and tend to be less catastrophic. In the thoracolumbar region, compression fractures are the most common type in young athletes. Compression fractures, as the name suggests, occur due to a compression force on the spine. This may happen during a traumatic injury such as a fall from a height, landing on the feet or buttocks (McRae and Esser 2008). More frequently, vertebral compression fractures occur in older people with osteoporosis or other preexisting spinal conditions where the bone is weak. There may not be one particular incident that causes it and pain may develop gradually.

Avulsion fractures of the spinous and transverse processes are also seen in athletes. Avulsion of the spinous process of the C7 and Th1 vertebrae are known as *clay-shoveler* fractures.

10.5 Spinal Injuries Associated with Specific Sports

Some sports are associated with a higher than normal percentage of spine injuries.

Acute spinal trauma can be seen in many sports and is related to an increased risk for trauma. These traumatic injuries do not differ significantly from those seen in non-sports-related trauma, e.g., falls or motor vehicle accidents.

More specific spine injuries are seen in chronic overload and/or strain to the spine occurring in some sports. These will be discussed in detail in this chapter.

The most common sports responsible for spinal injuries are equestrian events (41.8 %), rugby (16.3 %), diving (15.3 %), Gaelic football and hurling (9.6 %), cycling (4.2 %), and miscellaneous (12.7 %) (Boran et al. 2011). In general more males (74 %) than females (26 %) are injured, and the average age is 30.2 years (range 14–72 years).

Injuries are mostly to the cervical spine (60 %) and less to the thoracic (21 %) or lumbar spine (19 %). In 40 % of patients, more than one vertebral level is affected (Boran et al. 2011).

10.5.1 Sports Involving High-Velocity Incidents or Falls

10.5.1.1 Skiing and Snowboarding

Spinal injuries associated with recreational skiing and snowboarding mostly result from high-energy falls and to a lesser degree from collisions with other skiers, trees, or equipment. In competition snowboarding, spinal injuries are specifically related to the risks associated with jumping and performing moves.

Orthopedic injuries sustained in alpine skiing/snowboarding are numerous, with spinal injuries comprising between 1 and 20 % of all injuries (Floyd 2001; Levy and Smith 2000; Prall et al. 1995; Yamakawa et al. 2001). Snowboarding accidents result in more fractures, especially in the upper limbs, fewer knee injuries, and more severe injuries caused by impacts rather than by torsions (Yamakawa et al. 2001). Spinal injuries are more than two times more frequent in snowboarders compared to skiers.

The incidence of spinal injury in skiing and snowboarding is in general very low (0.001/1,000 skier-days). Although less frequent, spine and spinal cord injuries are the most debilitating and costly of serious injuries sustained by skiers (Prall et al. 1995). The majority (80 %) of spinal lesions are thoracic or lumbar, and multilevel lesions are seen in 20 % of patients. Compression fractures with loss of height of the anterior part of the vertebral body are the most frequent thoracic and lumbar lesions seen in 38–90 % of patients (Floyd 2001; Prall et al. 1995). Severe and/or unstable thoracic or lumbar fractures are seen in less than 5 % of patients. Snowboarders in general have the same pattern of lesions except for transverse process fractures that are significantly more frequent.

Cervical lesions on the other hand, although more rare, are usually more severe. In one major study, spinal cord injuries were seen in 17 % of ski accidents with spinal fractures, usually in association with cervical lesions (Prall et al. 1995).

There is a significantly higher incidence of spinal injury among beginner snowboarders than among beginner skiers. Furthermore, intermediate or expert snowboarders were more likely to be injured because of jumping than beginners, whereas about 70 % of spinal injuries caused by skiing results from a simple fall (Yamakawa et al. 2001).

As a final note in skiers and snowboarders under 13 years of age, helmet use does not increase the incidence of cervical spine injury but does reduce the incidence of head injury (Macnab et al. 2002).

10.5.1.2 Cycling

Although the vast majority of injuries suffered while cycling are minor, acute spinal injuries have been reported. Profound neurological deficits are reported in patients that are thrown over the handlebars while traveling downhill at speed

(McGoldrick et al. 2012). Spinal injuries are more frequently seen in mountain bikers, due not only to the characteristics of the terrain but also to the readiness to assume a higher risk compared to cycle racing (Schueller 2010).

Neck and back pain is extremely common in cyclists, occurring in up to 60 % of riders. To avoid or lessen spinal pain, proper fit of the bicycle is critical. Proper frame selection and adjustment can be made by following existing guidelines for frame size, seat height, fore and aft saddle position, saddle angle, and reach and handlebar height (Mellion 1991). Especially an appropriate pedal unit position may reduce low back pain. Positioning the pedals behind the saddle axis permits more physiological spine angles in comparison with the classic one having the pedals in front of the saddle axis (Fanucci et al. 2002). Lower back pain is the most prevalent overuse injury seen in cyclists, with an incidence up to 45 %, and low back pain causes the highest rates of functional impairment and medical attention in cycling (Clarsen et al. 2010). This high incidence might be caused by the creep induced in the viscoelastic tissues of the spine as a result of cyclic loading that subsequently desensitizes the mechanoreceptors within, allowing full exposure to instability and injury (Solomonow et al. 1999).

10.5.1.3 Horseback Riding

Horseback riding is the most common sport responsible for a spinal injury. Spinal injuries are an inevitable risk of horse riding with the rider high from the ground, relatively unprotected, and the horse that travels at speeds of up to 65 km/h. Moreover, the spines of the riders are relatively unprotected since effective gear to protect the spine still does not exist. Compared to other sports, horse riding accounts for the largest number of hospital admittance days by far and between 7 and 10 % of all riders requiring hospital admission suffer from spinal injuries (Hessler et al. 2014). In the United States, the rate of serious injuries from horseback riding has been reported to range from 1 per 350 to 1,000 h of riding. In British Columbia, Canada, the rate of hospital admissions for horseback riding injuries is 0.49 per 1,000 h of riding. In the Netherlands, every year, one out of seven riders will sustain an injury (Siebenga et al. 2006). Several studies have suggested that horseback riding is riskier than motorcycle riding, skiing, football, and hockey (Lin et al. 2011; Siebenga et al. 2006). In some countries, 70 % of all spine fractures caused by sports activities are sustained by equestrian activities (Hipp et al. 1977). Although numerically few, spine and spinal cord lesions from horse riding accidents are frequently catastrophic giving rise to paralysis or dead (Silver 2002). The injury of actor Christopher Reeve (“Superman”) in 1995, resulting in a complete C2-level SCI, heightened public awareness of the risks associated with horseback riding.

Up to 80–90 % of horseback riding accident victims are female (Hessler et al. 2014; Siebenga et al. 2006). Most spinal injuries are caused by falling of the horse (65–80 %), followed by being kicked by a horse. Around 80 % of the injuries occur at the thoracolumbar junction, either at Th12, L1, or L2 (Siebenga et al. 2006). Lumbar injuries being the most frequent (70 %), thoracic injuries second most frequent (30 %), while cervical injuries are more rare (Hessler et al. 2014). Other studies found relatively more thoracic injuries (Roe et al. 2003). The majority of fractures (85 %) are vertebral compression lesions (Hessler et al. 2014). Spinal cord injury from horseback riding affects an equal proportion of women and men, has a wide age range, and most commonly results in incomplete tetraplegia followed by complete paraplegia (Lin et al. 2011). Overall figures from the USA show that between 1973 and 1985, a total of 9,647 new admissions with spinal cord injury, 14.2 % were due to sport, of which 2 % represented horseback riding injuries (Stover and Fine 1987). A fall from a horse would appear to be most likely to cause a spinal cord injury. A kick, while it may cause a fracture of a transverse process, usually does not cause spinal cord injury (Silver 2002).

Consequences of injury caused by horse riding can be profound and the long-term effects should not be underestimated (Siebenga et al. 2006). Even years after a major trauma, 43 % of the patients have complaints and 11–20 % will remain permanently unfit for work (Dekker et al. 2003).

As far as stress or overload spine injuries in horse riding go, there is no conclusive MRI evidence to suggest that the cause lies in undue disk degeneration, spondylolysis, spondylolisthesis, or pathologic changes of the paraspinal muscles of the lumbar spine (Kraft et al. 2009). Still, compared to the general population, a high incidence of back pain is found among riders, but a significant correlation between the intensity of riding or the riding discipline and frequency or severity of back pain could is not found. For riders with preexistent back pain, the pace "walk" seems to have a positive influence on pain intensity (Kraft et al. 2009). Saddle types might play a role in the incidence of low back pain and is less often seen in riders that use a deep seated/Western style saddle than in those that use a traditional style/general purpose saddle (Quinn and Bird 1996).

10.5.1.4 Diving

Diving is the second or third most common cause of sports-related spinal injuries. In diving accidents the cervical spine is most often (>90 %) affected, with a highest number of fractures at C5 and C6, followed by C7. Most of these injuries are compression-flexion type injuries. Jefferson fractures, compression fractures of the ring of C1, are also frequently seen in diving accidents and occur by axial compression to the vertex such as diving in shallow water and hitting the bottom with the head first. Overall injury rates for diving are estimated as 4.00 injuries per 1,000 exposures for men and 3.78 injuries per 1,000 exposures for women (Amorim et al. 2011). Many spinal diving injuries result in tetraplegia, in some studies up to 45 % (Amorim et al. 2011). These injuries are associated with a very specific patient profile of a young, healthy, athletic male (>95 %) who suffered an injury to the cervical spine after diving into shallow water almost occurring exclusively during spring and summer time (Korres et al. 2006). Dangerous diving into swimming pools can result in spinal injuries with drastic consequences, including permanent physical disability and a profound impact on socio-professional status. Moreover, there are significant financial costs to society (Borius et al. 2010).

10.5.2 Contact Sports

In contact sports, also called “collision sports,” players directly or indirectly have physical contact with an opponent. The pattern of spinal injuries in American football, rugby, lacrosse, soccer, and ice hockey resembles closely. These injuries are induced by relatively high-velocity body contacts between athletes, usually of opposing teams. In ice hockey, impact of the head with the boards after being checked or pushed from behind is the most common mechanism of spinal cord injury (Tator et al. 2004).

The cervical spine is at greatest risk for injury in these sports, followed by thoracic and lumbar injuries in that order (Mall et al. 2012). Cervical spinal cord injuries have been the most common catastrophic football injury and the second leading direct cause of death attributable in American football (Cantu and Mueller 2003). The relatively common “stinger” is a neuropraxia of a cervical nerve root(s) or brachial plexus and represents a reversible peripheral nerve injury. Less common and more serious an injury, cervical cord neuropraxia is the clinical manifestation of neuropraxia of the cervical spinal cord due to hyperextension, hyperflexion, or axial loading (Rihn et al. 2009). Up to 2 out of 100,000 American football players are diagnosed with cervical cord neuropraxia. Characterized by temporary pain, paresthesias, and/or motor weakness in more than one extremity, there is a rapid and complete resolution of symptoms and a normal physical examination within 10 min to 48 h after the initial injury. Stenosis of the spinal canal, whether congenital or acquired, is thought to predispose the athlete to cervical cord neuropraxia (Rihn et al. 2009). Permanent neurological deficits or even dead after catastrophic cervical spine injuries are seen in 3–15 per 1,000,000 football players (Kim et al. 2003). These lesions mostly occur after cervical hyperflexion and are usually accompanied by facet joint fracture dislocations and/or anterior wedge compression fractures. Facet dislocations, in particular bilateral facet dislocations, are identified as the most common types of cervical spine injury in rugby. Trauma occurs most often at lower cervical spinal levels, notably the C4/5 and C5/6 motion segments (Kuster et al. 2012). Hyperextension lesions in contact sports are less common but might also have catastrophic results (Silva et al. 2006).

The complex biomechanics of heading in soccer are not completely defined, especially with regard to long-term effects on the neck and cervical spine. Existing studies of long-term effects suggest a predisposition to degenerative changes of the cervical spine, though they are somewhat limited, even when coupled with data regarding athletes in other sports (Mehnert et al. 2005).

10.5.3 Chronic Overload Sports

10.5.3.1 Gymnastics, Figure Skating, and Dance

Spinal injuries in gymnastics, figure skaters, and dancers are not uncommon. Because of the unique demands of these sports, which repetitively place significant forces across the spine, potential causes of back pain include spondylolysis, Scheuermann disease, intervertebral disk pathology, and mechanical sources of pain (Kruse and Lemmen 2009). The spine is a frequently injured area of the body in dancers, and many issues stem from poor technique and muscle imbalance (Gottschlich and Young 2011). In male dancers and figure skaters, there is a higher incidence of low back injuries allegedly due to their lifting requirements. However, imaging studies have failed to demonstrate higher rates of degenerative disk disease in gymnasts or female dancers than in control groups of the same age (Capel et al. 2009). Spondylolysis on the other hand is more frequent in elite-level gymnasts than in the general population (Bennett et al. 2006). Specific segmental muscle control exercises of the lumbar spine may be of value in preventing and reducing low back pain in young gymnasts (Harringe et al. 2007). Some studies even suggest lower levels of low back pain in dancers due to greater leanness, not smoking, displaying less anxious/depressive behavior, and developing increased muscle strength and flexibility (Cupisti et al. 2004).

10.5.3.2 Weightlifting

The lower back is one of the most commonly injured body regions in powerlifting, but the injury rate is low compared to other sports (Siewe et al. 2011). Other studies report a high frequency of lower back injuries in weightlifting (Alexander 1985). In a study of 12 discordant pairs of monozygotic twins, there were no effects of power sports (2,300 vs. 200 h of weightlifting) on disk degeneration seen on MRI (Videman et al. 1997). The effect of wearing a back belt on spinal injuries is also controversial, reducing spine loading according to some (Kingma et al. 2006), but increasing injury rate of the lumbar spine according to others (Siewe et al. 2011).

10.5.3.3 Golf, Tennis, and Cricket Fast Bowling

Injuries related to participation in golf and tennis become more common given the increased popularity of these sports. Golf is considered to be an activity associated with a moderate risk for sports injuries (Sutcliffe et al. 2008). Spinal injuries in golf, tennis, and bowling are usually attributable to overuse of the lumbar spine. More specifically these sports demand a combination of trunk and shoulder rotation while swinging a club or racket or moving a ball at high speeds and loads (so-called rotational sports). In tennis the spine is one of the most frequently injured body parts (Hjelm et al. 2010; Kondric et al. 2011). In golf, the mean peak compressive load at the lower lumbar spine is over six times the body weight during the downswing and the mean peak anterior and medial shear loads approach 1.6 and 0.6 times the body weight during the follow-through phases (Lim et al. 2012). These loads predispose the golfing population to muscle strains, lumbar disk disease, spondylolysis, and facet joint arthropathy (Hosea and Gatt 1996). In cricket fast bowlers, the pars interarticularis of each vertebra is vulnerable to injury due to repetitive flexion, rotation, and hyperextension (Elliott 2000). Fast bowling is directly associated with the development of symptomatic pars lesions of the lumbar spine, particularly unilateral L4 stress lesions, in a significant proportion of the adolescent bowlers (Engstrom and Walker 2007). Within cricketers, unilateral spondylolyses tend to arise on the contralateral side to the bowling arm (Gregory et al. 2004). Modic type I changes, especially asymmetrically and at the side of the golfers handedness, might be responsible for some of the low back pain complaints (Mefford et al. 2011).

Modification of sports kinematics reduces loads and spinal injuries in all of these sports. Adaptation of the swing in golfers and specifically more hip rotation, more trunk flexion, and less lumbar flexion is correlated with a lower incidence of low back pain (Lindsay and Horton 2002; Vad et al. 2004). In tennis one-handed strokes lay considerably less stress on the lower lumbar spine than double-handed strokes (Kawasaki et al. 2005). In cricket fast bowlers reducing the level of shoulder alignment counter-rotation significantly reduce the incidence and progression of lumbar disk degeneration (B. Elliott and Khangure 2002).

In severe cases, overloads might lead to acute lesions. Stress fractures and avulsion fractures of the cervical and/or upper thoracic spinous processes are documented in golfers (Kang and Lee 2009; Kim et al. 2012). Intradiscal hematoma is described in an elite tennis player (Baranto et al. 2010).

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Radiologic Imaging of Spine Injuries

11

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Contents

Abstract

Sports-related spinal injuries can be divided into acute "traumatic" injuries and chronic "overuse" injuries. They mainly occur in sports that either involve high-velocity incidents or falls from heights. In that respect, they do not differ much from other causes of acute spinal injuries. Injuries can be bony with fractures and/or dislocations, soft tissue injuries to ligaments or the disc or spinal cord injuries, and any combination of those.

Spinal injuries in chronic overuse occur due to repetitive training and microtrauma. In children and adolescents, they are a major source of morbidity and in fact exceed infectious diseases as a cause of morbidity (Haus and Micheli, Clin Sports Med 31: 423–440, 2012). The most frequent source of back pain in adolescents is spondylolysis; in young adults, disc disease is most frequent, and in older subjects, facet joint disease is most prevalent (Micheli and Wood, Arch Pediatr Adolesc Med 199:15–18, 1995).

Recently, the more competitive nature of organized sports and the increased training load, necessary to obtain higher levels of competence, result in more repetitive microtrauma that may lead to overuse failure of spinal structures.

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11.1 Introduction

The spine is the most complex "joint" of the human body. In essence, it is made out of multiple units with a similar recurring layout but with changing dimensions to compensate for different loads. Special units exist for the "start" (craniocervical junction) and "end" connections (sacroiliac junction), articulating the spine, respectively, with the head and with the pelvis. The basic unit is a triple joint complex. The first joint is the discovertebral unit which is the main weight-bearing element and is made out of an elastic and gelatinous central nucleus pulposus that is responsible for disc height and flexibility and the surrounding annulus fibrosus that binds the two adjoining vertebrae with strong collagen fibers. These fibers run diagonally allowing some rotation, flexion, and extension at each disc level. The second and third joints are the symmetrically positioned posterior located facet joints that restrict motion and that are also partly responsible for weight bearing especially when the discovertebral units fail.

Sports-related spinal injuries can be divided into acute "traumatic" injuries and chronic "overuse" injuries.

11.2 Sports-Related Spine Injuries

11.2.1 Acute Traumatic Spinal Injuries

Traumatic sports-related spine injuries account for 11 % of all spinal injury admissions (Boran et al. 2011). They mainly occur in sports that either involve high-velocity incidents or falls from heights. In that respect, they do not differ much from other causes of acute spinal injuries. Injuries can be bony with fractures and/or dislocations, soft tissue injuries to ligaments or the disc or spinal cord injuries, and any combination of those.

11.2.1.1 Fractures and Dislocations

Flexion injuries of the cervical spine can cause compression fractures of the vertebral bodies. Flexion fractures occur most frequent at the level C5 and C6 in adolescents (Fig. 11.1). When combined with significant axial loading, flexion injuries can result in burst fractures of the vertebral bodies with retropulsion of bony fragments into the spinal canal (Maxfield 2010). In diving accidents, the cervical spine is most often (>90 %) affected, with a highest number of fractures at C5 and C6, followed by C7. Most of these injuries are compression-flexion-type injuries. Jefferson fractures, compression fractures of the ring of C1, are also frequently seen in diving accidents and occur by axial compression to the vertex such as diving in shallow water and hitting the bottom with the head first (Fig. 11.2). The cervical spine is at greatest risk for injury in contact sports, followed by thoracic and lumbar injuries in that order (Fig. 11.3) (Mall et al. 2012). The spine is particularly vulnerable for

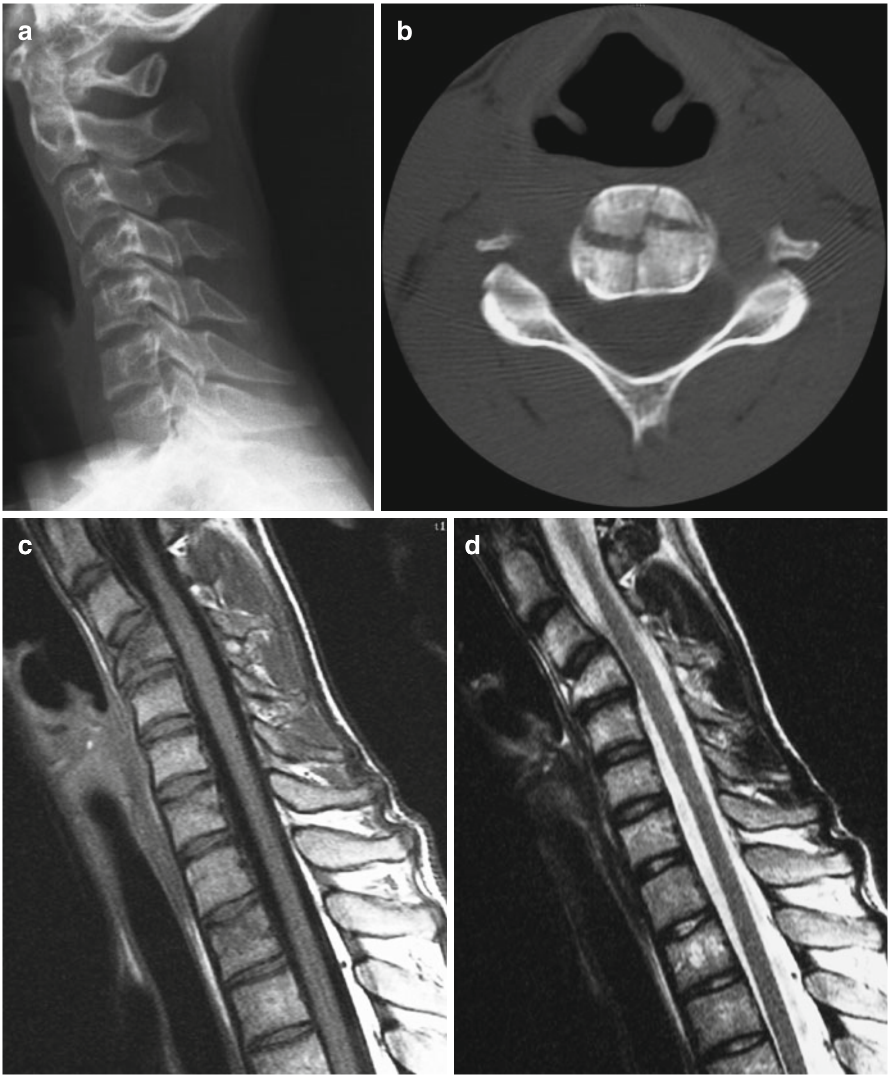


Fig. 11.1 A young girl that fell off her horse. Plain film (**a**), CT (**b**), and MR with sagittal T1–WI (**c**), T2–WI (**d**), and STIR (**e**). This 17-year-old girl suffered an unusual spinal lesion for a horse riding accident. Although cervical lesions form a minority of spinal fractures (<10 %) in this sport, they are the most feared lesions because of the possibility of permanent neurological dysfunction and even death. Plain films showed a wedge compression fracture of C4, and subsequent CT revealed a sagittal and a coronal fracture through the vertebral body making this an instable lesion. Because of paresthesias and motor weakness in both arms, a neuropraxia of the cervical spinal cord was diagnosed. Although there was a rapid and complete resolution of symptoms, MRI was warranted. No medullary lesion was seen. STIR images reveal bone bruises to C7 and Th2 and lesions of the intraspinous ligaments at C4–C5, C5–C6, C6–C7, and Th1–Th2 in this hyperflexion trauma

Fig. 11.1 (continued)

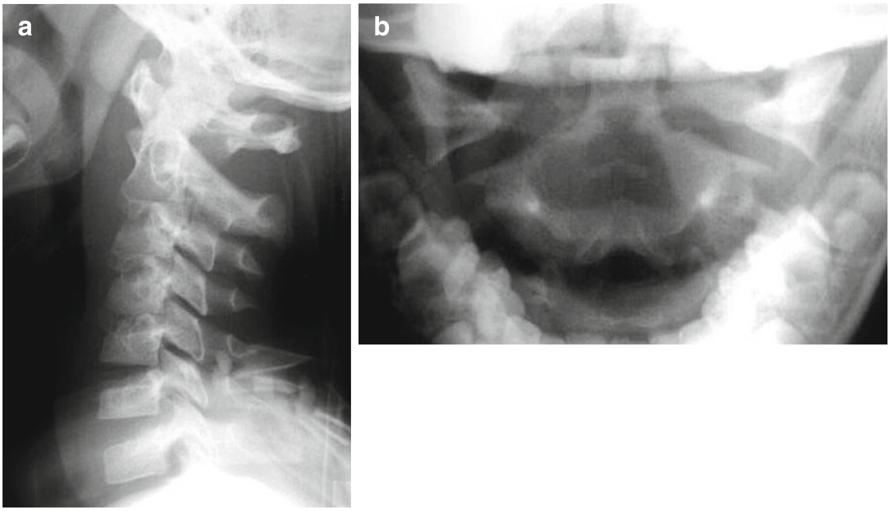


Fig. 11.2 A 6-year-old boy that dived off a ledge in shallow water. Lateral (**a**) and open-mouth (**b**) plain film. When diving in shallow water and landing on the head with axial loading of the spine, typically cervical spine lesions are found. The most typical fracture is of the ring of C1, a so-called Jefferson fracture. It was originally described as a 4-part fracture with double fractures through the anterior and posterior arches, but 3-part and 2-part fractures have also been described. It results from the occipital condyles being driven into the lateral masses of C1. This case recovered completely without surgical intervention

rotational forces; combined rotational forces can result in more severe subluxation due to increased disruption of supporting tissue. Because of the small, flat, almost horizontal configuration of the articular processes of the cervical spine, dislocation can occur relatively easy in case of trauma (Boran et al. 2011). Acute fractures of the thoracolumbar spine are less frequent than cervical injuries and tend to be less catastrophic. Most horse riding spinal injuries are caused by falling of the horse (65 %), followed by being kicked by a horse. Around 80 % of the horse riding spinal

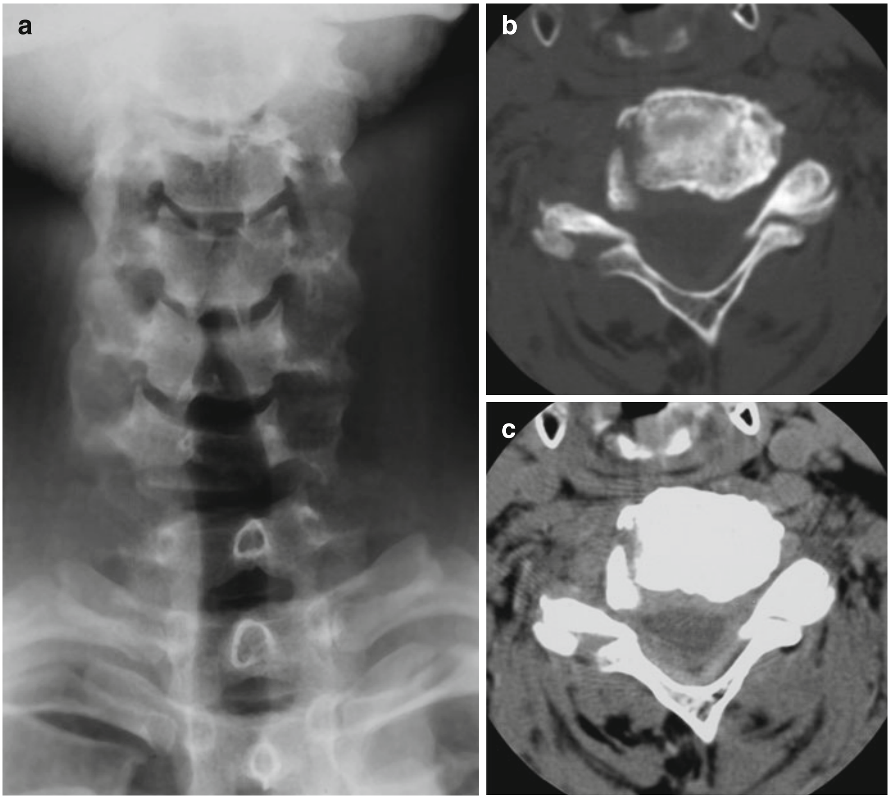


Fig. 11.3 A 19-year-old with cervical pain after a rugby game. Plain film (**a**), CT (**b**, **c**). This young man was sitting in the X-ray department waiting room on Monday morning with persisting cervical pain after a rugby game on Sunday. AP plain film shows a lateral C6–C7 dislocation. CT confirms the dislocation and demonstrates a unilateral facet fracture. Always carefully examine the soft tissue windows (**c**) also: in this case, a large epidural hematoma is shown while compressing the dural sac

injuries occur at the thoracolumbar junction, either at Th12, L1, or L2 (Fig. 11.4) (Siebenga et al. 2006). In the thoracolumbar region, compression fractures are the most common type in young athletes (Fig. 11.4). Avulsion fractures of the spinous and transverse processes are also seen in athletes. Avulsions of the spinous process of the C7 and Th1 vertebrae are known as *clay-shoveler* fractures. Facet dislocations, in particular bilateral facet dislocations, are identified as the most common types of cervical spine injury in rugby. Trauma occurs most often at lower cervical spinal levels, notably the C4/5 and C5/6 motion segments (Kuster et al. 2012). Patients with radiographic abnormalities or high-risk traumas require a CT examination (Fig. 11.1). CT is the best technique for detection and delineation of spinal fractures. If a neurologic deficit is present, MRI can provide important information about the spinal cord and the surrounding ligaments (Fig. 11.1).

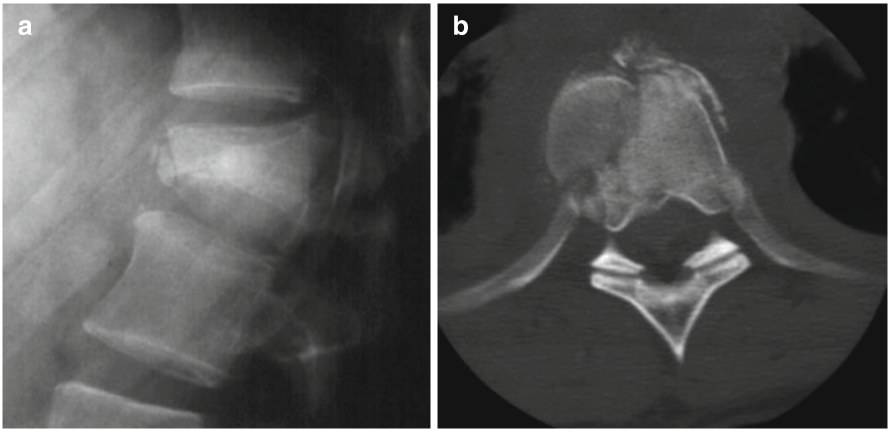


Fig. 11.4 Low thoracic burst fracture: lateral film (**a**), axial CT (**b**). Th12 burst fracture in a young woman that fell off her horse. Th12, L1, and L2 burst fractures are the most common spinal lesions in horseback riding accidents. They occur when riders fall of, or are thrown off, of their horse and land on their buttocks or lower back. Although plain films are helpful in the diagnosis, CT is obligatory in order to evaluate lesion stability and displacement of bone in the spinal canal and/or foramina

11.2.1.2 Muscle and Ligamentous Lesions

Sprain represents stretching of a ligament beyond its elastic limit. Diagnostic imaging is negative except for ultrasonography or MRI that may show edema in the soft tissues, muscle tear, and/or hematoma (Fig. 11.5). Imaging is not necessary if there is no neurologic deficit and if the injury did not occur with an excessive amount of force or if fracture is to be excluded (Haus 2012; Trainor 2002).

11.2.1.3 Disc Injuries

Discogenic pathology, including disc herniation, is responsible for 11 % of lumbar pain in pediatric athletes. The majority of athletes with a disc herniation are older than the age of 12. The most common locations for disc herniations are at the L4–L5 and L5–S1 levels (92 % of cases in adolescents). Most of the disc herniations remain subligamentous. Athletes at risk are those participating in collision sports and weight lifting due to the increased axial forces exerted on the spine. Often these patients have underlying vertebral anomalies such as scoliosis, transitional vertebrae (lumbarization and sacralization), lysis or spinal canal narrowing that may cause early disc degeneration, and subsequent herniation. Pain is typically located in the low back with or without leg pain. Overt neurologic deficits are rare. MRI remains the best modality to assess the herniated disc (Haus 2012).

11.2.1.4 Spinal Cord and Nerve Root Injuries

Cervical spinal cord injuries have been the most common catastrophic football injury and the second leading direct cause of death attributable in American football

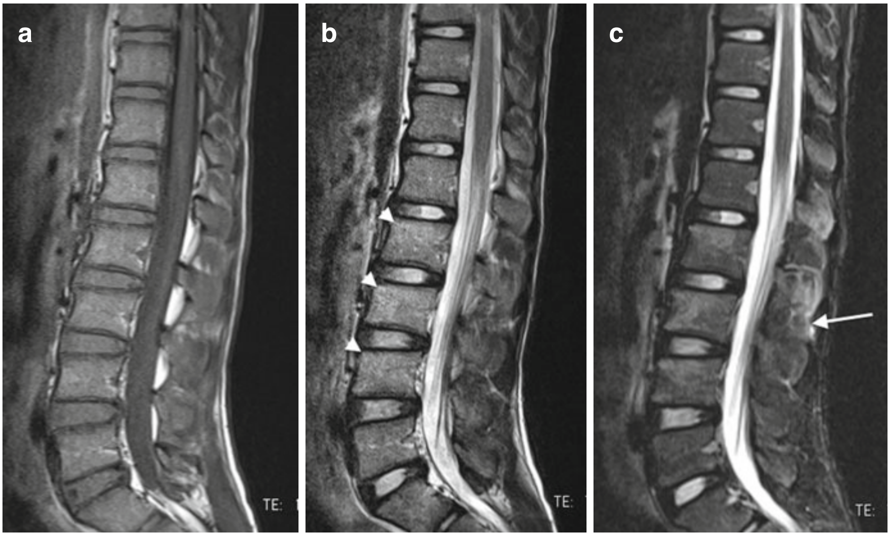


Fig. 11.5 Low back soft tissue lesion in a trampoline accident: MR with sagittal T1–WI (**a**), T2–WI (**b**), and STIR (**c**). This 14-year-old girl suffered a trampoline accident with acute low back pain. Plain films and CT were normal. MRI was performed several days later because of persisting severe low back pain. T1–WI and T2–WI show subtle signal intensity changes in the upper/anterior part of the vertebral bodies L2, L3, and L4. These bone bruises are much more obvious on the STIR images confirming the need for robust fat-suppressed imaging. Moreover, there are lesions of the intraspinous ligaments L1–L2 and especially L2–L3 confirming a flexion-type injury

(Cantu and Mueller 2003). The relatively common "stinger" is a neuropraxia of a cervical nerve root(s) or brachial plexus and represents a reversible peripheral nerve injury. Less common and more serious an injury, cervical cord neuropraxia is the clinical manifestation of neuropraxia of the cervical spinal cord due to hyperextension, hyperflexion, or axial loading (Rihn et al. 2009).

11.2.2 Chronic Overuse Spinal Injuries

Spinal injuries in chronic overuse occur due to repetitive training and microtrauma. In children and adolescents, they are a major source of morbidity and in fact exceed infectious diseases as a cause of morbidity (Haus 2012). The prevalence of specific etiologies of back pain is different depending on the age of the athletes. The most frequent source of back pain in adolescents is spondylolysis; in young adults, disc disease is most frequent, and in older subjects, facet joint disease is most prevalent (Micheli 1995).

Recently, the more competitive nature of organized sports and the increased training load, necessary to obtain higher levels of competence, result in more repetitive microtrauma that may lead to overuse failure of spinal structures.

11.2.2.1 Spondylolysis

Radiography

When spondylolysis is suspected, anteroposterior, lateral, oblique left and right, and collimated lateral views of the spine are performed. Using these five views, most spondylolytic defects are detected. In the acute setting, the defect is narrow with irregular borders, whereas more chronic lesions have smoother and more rounded edges. The width of the gap depends on the grade of spondylolisthesis. Indirect signs of spondylolysis on the AP view are lateral deviation of the spinous process and sclerosis of the contralateral pedicle. The oblique views may show the "scotty dog" sign (a break in the neck of the dog representing the isthmic defect). Although 45° oblique views have long been thought to be the best projections for detecting spondylolysis, the study is only 32 % sensitive (Haus 2012). They demonstrate isthmic defects only well if the X-ray beam is perpendicular to the pars, while the orientation of lysis is in the majority of cases close to the coronal plane. This is why the collimated lateral view actually shows the majority of defects (Leone et al. 2011). Also a hypoplastic L5 vertebral body is evidence of an L5 spondylolytic defect. The forward displacement in spondylolisthesis is determined on the lateral view. Listhesis can be graded according to the percentage of slipping by dividing the subjacent vertebral body into four equal parts. A slip in the first quarter is grade I and a slip in the last quarter is grade IV. In symptomatic spondylolisthesis, dynamic flexion and extension views should be obtained to determine lumbar intervertebral instability. Most spondylolisthesis occur in flexion. Axial or extension spondylolisthesis more often give nerve root compression. Sometimes this is the only anomaly found in young people with low back pain complaints. The distinction between normal and abnormal movement is however difficult with a substantial overlap between symptomatic and asymptomatic motion patterns. General values of 10 % for sagittal rotation (i.e., variation of the angle between vertebral endplates adjacent to the disc) and 4 mm for sagittal translation (i.e., slip of one vertebra relative to the vertebra below) are used as cutoff.

Single-Photon Emission Computed Tomography

When radiographs are negative for spondylolysis, but clinical suspicion is high, the more sensitive test is single-photon emission computed tomography (SPECT). SPECT is useful in early stages as it can identify patients with symptomatic (pre-) spondylolysis before radiography does. Positive SPECT suggests symptomatic spondylolysis, stress reaction, stress fracture, or healing (Fig. 11.6). It can differentiate between acute spondylolysis and a nonunion of the pars. Radiographic pars defects without uptake on SPECT are often asymptomatic. There has, however, also been documented positive SPECT imaging in asymptomatic athletes. Furthermore, activity on SPECT is nonspecific and has to be differentiated from other entities, for example, facet arthritis, infection, or osteoid osteoma. Therefore, if SPECT is positive, a CT scan should be performed for further evaluation. Therefore, SPECT is not recommended as screening tool in young patients. SPECT can be used to guide therapy. SPECT-positive spondylolytic lesions may better respond to conservative therapy (Leone et al. 2011; Papanicolaou et al. 1985; Maxfield 2010).

Computed Tomography (CT)

CT is the best technique to evaluate complete and incomplete pars fractures because of its great bony detail. CT can assess bony healing in the follow-up of acute lesions

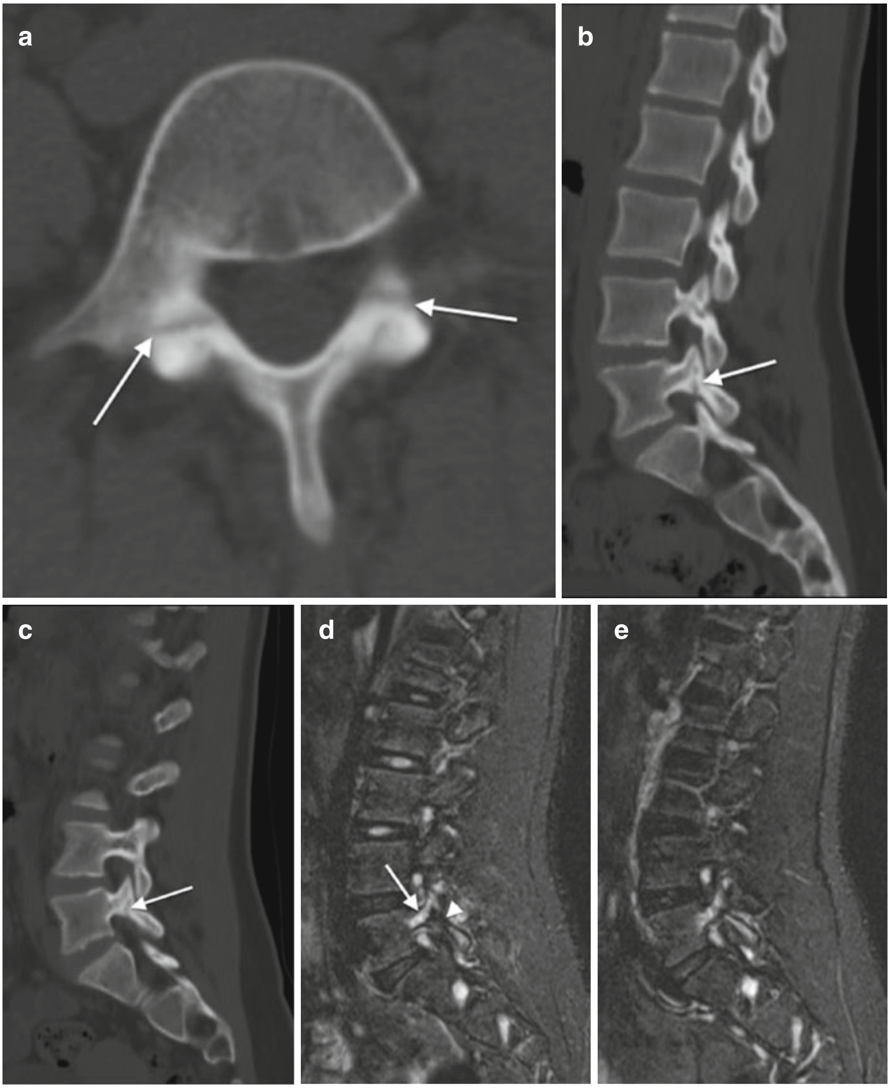


Fig. 11.6 Young gymnast with subacute/chronic low back pain: axial CT (**a**), parasagittal CT right (**b**) and left (**c**) (CT performed as part of a SPECT-CT exam), parasagittal STIR MR right (**d**) and left, (**e**) and SPECT-CT (**f**). These are images of a 14-year-old gymnast. Because of persisting low back pain, imaging was performed. When suspecting spondylolysis, CT is a very sensitive and specific imaging modality. In this case, a bilateral spondylolysis is shown although it may be incomplete on the right. MRI confirms an active process with edematous changes bilaterally but more extensive edema on the left. On the right (**d**), there is a band of low signal intensity at the spondylolytic lesion. SPECT-CT is asymmetric showing more activity on the *right*. The reduced bone edema with more SPECT activity on the right might be an indication of healing

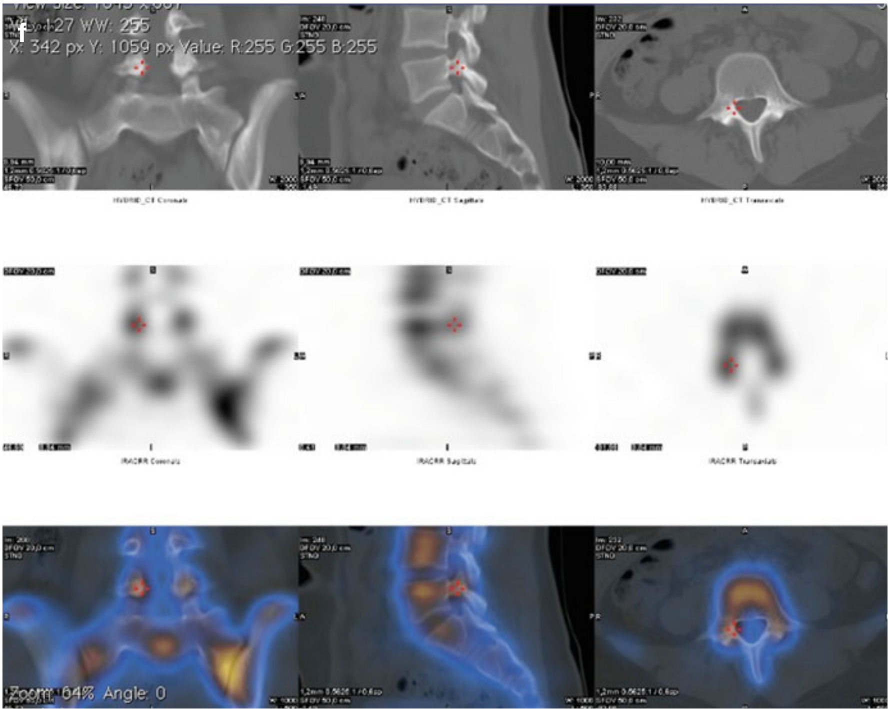


Fig. 11.6 (continued)

and can be used in management decisions. In unilateral spondylolysis, CT is more accurate than radiography for demonstrating contralateral hypertrophy or sclerosis of the pedicle. The disadvantage of CT is that the evaluation of the relationship between the nerve root, tissue filling the defect, and disc material is suboptimal compared to MRI. Moreover, CT cannot reliably distinguish between active and inactive lesions and exposes (often young) patients to radiation (Leone et al. 2011).

Magnetic Resonance Imaging (MRI)

MRI is increasingly used as the primary imaging method in patients with low back pain and radiculopathy and is a useful tool in the diagnosis and workup of spondylolysis. Although MRI is less sensitive than CT in detecting pars lesions, its ability to detect complete pars defects is improving. The great advantage of MRI is that it can detect marrow edema early in the course of stress lesions and may thus be useful in detecting early lesions that better respond to therapy (Fig. 11.6). Table 11.1 shows a classification system for MR imaging in the diagnosis and grading of lumbar spondylolysis (Hollenberg et al. 2002). The reported classification system uses both morphological information and the presence or absence of marrow edema on fluid-sensitive sequences. It can distinguish between stress reactions and active or chronic spondylolysis. The recognition of incomplete (grade 2) fractures and the healing process of pars defects remain challenging for MRI and are better depicted with CT. The MR diagnosis of spondylolysis can be difficult in the absence of

Table 11.1 Classification system for MR imaging in the diagnosis and grading of lumbar spondylolysis (Hollenberg et al. 2002)

Grade	Description	MRI features
1	Normal	Normal marrow signal
		Intact cortical margins
2	Stress reaction	Marrow edema
		Intact cortical margins
3	Incomplete stress fracture	Marrow edema
		Cortical fracture incompletely extending through pars interarticularis
4	Acute complete fracture	Marrow edema
		Fracture completely extending through pars interarticularis
5	Chronic established defect (nonunion)	No marrow edema
		Fracture completely extending through pars interarticularis

spondylolisthesis, but hypoplasia of the lower vertebral body is a very helpful sign. Also a widened sagittal diameter of the spinal canal, wedging of the posterior aspect of the vertebral body at the level of the spondylolysis, and reactive marrow changes in lumbar pedicles adjacent to a pars defect are suggestive for a spondylolysis (Maxfield 2010; Leone et al. 2011).

11.2.2.2 Disc Degeneration

MRI allows excellent evaluation of the intervertebral disc and may show early degenerative changes including disc signal reduction, loss of height, bulging, apophyseal abnormalities, and Modic changes. However, many asymptomatic patients will have abnormal MRI studies and this should be kept in mind. Indeed, in a study of 12 discordant pairs of monozygotic twins, there were no effects of power sports (2,300 vs. 200 h of weight lifting) on disc degeneration seen on MRI (Videman et al. 1997).

11.2.2.3 Scheuermann Disease and Schmörl Nodes

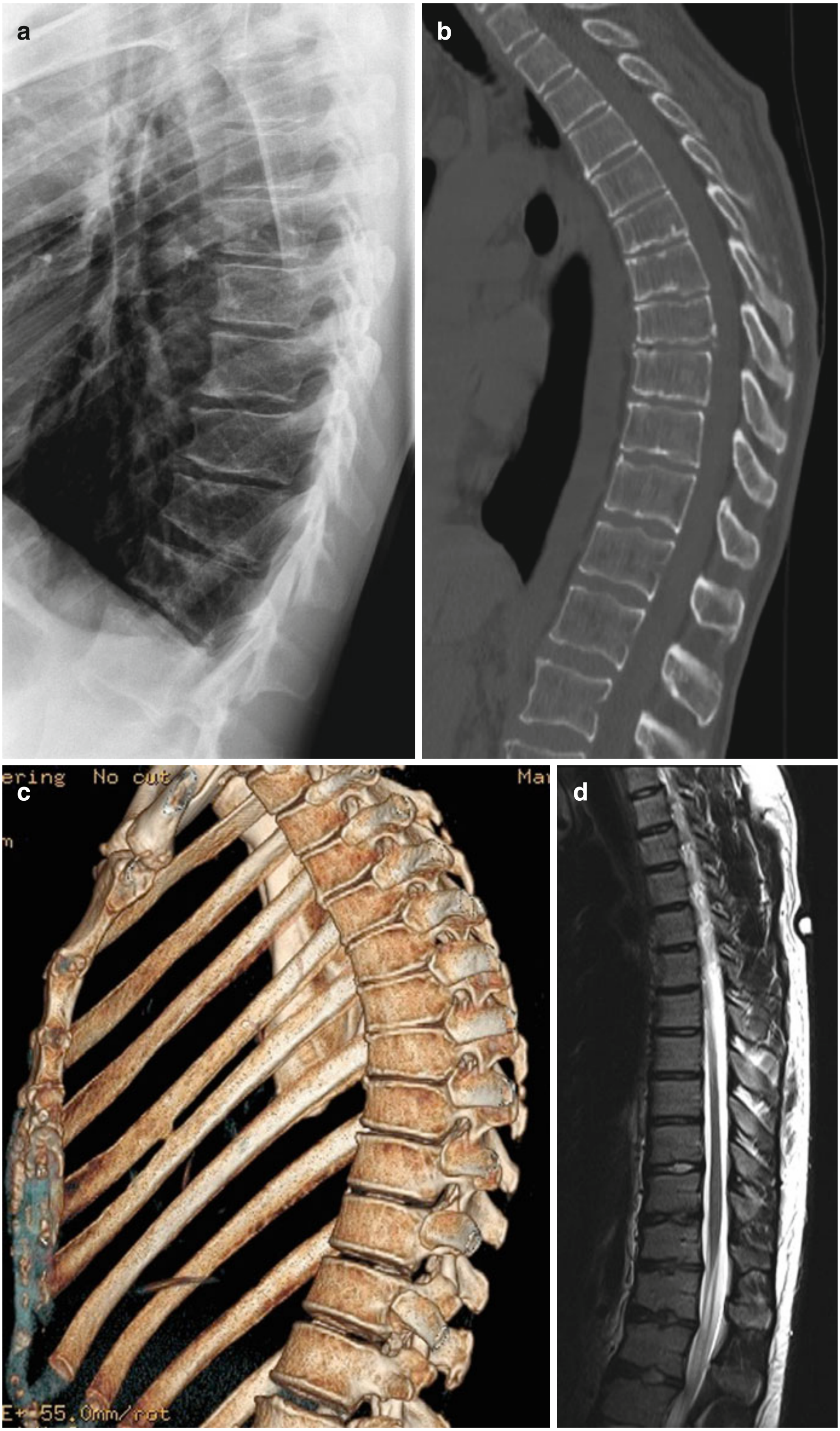
Schmörl nodes, also called cartilaginous nodes or intravertebral disc herniations, occur when a portion of an intervertebral disc herniates into an adjacent vertebral body as a result of the disruption of the cartilaginous plate of the vertebral body. They occur in different osseous diseases and are commonly discovered as incidental findings. There are different theories about their origin. Generally, there is assumed that the basic pathogenesis is osteonecrosis beneath the cartilaginous endplate with secondary herniation of the nucleus pulposus. Damaged vascularity could be the result of repetitive or acute stress or an underlying process like Scheuermann disease, osteomalacia, or hyperparathyroidism. There are some genetic factors with a heritability of more than 70 %. Schmörl nodes are more often located in the lower than in the upper endplates. Most often they are located at the levels Th10–L1, followed by Th6–Th9 and L2–L5. The posterior portion of the vertebra is more involved than the middle portion. The anterior portion of the vertebra is rarely involved. Generally, it is considered an asymptomatic condition, most of the time associated with degenerative disc disease. But nevertheless, the frequency of low back pain is doubled in patients with Schmörl nodes. The pain in patients with Schmörl nodes correlates with bone marrow edema on MRI and/or enhancement. It is a self-limited process with evolution of the bone marrow edema to sclerosis and usually treatment with analgetics will satisfy (Resnick and Nlwayama 1978; Price et al. 1984). Schmörl nodes are common, but not obligate in Scheuermann disease. Scheuermann disease is a condition that by general agreement is defined by wedging of more than 5° in three consecutive vertebrae (Fig. 11.7). Other radiological findings are an increased thoracic kyphosis, irregular endplates, disc space narrowing, lengthening of the vertebral bodies, and Schmörl nodes. A kyphosis of more than 40° is considered abnormal in the thoracic spine. The prevalence of Scheuermann disease is approximately 3 %. The typical presentation is in the late juvenile age period (8–12 years). The specific etiology remains unknown but is probably multifactorial. Genetic factors, failure in endplate ossification, chronic trauma (sports, hard labor), and hormonal factors are mentioned. Besides the most frequent "classic" Scheuermann found at the mid-thoracic spine, there also is a "lumbar" type (type II) localized at the thoracolumbar junction. This type II is typically seen in athletically active adolescent males or those involved in heavy lifting. There is a strong association with repetitive activities involving axial loading of the immature spine. In lumbar Scheuermann, typically there is no kyphosis. Endplate irregularities can be more severe and can be confused with tumor, infection, or other conditions.

Cosmetic deformity is the most common complaint of patients with Scheuermann disease and is typically the primary reason for young patients to seek medical attention. The natural history remains controversial. Scheuermann disease tends to be symptomatic in the acute phase (during the teenage years) with thoracic pain worsening by activity and diminishing later in life. Patients with Scheuermann have more back pain than their healthy peers. This pain is believed not to interfere with daily activities. A recent study, however, reports a lower quality of life and more risk for disability in the activities of the daily living. Treatment of classic Scheuermann is controversial. Physical therapy is recommended, and patients that are skeletally immature with a kyphosis between 45° and 65° are candidates for bracing. Surgery is generally considered if kyphosis is more than 65° and is associated with pain not alleviated by other methods. Unlike the classic type, the treatment of lumbar Scheuermann is more straightforward as its course is nonprogressive. Symptoms generally resolve with rest, activity modification and time (Wenger 1999; Ristolainen et al. 2012; Afshani and Kuhn 1991; Murray et al. 1993).

11.2.2.4 Facet Joint Arthropathy

Degenerative osteoarthritis of the zygapophyseal joints occurs mostly in the lumbar and cervical regions, rarely in the thoracic level. The facets between L3–L4, L4–L5, and L5–S1 experience the greatest amount of stress with forward and lateral flexion. Older age, lesser height, and greater weight are independently and together with heavy repetitive stress for 3 or more hours per day associated with osteoarthritis at the

Fig. 11.7 Three different patients with Scheuermann disease. Plain film (**a**), CT (**b**) and 3DCT, (**c**) and T2–WI MRI (**d**). All three of these patients show wedging of more than 5° in three consecutive vertebrae and as such have Scheuermann disease. Scheuermann disease is often accompanied by Schmörl nodes, irregular endplates, and degenerative disc disease. It persists in adult life as shown in figures (**b**) and (**c**) of a 52-year-old woman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zygapophyseal joints (Suri et al. 2015). Degenerative changes include joint space narrowing, osteophytosis, articular process hypertrophy, articular erosions, subchondral cysts, and intra-articular vacuum phenomenon. Specific loads in golf, tennis, and cricket predispose to facet joint arthropathy. Trauma at the level of the facet also may initiate the inflammatory process, leading to facet hypertrophy. Hypertrophy of the zygapophyseal joints can cause stenosis in the spinal canal or the area where spinal nerve roots exit. Changes in the facets can be seen on radiographs, but CT scans are preferred. CT scans are also more useful than MRI to view the hypertrophy of the facets.

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Nuclear Medicine Imaging of Spine Injuries

12

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Contents

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Abstract

Modern sports activities are associated with a high incidence of spine pain. Generally, the injuries seen are classified to their time of onset or specific injuries related to the vulnerable skeletal locations. Spinal fracture is fortunately very rare for incidences that are associated in contact sports activities. Prevention of spinal injuries and early diagnosis are the first priorities since delayed diagnosis may cause structural instability and early osteoarthritis or abnormal bony maturity. When plain radiographs of a patient with persistent symptoms reveal negative findings, a bone scan with single-photon emission computed tomography, computerised tomography scan or magnetic resonance imaging scan can be performed. Nuclear medicine imaging techniques, encompassing the visualisation and characterisation of biological processes at the molecular and cellular level, are useful techniques in localising the site of spinal injuries which are inconspicuous on the structural conventional imaging techniques.

Abbreviations

CT	Computed tomography
Ga (GS)	Gallium-67
GS	Gallium scan
HMPAO	Hexamethylpropyleneamine oxime
i.e.	That is
In	Indium-111
LBP	Low back pain
MDP	Methyl diphosphonate
MIP	Multiple image projection
MRI	Magnetic resonance imaging
SAP	Superior articular process
SPECT	Single-photon emission computed tomography
Tc	Technecium-99
WBC	White blood cells

12.1 Introduction

Nuclear medicine imaging techniques encompass the visualisation and characterisation of biological processes at the molecular and cellular level in vivo and in vitro. The bone structure is strong. Therefore injuries commonly occur in the ligamentous and muscular structures because they are the weaker points. Modern sports activities predispose a high incidence of spine pain. For instance, lower back pain (LBP) occurs in up to 50 % of elite athletes. Generally, the injuries seen in involving the spine are acute stress injuries, overuse injuries, or immature skeletal-related stresses. Fortunately acute spinal fractures relatively rarely occur. They occur most frequently in contact sports such as rugby, American football, and high-velocity sports such as skiing and motor sports. Prevention and early diagnosis of spinal injuries are a first priority as the delayed diagnosis may cause structural instability and early osteoarthritis or abnormal bony maturity. Whenever an athlete sustains an injury with suspicion of a spinal fracture, they should be immobilised and transferred to a hospital for an immediate evaluation. Bone and ligamentous injury are evaluated with CT and MRI to assess fracture stability.

MRI is recommended as the primary imaging modality for investigation of athletes presenting with back or radicular pain. When bony injury is suspected, radiography technique or targeted CT should be obtained to help localise the injury and grade its severity. Bone scintigraphy is used when the primary diagnostic imaging measures fail to identify the site of injury in symptomatic individuals. In particular nuclear medicine techniques, i.e. gamma camera or single-photon emission tomography (SPECT) exploiting molecular probes (technetium-99) being tagged to a particular radionuclide (MDP) (Subramanian 1996), are useful tools in providing information on the targeted inflammatory or active sites of new bone formation or resorption for which visualisation are imperceptible on the MRI or CT. The sensitivity of bone scanning with SPECT is hampered by the lack of anatomical details (Bellah et al. 1991). However, integrated SPECT/CT has increased the interest in nuclear medicine of orthopaedic surgeons and sports medicine specialists, especially in diagnostics and management of sports-related injuries. SPECT in combination with CT enables a direct correlation of functional information and anatomical information, leading to a better diagnostic accuracy in scintigraphic evaluation. SPECT/CT therefore represents a clinically relevant component of the diagnostic process in patients with non-oncological orthopaedic conditions referred for bone scintigraphy (Even-Sapir et al. 2007; Scharf 2009). This chapter addresses the importance of the nuclear imaging tool and in particular the SPECT/CT in evaluating causes of pain among athletes with spine-related injuries.

12.2 Acute Injury (Muscle Contusions and Sprains and Stress Fractures)

Acute injuries include the full spectrum of ligament, tendon, and muscle injuries and acute fractures. The most common problem among athletes is self-limiting pain caused by muscle contusions and sprains (Table 12.1). Acute pain is most intense 24–48 h after injury. It is often associated with spasm that, after a couple of days, may be localised to a so-called trigger point. Therefore, imaging tools that comprise metabolic information are useful in determining the origin of pain in this group of patients, since plain radiography may fail to show non-displaced fractures.

Traditionally, three-phase bone scintigraphy is commonly exploited in the evaluation of athletes with traumatic pain. The high-contrast resolution of bone scan allows early detection of acute spine trauma when imaging is performed within 6–72 h following the onset of symptoms.

Table 12.1 Common classification of spine injuries by onset of symptoms

Acute injury	Overuse injury
Muscle contusion	Fatigue fracture
Ligament sprain	Spondylosis
Joint sprain	Spondylolisthesis

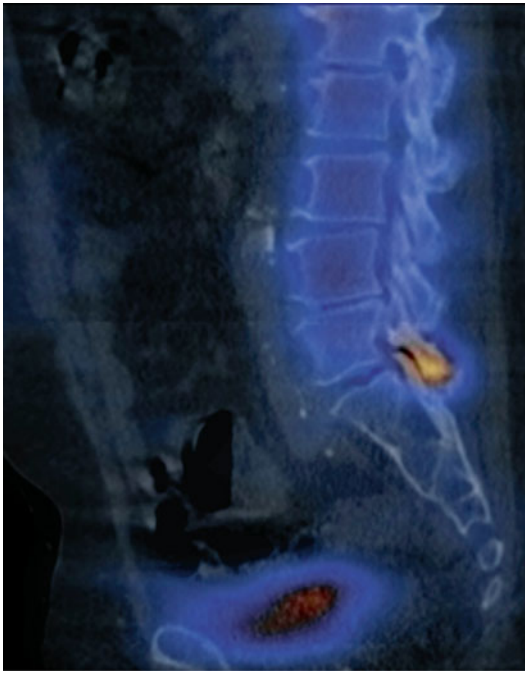

Fig. 12.1 L5 pars fracture. A 66-year-old female with lower back pain. MIP ^{99m}Tc-MDP SPECT/CT image shows the location of the metabolic activity indicating an acute stress reaction of the pars interarticularis without an obvious fracture

SPECT/CT in particular can complement the management of sports-related stress injuries when structural imaging methods, i.e. radiography or computed tomography failed to yield adequate information on their sites and nature of the attributed abnormalities.

Bone stress injuries account for about 10 % of general sports medicine practice (Anshu 2010; Traughber and Havlina 1991). Lower extremity bones are most commonly affected (70–95 %) followed by the spine.

Bone scintigraphy with SPECT/CT has high diagnostic accuracy in localising acute stress reactions and stress fractures involving the posterior elements of the spine (Fig. 12.1). SPECT/CT images confirm a fracture by high metabolic activity at the site of injury and the absence of osteoblastic or osteolytic pathology connote active degenerative osteoarthrosis.

Stress fractures will show a focal abnormal uptake corresponding to the fracture defect seen on the computed tomography (CT) of the fused SPECT/CT. Focal uptake in the pars or pedicle of the lumbar spine, without any morphological abnormality, is consistent with a stress reaction (pre-fracture phase) and ascertains the reason for back pain in an athlete (Anshu 2010).

12.3 Overuse-Related Injuries

Overuse injuries of the spine are more subtle and usually occur over time in a repetitive manner as a result of micro-trauma to the tendons, bones, and joints. “High-risk” overuse injuries render a long period of recovery with significant loss of time from sports participation. These include certain stress fractures, physeal stress injuries, spondylosis, spondylolisthesis, and sacroiliac joint injury/inflammation (Table 12.1).

12.3.1 Fatigue Fracture

Fatigue fractures are also related to the chronic repetitive stress applied to healthy bone (Southam et al. 2010). An example of this is the fatigue fracture of the sacral spine (Fig. 12.2). A vertical concentration of cycling overloading in the sacral bone combined with impaired shock absorption due to associated muscle fatigue has been postulated as a potential mechanism in regard to sacral fatigue fracture pathogenesis (McFarland et al. 1996). High-intensity training or rapid changes in training system are common predisposing factors (Major et al. 2000). Leg length discrepancy, footwear more than 6 months old, poor training surface, nutritional deficiencies, and the female athlete triad have also been implicated as risk factors, among others (Major et al. 2000; McFarland et al. 1996).

This type of fracture causes often an unsuspected and undiagnosed local limb pain in athletes. To ensure early diagnosis when an effective selective treatment is required, bone scintigraphy with SPECT/CT will be a useful tool especially in recognising high bone turnover as signalled by increased MDP metabolic activity.

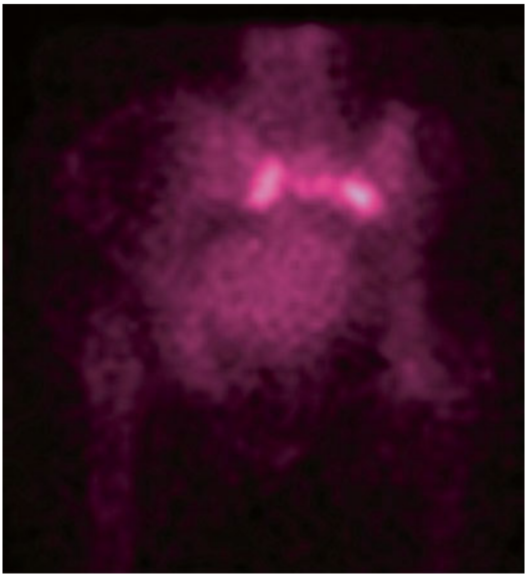

Fig. 12.2 A 62-year-old female with a fatigue fracture of the ala sacrum. Coronal ^{99m}Tc-MDP SPECT/CT image reveals an “H”-shape configuration sign

12.3.2 Spondylosis

Spondylosis is an age-related chronic process defined as the development of vertebral osteophytes, succeeded by osteochondrosis related to disc disease with disc space narrowing and secondary osteoarthritis of the facet joints. Premature spondylotic changes are likely to affect athletes with a history of vigorous load-bearing body stress activities. The more advanced stages of the process may produce a wide range of symptoms related to neuronal conflict of osteophytes or disc protrusion and facet osteoarthritis including pain. The degenerative disc changes include desiccation of the nucleus pulposus, loss of annulus fibrosus elasticity, and narrowing of the disc space with or without disc bulging or protrusion with or without annulus fibrosus rupture. Spondylosis is most often non-symptomatic. Not infrequently, however, these patients will have very few neck symptoms and will present with referred pain patterns: occipital headaches and pain in the shoulder, suboccipital and intrascapular areas, and anterior chest wall.

In certain circumstances, bone scintigraphy with SPECT/CT may have a complementary role to plain radiography and CT in isolating the site of increased bone turnover as signalled by marked uptake of MDP (Fig. 12.3). Spondylolysis has been reported to be the most common cause of lower back pain seen in a sports medicine clinic (Stasinopoulos 2004). It remains the major cause of spondylolisthesis and spine instability. AP and standing lateral lumbar radiographs are supplemented by oblique views. On oblique views the defect is seen as the so-called fracture in the "neck of the Scotty dog". Collier et al. and others reported that SPECT is more sensitive than planar bone scintigraphy in the identification of symptomatic sites in spondylolysis (Collier et al. 1985). SPECT improves the detection of spondylolysis compared to planar bone scintigraphy (Bellah et al. 1991).

For spondylolysis or stress fracture in athletes, bone scintigraphy with SPECT/CT was found more sensitive than lumbar MRI; this is related to the non-visualisation of the pars interarticularis on MRI examinations performed for disc disease (Masci et al. 2006). A SPECT/CT bone scan is also recommended for those cases in which a pars defect is suspected on plain radiographs. It may help to determine if a pars defect seen on X-ray is "hot" and therefore likely to be a cause for the pain. Most frequently, spondylolysis is associated with repetitive microtrauma, occurring in the adolescent during spinal growth. An increased incidence of spondylolysis is seen in adolescent athletes who practice sports with repetitive and excessive hyperextension such as gymnastics, diving, ballet, and soccer (d'Hemecourt et al. 2000, 2002).

12.3.3 Spondylolisthesis

Spondylolisthesis is a spinal condition in which all or a part of a vertebra has slipped forward on another (Fig. 12.4). There are several types of spondylolisthesis, but the most common in sports are stress fractures in the isthmus or pars interarticularis (Seimon 1983). The most common clinical manifestation of

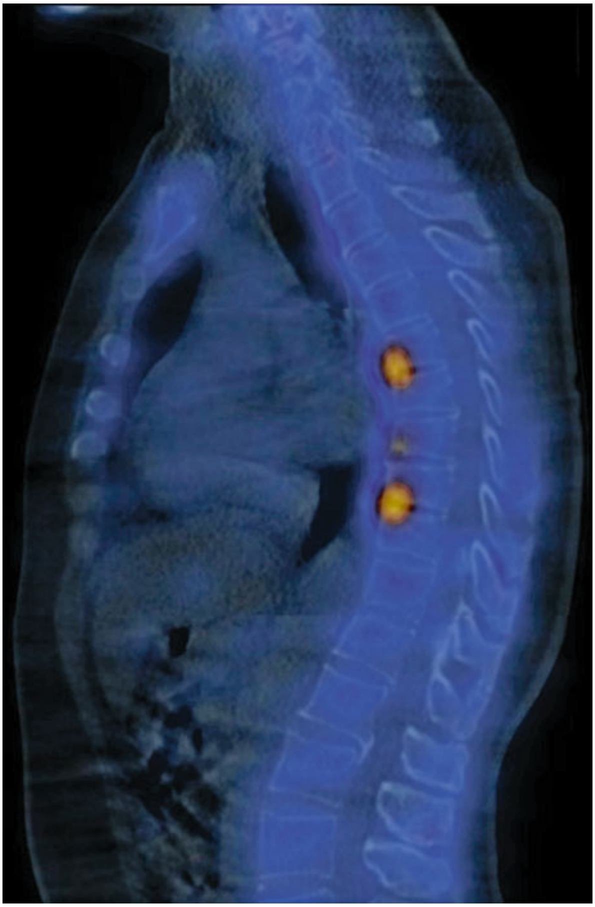

Fig. 12.3 A 29-year-old female with back pain. MIP ^{99m}Tc-MDP SPECT/CT shows increased metabolic activity in the disc plates of the lower thoracic spine with T9 and C10 anterior wedging denoting chronic spondylosis

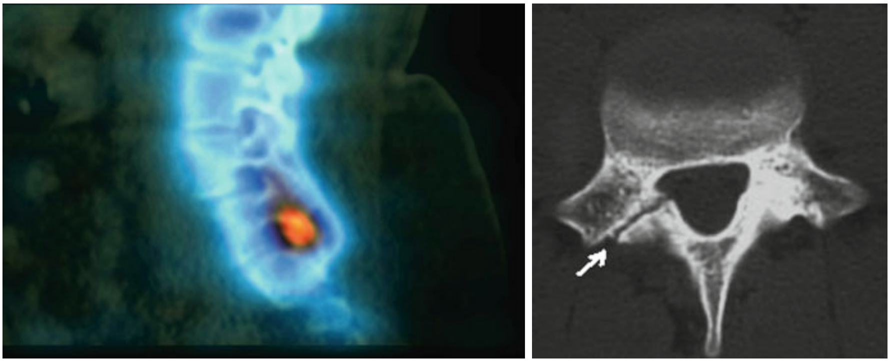

Fig. 12.4 A 46-year-old male with L4–L5 pars interarticularis defect. MIP ^{99m}Tc-MDP SPECT/CT shows increased metabolic activity at the site of a L4–L5 interarticularis fracture resulting in anterolisthesis of L3 on L4 vertebra. The axial CT image confirms presence of the fracture involving the right pars interarticularis (*arrowed*)

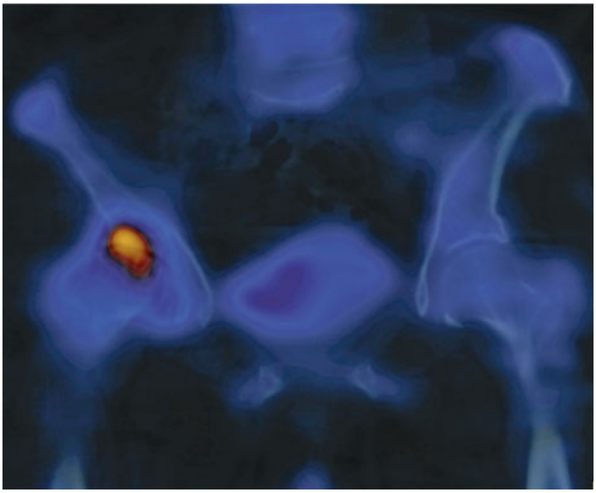

Fig. 12.5 A 44-year-old female with right lower lumbar pain. MIP ^{99m}Tc-MDP SPECT/CT shows increased metabolic uptake of the right hip joint representing osteoarthritis as a cause of referred pain to the lower lumbar region

spondylolisthesis is lower back pain. Although the cause of this type of back pain in the adult has been studied extensively, its origin is still unclear. Bone scintigraphy with SPECT/CT has a role when the acuity of a pars defect is in question and it can be documented within 3 months after the injury; if the defect is longer existing, the scan will become negative.

12.4 Specific Spine Injuries

12.4.1 Acute and Chronic Lumbago

Pain in the lower back in athletes can be caused by a variety of conditions including musculo-ligamentous, osteoarticular, and neurologic disorders. It is a common source of pain in athletes, leading to significant time missed and disability (Petering Ryan and Charles 2011). Undifferentiated lower back pain in the general population is a well-established indication for planar bone scintigraphy (Bombardieri et al. 2006; Kanmaz et al. 1998). SPECT/CT imaging is useful for anatomic and functional evaluation of benign and malignant spine bone diseases, particularly for evaluation of chronic back pain (Schillaci 2005). Mechanical lower back pain accounts for up to 97 % of lower back pain diagnoses in the general population (Kalichman and Hunter 2007; Deyo and Weinstein 2001). A clinical examination of mechanical lower back pain is non-specific and is not able to discriminate vascular, infectious, inflammatory, and neoplastic aetiologies. Lumbar facet joint capsules are richly innervated with autonomic nerve fibres and may become a potential source of pain (Willard 1997). Lower back pain getting worse when sitting may indicate a

Table 12.2 Pain and the potential attributes

Symptoms	Causes
Acute and chronic local pain	Direct trauma, spondylolisthesis, sacral insufficiency fracture, facet joint osteoarthritis
Sciatica	Disc prolapse
Referred pain (Fig. 12.5)	Osteoarthritis of knee or hip joint

herniated lumbar disc. Pain with acute onset may suggest a herniated disc or a muscle strain, as opposed to a more gradual onset of pain, which fits more with osteoarthritis, spinal stenosis, or spondylolisthesis (Table 12.2).

Sports persons who continue to complain of lower back pain for more than 6 weeks should have plain radiographs including oblique views (Logroscino et al. 2001). The vast majority of patients with predominantly lower back pain will have normal plain radiographs. In these patients with suspected clinically bone abnormality, bone scintigraphy with SPECT/CT may be considered as a second-line imaging test (Table 12.3).

The major goal of bone scintigraphy is to establish whether the patient's pain is related to an active bony process. Gates and McDonald argued that a normal bone scan effectively excludes a bony-based lesion (Gates and Mc Donald 1999). When bone pathology is present, nuclear scintigraphy has a proven role in the identification of a number of conditions including facet joint disease or instability, sacroiliac disease, pseudoarthrosis, fracture, and post-operative infection (Table 12.4). In particular, bone scans have the potential to detect active bone remodelling, whereas corresponding radiographs may be normal or document past structural change in the joint (Okamoto 1995). For instance, the sacral insufficiency fracture represents a repetitive, prolonged muscular action on the bone that has not accommodated itself to the action, resulting in stress fractures. The use of SPECT in addition to CT helps determine the cause of lower back pain (Fig. 12.6).

The use of SPECT in bone scanning has improved the sensitivity and location capacity of these lesions by 20–50 % when compared to planar bone scan (Even-Sapir 2005) as is shown in Table 12.3.

Ghormley first coined the concept "facet joint syndrome" in 1933 when discussing alternate sources of lower back pain (Ghormley 1933). Lumbar spine facet joint pain may affect many patients with chronic lower back pain, with a wide estimation between 5 and 90 % (Cohen and Raja 2007). A small study using a computer algorithm to fuse the SPECT and CT data demonstrated an improved ability over SPECT alone in differentiating activity between L4/L5 and L5/S1 facet joints (McDonald 2007).

12.4.2 Cervicalgia and Cervicobrachialgia

Cervical spine strains and sprains frequently occur as a result of a whiplash injury, which often occurs as the result of motor vehicle accidents, falls, sports-related accidents, or other traumatic events that cause a sudden jerk of the head and neck

Table 12.3 Differential diagnosis of lower back pain and diagnostic imaging tools that may be indicated

Evaluation	Back sprain	Disc prolapse	Spinal stenosis	Spondylolisthesis	Spondyloarthropathy	Infection	Tumour	Metabolic
Predominant pain	Back	Leg	Back/leg	Back	Back	Back	Back	Back
Radiography		+	+	+	+	+/−	+/−	+
CT		+	+			+	+	
MRI	+	+	+	+	+	+	+	+
Bone scan with SPECT					+	+	+	+
Bone scan with SPECT/CT	+	+	+	+	+	+	+	+

Table 12.4 Indications of bone scintigraphy with SPECT/CT in spine-related trauma

Negative CT or radiographic results
Focal neurologic deficit
Immunosuppression, diabetes mellitus
Significant cumulative traumata
Duration more than 6 weeks

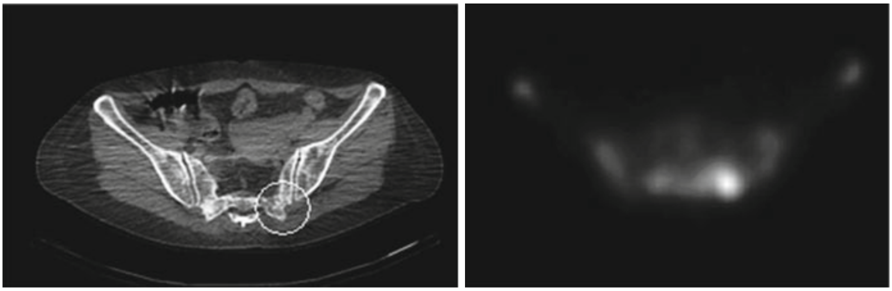

Fig. 12.6 A veteran female athlete with left pelvic pain. There is an old insufficiency fracture seen involving the left ala sacrum (*round white marker*) on the axial CT image. MIP ^{99m}Tc-MDP SPECT image shows slightly increased metabolic activity at the fracture site

(Rodrigo and Leonardo Oliveira 2006). The intensity of athletic competition has led to a large number of injuries that result in neck (cervicalgia) or upper limb pain (cervicobrachialgia), a situation made worse by the heavy backpacks among school-going adolescents and young athletes. Most injuries are a result of muscle strain or physical therapy. In older patients predominant arm pain (brachialgia) is related to mechanical pressure and inflammation of the involved nerve roots which is likely attributed to bone proliferation related to degeneration.

In many conditions, such as suspected infection or suspected acute osteoporotic crush fracture, MRI is the investigation of choice. CT is highly accurate for assessment of bone lesions such as suspected tumours or pars interarticularis defects. Bone scintigraphy with SPECT/CT is useful in distinguishing between abnormalities that are caused by fractures of the pars and other focal areas of increased activity that include facet joint osteoarthritis (Elster 1989).

Bone scintigraphy is also indicated to exclude spinal metastases, when there is a known primary tumour or a suspected pars interarticularis fracture for which changes may be difficult to see on plain radiographs, particularly in young patients with subtle stress fractures (Table 12.5). The majority of patients with non-specific cervicalgia show improvement of symptoms within 12 months. In this group there is value in identifying those in whom the cause is active facet arthropathy, since a corticosteroid injection to the culprit joints can hasten their symptomatic recovery (Fig. 12.7). SPECT/CT imaging is the ideal investigation in this group, given the additive information derived from the combination of functional and structural changes obtained.

Table 12.5 Differential diagnosis of cervicalgia and the diagnostic imaging tools that may be indicated

Evaluation	Neck strain	Degenerative disc disease	Myelopathy	Spondyloarthropathy	Tumour	Metabolic	Infection
Predominant pain	Neck	Neck	Neck	Neck	Neck	Neck	Neck
Radiography		+	+/–	+	+/–	+	+/–
CT		+	+		+		
MRI	+	+	+	+	+	+	+
Bone scan with SPECT				+	+	+/–	+
Bone scan with SPECT/CT	+	+	+	+	+	+	+

Fig. 12.7 A 59-year-old-female with neck pain. MIP ^{99m}Tc-MDP SPECT/CT shows increased metabolic activity of the C7–T1 apophyseal joint – cervical discogenic spondylosis

12.4.3 Intervertebral Disc Injuries and Radiculopathy

Because of excessive weight bearing and stress, athletes sometimes damage an intervertebral disc. A herniated intervertebral disc is defined as the displacement of nucleus pulposus through the torn fibres of the annulus fibrosus. Most disc herniations occur during the third and fourth decades of life while the nucleus pulposus is still gelatinous. The two most common levels are L4–L5 and L5–S1. Not everyone with a disc herniation has significant discomfort.

A large herniation in a capacious canal may not be clinically significant since there is no compression of the neural elements, while a minor protrusion in a small canal may be crippling since there is not enough room to accommodate both the disc and the nerve root. The major interest of nuclear imaging in disc herniation is to enhance the identification of a vital associated cause, i.e. compression vertebral fractures or primary

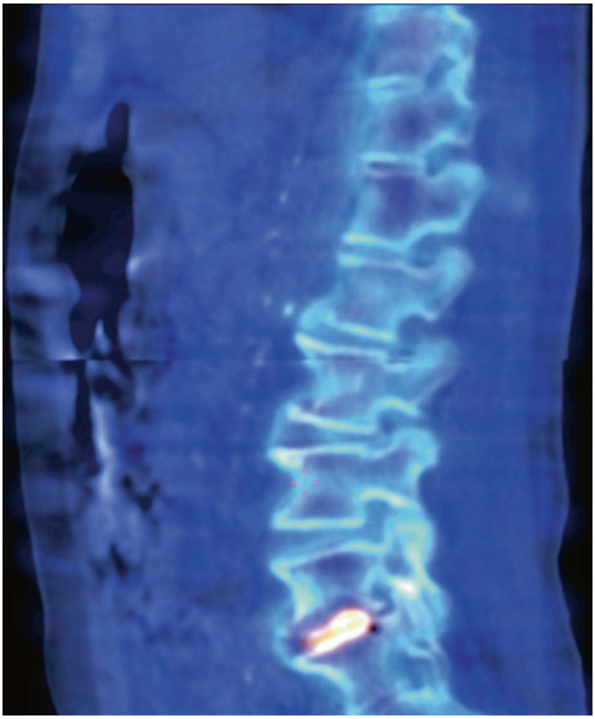

Fig. 12.8 A 37-year-old male with acute lower back pain and sciatica following a mishap in sports activity. MIP ^{99m}Tc-MDP SPECT/CT shows a severely prolapsed L4–L5 disc with increased metabolic activity denoting discitis

disc diseases. In this regard, bone scan is helpful to establish the age of compression fractures (Gates 1998) Bone scan is used if MRI is not available or non-specific. MRI was found helpful in determining which fractures were acute (Park et al. 2013). Indeed particularly challenging in patients with sports injuries is the discrimination of active and old injury or anatomical abnormalities. The information of planar bone scintigraphy may be helpful in managing patients with pain and disability, but nowadays accurate localisation of the involving fractures by means of SPECT/CT is critical because of the advent of vertebroplasty and kyphoplasty (Maynard et al. 2000). The role of SPECT/CT in personalising the treatment for specific pain-related injury attributable to sports are of paramount importance as to avert unnecessary long wasting rehabilitative therapy. In a retrospective study, Maynard et al. (2000) found that increased activity on a bone scan strongly predicted a positive clinical response (i.e. relief of pain) to percutaneous vertebroplasty in osteoporotic vertebral compression fractures.

Although the bone scan can be used to age fractures or stress injuries, only SPECT/CT depicts details of complicated combinations of old and new injuries especially in patients with crippling pain (Fig. 12.8). In a study by Auerbach et al. (2008), negative findings on bone scintigraphy with SPECT were found 100 % predictive of mechanical back pain for children with less than 6 weeks of symptoms regardless of radiological examination finding. Bone scintigraphy with SPECT is a good diagnostic option for early presentation of lower back pain in children (Auerbach et al. 2008).

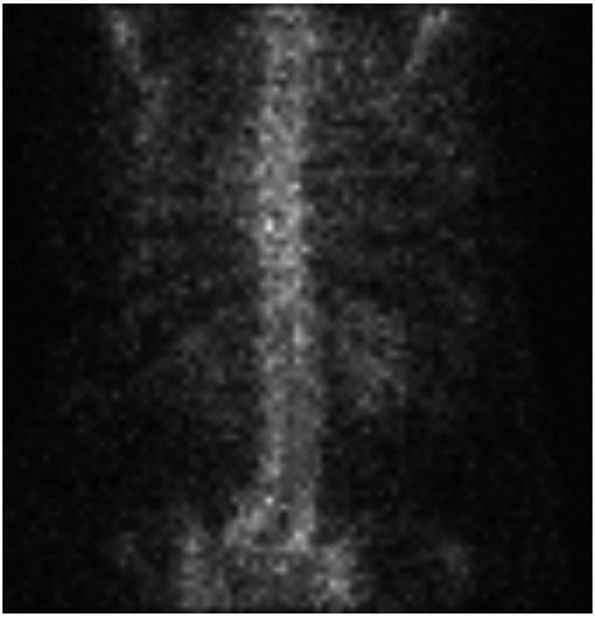

Fig. 12.9 A 28-year-old female with idiopathic scoliosis with pain. MIP ^{99m}Tc-MDP SPECT shows no notable increased metabolic activity to suggest a leading cause for the scoliotic pain

Table 12.6 Common causes of scoliosis and scoliotic spine position

Causes of scoliosis	Aetiology
Primary	Idiopathic
	Congenital
	Scheuermann's disease
Secondary	Tumour, i.e. osteoid osteoma, neurofibromatosis
	Neuromuscular condition, i.e. cerebral palsy
	Degenerative spine disease in elderly
	Infection
Secondary not spine related	Muscle contusion, bowel obstruction, renal stone

12.4.4 Scoliosis

Scoliosis refers to abnormal curvature of the spine, with a lateral component of >10°. Most commonly, scoliosis is idiopathic. Idiopathic scoliosis is classified according to the age of onset with three major groups described: infantile, juvenile, or adolescent (Fig. 12.9). The cause of scoliosis can either be primary or secondary (Table 12.6). Primary causes include congenital defects due to abnormal vertebral segmentation. Traditional imaging tools, i.e. plain radiographs or CT, may be inaccurate in determining the cause of scoliosis. This is important when scoliotic spine position is non-idiopathic and related to problems listed in Table 12.5. In one study, 30 % of children with idiopathic scoliosis had back pain (Ramirez et al. 1997).

Scoliosis may be evident in young athletes, with a prevalence of 2–24 % (Dickson 1999). The highest rates are observed among dancers, gymnasts, and swimmers. The

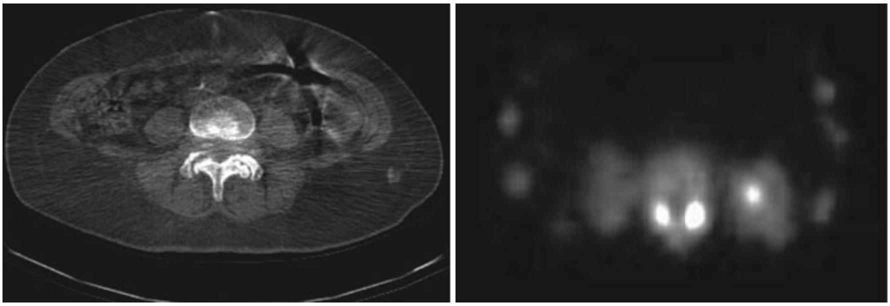

Fig. 12.10 A 57-year-old male with facet joint arthrosis and the resulting scoliosis. Axial CT (*left*) and the correlated MDP SPECT (*right*) image showing facet joint degeneration with increased metabolic uptake

scoliosis may be due in part to loosening of the joints, delay in the onset of puberty (which can lead to weakened bones), and stresses on the growing spine. There have also been isolated reports of a higher risk for scoliosis in young athletes who engage vigorously in sports that put an uneven load on the spine. These include figure skating, dance, tennis, skiing, and javelin throwing, among other sports. In most cases, the scoliosis is minor, and everyday sports do not lead to scoliosis. Exercise has many benefits for people both young and old and may even help patients with scoliosis.

Acute painful scoliosis may indicate the presence of vertebral infection or a tumour such as osteoid osteoma. Bar-Shalom et al. evaluated the role of nuclear medicine by using ^{67}Ga (GS)- or ^{111}In-labelled white blood cells (WBC) and SPECT/CT in the diagnosis and localisation of infections. These techniques improved diagnosis, localisation, and definition of extent of disease (Bar-Shalom et al. 2006). In another study, an improved utility of the SPECT/CT using ^{99m}Tc-HMPAO-labelled leukocytes was shown in patients with suspected osteomyelitis by providing accurate anatomic localisation and precise definition of the extent of infection (Luca and Orazio 2006). Osteoid osteoma of the spine must be considered when backache is associated with muscle spasm and scoliosis. Bone scintigraphy with SPECT/CT provides information about the metabolic activity of the bone and surrounding tissue and for the evaluation of back pain in particular as an attribute to scoliosis (Fig. 12.10).

12.4.5 M. Scheuermann

The adolescent athlete may also suffer from lower back pain that is caused by growth-related problems such as scoliosis and Scheuermann's kyphosis. These problems may or may not be related to sports activity, but they can affect an athlete's ability to perform up to his or her standards. Juvenile kyphosis known as Scheuermann's disease has no clear aetiology. The prevalence of back pain in children and adolescents varies widely from 12 to 50 %. Jones et al. reported an average lifetime prevalence of back pain of 40.2 % in 500 children between 10 and 16 years of age (Jones et al. 2004). Back pain in children occurs less frequently than in adults. The incidence of back pain in adults with M. Scheuermann has been

Table 12.7 Radiological characteristics and diagnostic criteria for Scheuermann's disease

Radiological characteristics
Anterior vertebral body wedging
Endplate irregularity
Disc space narrowing
Schmorl's nodes
Diagnostic criteria
Hyperkyphosis 94°
Wedging 95° in three or more consecutive vertebral bodies
Irregular endplates
Disc space narrowing

estimated to be as high as 60–80 % (Kelsey and White 1980); the actual incidence of back pain in children, however, is unknown. Neurologic complications secondary to Scheuermann's disease are rare but have been reported (Bradford and Garica 1969).

Differentiation between Scheuermann's disease and postural kyphosis is facilitated by viewing the patient, in the forward flexed position, from the side. Patients with postural kyphosis have a smooth, rounded curve, which reverses on voluntary extension. A variant of type II lumbar Scheuermann's is known as "acute traumatic intraosseous disc herniation". This is characterised by a history of a traumatic event, i.e. a fall. These patients will experience severe pain after their injury and can pinpoint when their symptoms began (Bowles and King 2004).

No definitive aetiology has been identified; one accepted cause for Scheuermann's kyphosis is repeated or acute trauma of the immature spine, as is seen with adolescent athletes performing gymnastics (Hollingworth 1996). The typical deformity of Scheuermann's kyphosis involves a sharp, angular gibbus that does not correct on extension of the spine. Other radiological criteria for the diagnosis of Scheuermann's kyphosis include irregular upper and lower endplates with Schmorl's nodes, disc-height loss, and associated apophyseal ring fractures (Table 12.7).

Bone scintigraphy findings are generally not pathognomonic, appearing as subtle increases in isotope uptake at the sites involved by the disease (Holt et al. 1997). MRI may be helpful to rule out discitis if this is the concern. In addition, MRI will further evaluate Schmorl's nodes and disc prolapse beneath the vertebral apophyses (Khoury et al. 2006) (Fig. 12.11).

12.4.6 Spinal Stenosis and Intervertebral Disc Injuries

Cervical stenosis is prevalent in athletes and has been reported in a 2011 study published in the medical journal "Neurosurgical Focus". (Aaron et al. 2011) The condition is serious as it poses risks of developing more severe spinal conditions in the future.

These patients usually have symptoms secondary to mechanical pressure and inflammation of the nerve roots that originate in the back and extend down the leg. The aetiology of the mechanical pressure can be soft tissue-herniated disc, bone protrusions, or a combination of these two. The diagnosis of spinal stenosis usually can

Fig. 12.11 A 9-year-old girl with back pain. Sagittal T2-weighted MRI showing multi-levels of lumbar disc prolapses and Schmorl's nodules (*white arrows*) with abnormal paradiscal disc plate suggestive of atypical Scheuermann's disease (Image courtesy of the Lourdes Medical Centre)

be settled by plain X-ray which will demonstrate facet degeneration, disc degeneration, and decreased interpedicular and sagittal canal diameter (Greenberg 1997). The anteroposterior (AP) diameter of the normal adult male cervical canal has a mean value of 17–18 mm at vertebral levels C3–C5. The lower cervical canal measures 12–14 mm. Cervical stenosis is associated with an AP diameter of less than 10 mm, whereas diameters of 10–13 mm are relatively stenotic in the upper cervical region.

The thoracic spinal canal varies from 12 to 14 mm in diameter in the adult. Primary central thoracic spinal stenosis is rare. Occasionally, hypertrophy or ossification of the posterior longitudinal ligament results in central canal stenosis. Lateral thoracic stenosis may result from hypertrophy of facet joints with occasional synovial cyst encroachment. The diameter of the normal lumbar spinal canal varies from 15 to 27 mm. Lumbar stenosis results from a spinal canal diameter of less than 12 mm in some patients; a diameter of 10 mm is definitely stenotic.

Table 12.8 Spinal stenosis and the related anatomy of the surrounding structures compromise

Posterior compartment	Lateral recess	Pars region	Intervertebral foramen
Contents	Lumbar nerve root	Dorsal root ganglia Ventral motor root	Spinal nerve
Potential cause	Hypertrophic facet joints (SAP)	Osteophytes under the pars	Hypertrophic facet joints (SAP)
Affected nerve root	Same as the vertebrae (L3 SAP involve L3 roots)	Same as the vertebrae (L3 pars involve L3 roots)	One level up from the vertebrae (L4 SAP or L3–L4 disc involve L3 roots)

Note: *SAP* superior articular facet

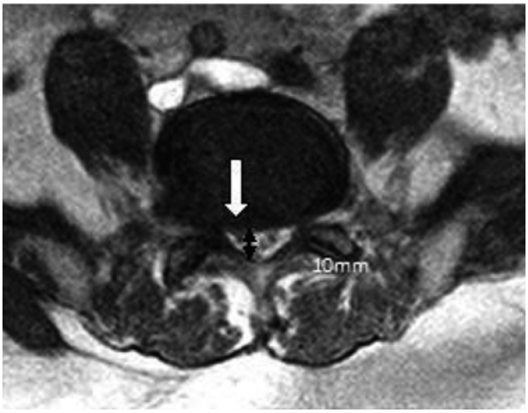

Fig. 12.12 A 46-year-old male with sciatica. Axial T2-weighted MRI at L4–L5 level showing stenotic spinal column caused by a diffuse disc bulge (*white arrow*) with adjoining exiting neural foramina impingement. The remaining spinal canal diameter (*double-sided arrow*) being 10 mm (Image courtesy of the Lourdes Medical Centre)

Pain and neurologic deficits are related to the degree of stenosis which compromise the respective nerve root at the respective lumbar levels (Table 12.8).

Spinal MRI is the most universally suitable technique for the diagnosis of spinal stenosis (Fig. 12.12). SPECT bone scintigraphy is sensitive to diseases that actively affect bone pathophysiology, but spatial resolution is limited (Fig. 12.13).

12.4.7 Vertebral Body Fractures

Vertebral fractures of the thoracic and lumbar spine are usually associated with major trauma and can cause spinal cord damage that result in neural deficits. Major causes of these fractures include trauma related to motor vehicle accidents or sports. Thoracolumbar fractures are more common in older children and adolescents, while cervical fractures are more common in younger children. In athletes, acute fractures of the thoracolumbar spine are rare (Curtis and d'Hemecourt 2007). Thoracolumbar pain is a frequent complaint of many athletes, but the cause is often uncertain. Compression fractures of the spine are rarely seen in athletics and are not always recognised as a potential cause of the symptoms (Vicki et al. 1995).

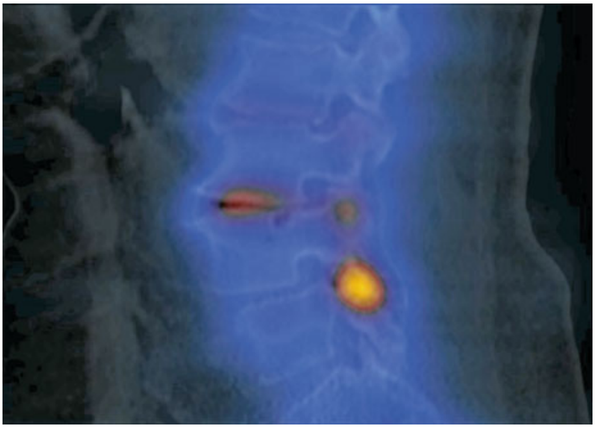

Fig. 12.13 A 37-year-old female with spinal stenosis secondary to spondylolisthesis. MIP ^{99m}Tc-MDP SPECT/CT shows increased metabolic activity involving the L4–L5 pars interarticularis fracture

Radiographs are useful to assess the degree of compression of the vertebral body. Compression of less than 25 % indicates stability, with a single anterior column involvement. CT is the major imaging tool to stage traumatic spine fractures. MRI is often used, but cannot be performed in some patients and is non-specific in others. With CT or MRI, compression fracture can be distinguished from severe degenerative disease, both of which show increased uptake on bone scintigraphy.

Bone scintigraphy with SPECT/CT in patients with acute back pain and a history of compression fractures is helpful in locating the acute injury site (Fig. 12.14). Furthermore, SPECT/CT allows discrimination of the osteonecrotic core from nearby hyperactivity due to viable bone if the primary cause of concern was an infection or malignancy. In this regard, MRI is not able to visualise bone destruction, but proved helpful to detect soft tissue involvement (Dore et al. 2009).

Thoracolumbar compression fractures of less than 25 %, without neurologic symptoms, are not associated with posterior instability. Posterior instability, however, becomes a concern as the compression approaches 50 % (Keane 1987). Collins et al. demonstrated that bone scintigraphy with SPECT/CT provides additional information compared to SPECT alone in up to 62.5 % of cases of perioperative evaluation of vertebral compression fractures, resulting in significant changes in the final assessment (Collins et al. 2004; Punit et al 2013).

12.4.8 Ankylosis Spondylitis

Ankylosing spondylitis, also known as Bechterew's disease, is a chronic inflammatory seronegative type disease of the axial skeleton. It is a subtype of spondyloarthritis and could also be the outcome of spondyloarthritis. It mainly affects joints in the spine and in the sacroiliac joint. The clinical diagnosis of early sacroiliitis, the most frequent clinical symptom often accompanied by inflammatory back pain, is often difficult because of the deep location and lack of motion.

The most common cause of this is inflammation of the sacroiliac joint – sacroiliitis. Early diagnosis of sacroiliitis of the spine on MRI is important as it ensures

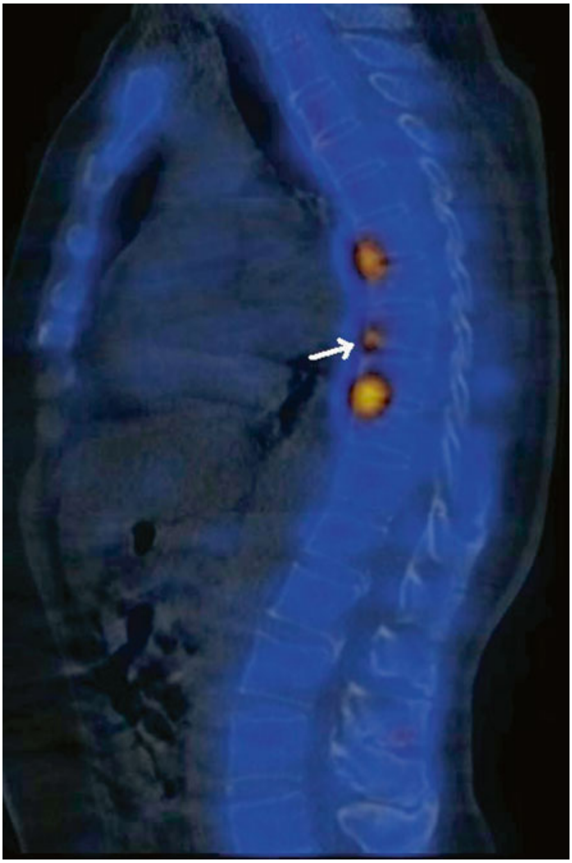

Fig. 12.14 A 37-year-old athletic female with compression fracture of T-11 vertebra. Sagittal MIP ^{99m}Tc-MDP SPECT/CT shows vertebral height compression with increased activity denoting an increased metabolic turnover in the fractured vertebra (*arrow*)

the sustainability of the performing athletes in their future endurance. Early diagnosis of sacroiliitis and other inflammatory lesions of the spine, i.e. spondylitis, can be detected by MRI. CT may not be accurate in assessing early sacroiliitis before the manifestation of erosions and other overt changes or in evaluating disease activity in cases with advanced sacroilitis. The role of bone scintigraphy in the evaluation of sacroilitis is controversial. At least three-phase bone scintigraphy is obligatory. However, the uptake can also be related to other skeletal problems. The disparity in opinion on the clinical utility of bone scintigraphy may partly be due to technical problems associated with increased accumulation of radiopharmaceutical at normal bone sites in close proximity to the sacroiliac joints. In one study, it is suggested that ^{99m}Tc MDP scanning is a useful primary investigation for the detection of spinal pseudarthrosis in patients with chronic ankylosing spondylitis who suffer late-onset back pain (Park et al. 1981).

SPECT/CT scanning overcomes these difficulties by improving the localisation in and around the sacroiliac joints. SPECT/CT scanning is superior to planar scintigraphy in distinguishing between inflammatory and mechanical causes of symptoms of sacroiliitis (Hanly et al. 1994) (Fig. 12.15). The sensitivity and specificity

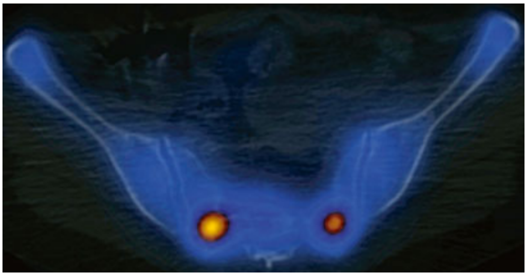

Fig. 12.15 A 68-year-old female with sacroiliitis. MIP ^{99m}Tc-MDP SPECT/CT shows increased metabolic activity involving both posterior sacroiliac joints

of MRI for the detection of sacroilitis were reported to be 54 and 67 %, respectively. For bone scintigraphy with SPECT, this was 38 and 100 %, respectively (Hanly et al. 1994). However, these results were published before the era of the hybrid camera imaging.

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Part IV

The Musculoskeletal System Topographically: Chest

Chest Injuries

13

M.C. de Bruijn

Contents

Abstract

Chest pain is a common complaint in athletes and has a number of possible underlying causes. Although chest pain in athletes is most often caused by the musculoskeletal system, pain may originate from organs within the thoracic cage, such as the heart, lungs, or esophagus. Musculoskeletal chest injuries in athletes can be caused by direct trauma to the chest or arise from extreme or repetitive forces that occur through the structures comprising the thoracic cage during sports. Overuse injuries may affect the ribs, sternum, joints, and muscles of the chest wall. Referred pain from the thoracic spine may also be perceived as chest pain. This chapter focuses on functional anatomy, injury mechanisms, and clinical description of specific sports-related injuries of the chest wall.

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Rib and sternal fractures are common traumatic chest injuries in athletes, caused by a direct blow. Elbows and other body parts may cause a hard-enough strike, as may bats, sticks, or projectiles. Overuse injuries of the chest wall, such as stress fractures of the ribs, are caused by repetitive forces of contracting muscles due to rowing or playing golf and may be harder to diagnose. Tietze's syndrome and costochondritis, conditions of unknown etiology, may also occur in athletes and may be difficult to assess.

13.1 Introduction

Chest pain is a common complaint in athletes and has a number of possible underlying causes. However, exact numbers on the general incidence of chest injuries are not available in sports medicine literature. Although chest pain in athletes is most often caused by musculoskeletal causes, pain may originate from structures within the thorax, such as the heart, lungs, or esophagus. Cardiac disease must be considered especially when associated symptoms as shortness of breath and palpitations occur or when there is a family history of cardiac disease. The differential diagnosis should include peptic ulceration, gastroesophageal reflux, infection, and malignancies.

Musculoskeletal chest injuries in athletes can be caused by direct trauma to the chest or may arise from extreme and repetitive forces that occur through the structures comprising the thoracic cage during sports. Overuse injuries may affect bones, joints, and muscles of the chest wall.

Referred pain from the thoracic or cervical spine is also a common cause of chest pain. Because of their developmental origin, the intercostal nerves, supplying the chest wall, may refer pain to the chest from cervical structures. Visceral structures may also refer pain to the anterior chest wall, as can posterior structures, such as the vertebrae. This chapter focuses on conditions arising from the chest wall itself. In any case of chest injury, it is important to rule out any possible associated injury to the intrathoracic organs.

13.2 Functional Anatomy

The chest is the part of the body between the neck and abdomen. The chest wall consists of 12 paired ribs, 7 of which attach anteriorly to the sternum, via the costochondral cartilage (Fig. 13.1). These "true" ribs allow movement during in- and exhaling due to their elasticity. The 8th through 10th "false" ribs articulate with each other by the costochondral cartilage. The 11th and 12th ribs form no articulations anteriorly and remain unattached or "floating." The intercostal spaces contain the internal and external intercostal muscles and the neurovascular bundle. Posteriorly, the 2nd through 10th ribs attach to the vertebral bodies and transverse processes of the two adjacent vertebrae by the costovertebral and costotransverse

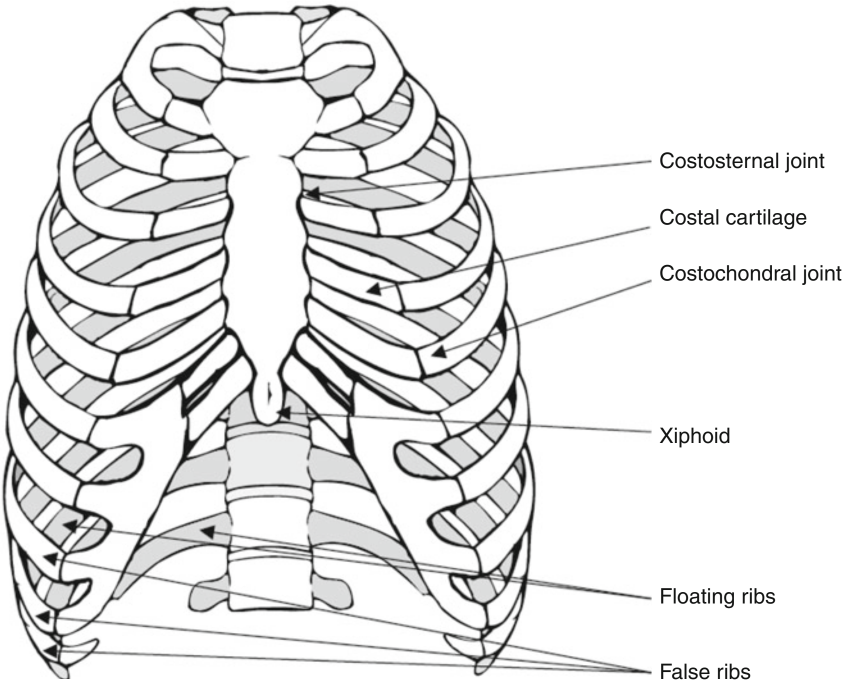

Fig. 13.1 Anatomy of the thoracic wall (Illustration from Gregory et al. (2002) © Adis, Springer)

joints. The remaining ribs articulate with only one vertebra. Anteriorly, the sternum has a sternal body, a sternal manubrium, which is the upper part of the sternum, and a xiphoid process, which attaches to the lower part of the sternum by fibrocartilage. The chest wall has both a structural and a functional role. It functions as a protective cage around vital organs as the heart, lungs, esophagus, and liver and provides a flexible skeletal framework to stabilize movement of the shoulders and arms and to promote respiratory movement, together with the contraction of the diaphragm (Brukner and Khan 2012; Clemens et al. 2011; Gregory et al. 2002).

13.3 Injuries

13.3.1 Rib Contusions and Fractures

A direct trauma to the chest during sports participation may result in an injury to the ribs. The consequence may range from bruising or a rib contusion to a (un)displaced rib fracture. A rib fracture is a common sports injury in contact sports and is regularly caused by a fast and intense blow directly to the chest. Elbows and other body parts may cause a hard-enough strike, as may sports attributes as bats, sticks, or projectiles. Traumatic fractures of the first and second ribs suggest a very significant transfer of energy with the trauma and are associated with secondary injury to underlying neurovascular structures.

Following the direct trauma of motion that lead to the fracture, athletes will notice a sharp pain in the affected region. This pain can be aggravated by deep breathing, coughing, sneezing, or squeezing. Breathing symptoms may lead to quick, shallow breaths to avoid complaints. Examination reveals local tenderness over one or more ribs and with compression of the thorax. The area surrounding the injury may be bruised. Respiratory examination can be used to exclude pneumothorax.

When rib fractures occur, a constant alertness to the possibility of serious complications is needed, since there is a possible risk of pneumothorax or, rarely, a hemopneumothorax and trauma to other underlying structures (Brukner and Khan 2012; Gregory et al. 2002).

13.3.2 Rib Stress Fracture

Most reports of stress fractures of the ribs in athletes concern the first rib. First-rib stress fractures are most often seen in overhead athletes. Baseball, basketball, or tennis players and weightlifters are typically at risk (Aitken and Lincoln 1939; Brooke 1959; Gregory et al. 2002). Repetitive contraction of the anterior scalenus muscle causes bending stress on the subclavian sulcus, which is the most common area of first-rib stress fractures to occur (Gupta et al. 1997). Repetitive traction on the arm with a contracted scalenus muscle may have the same etiological effect; training mistakes may also contribute to the emergence of stress fractures (Bailey 1985; Brooke 1959; Lankenner and Micheli 1985).

Athletes with a stress fracture of the first rib will feel pain around the shoulder, the top of the scapula, or front of the neck, with possible radiation to the sternum and pectoral region. The onset is most often insidious, although acute onset also has been reported in cases (Gregory et al. 2002; Mamanee et al. 1999). Examination reveals tenderness medial to the superior angle of the scapula, at the root of the neck, at the supraclavicular triangle, or deep in the axilla (Bailey 1985; Gregory et al. 2002; Gurtler et al. 1985; Mintz et al. 1990). Shoulder movements may be restricted and painful.

Rib stress fractures to other ribs are less common and most often seen in high-level rowers or novice golf players (Bojanic and Desnica 1998; Christiansen and Kanstrup 1997; Holden and Jackson 1985; Lord et al. 1996). Among elite rowers incidences of 8.1–16.1 % were reported, while amateur rowers have a lower reported risk (McDonnell et al. 2011). In novice golf players, a poor technique or sudden increase in training load is thought to produce stress fractures (Gregory et al. 2002).

The injury mechanism of rib stress fractures in rowers is multifactorial, with intrinsic and extrinsic risk factors contributing to the emergence. A recent review suggests that the posterior-directed resultant forces from the combined oar handle force and scapula retractors during mid-drive or repetitive stress from the external oblique muscles and rectus abdominis muscle may result in stress fractures

(McDonnell et al. 2011). Another hypothesis is that stress fractures are caused by co-contraction of the serratus anterior muscle and external oblique muscles. The serratus anterior muscle inserts on the anterolateral end of the 1st to 9th ribs, interweaving with the external oblique muscles. With these muscles contracting together, a downward bending stress is subjected to the ribs, mostly at the posterolateral angle, which may result in a stress fracture (Gregory et al. 2002; Lord et al. 1996; McDonnell et al. 2011). Case reports have shown increased risk of rib stress fractures associated with amenorrhea, low bone mineral density, or poor technique, in combination with errors in building training load or volume and technique (Gregory et al. 2002; Karlson 1998; McDonnell et al. 2011; McKenzie 1989). Other possible etiological factors could be joint hypomobility, vertebral malalignment, and lack of strength or flexibility (Bojanic and Desnica 1998; Christiansen and Kanstrup 1997; Holden and Jackson 1985; McDonnell et al. 2011).

Symptoms of rib stress fractures include generalized rib pain most commonly in the lateral chest region that increases with specific activity (Hickey et al. 1997; Warden et al. 2002). The pain gets worse with activity and better with rest and may be worsened by deep breaths, coughing, using the arm overhead, or due to pressure on the affected region by lying in lateral position. Physical examination reveals tenderness directly over the affected rib and sometimes with compression of the thorax.

13.3.3 Fracture of the Sternum

Fractures of the sternum mostly result from a direct high-energy trauma in vehicle accidents, when the chest strikes the steering wheel or the dashboard. A small number of traumatic sternal fractures are caused by direct blows received during sports activities as rugby, American football, hockey, or soccer (Culp et al. 2010). The sternal fractures in this group are often accompanied by rib or spine fractures. Intrathoracic organ injury should be ruled out (Jones and Matthews 1988; Robertsen et al. 1996).

Stress fractures of the sternum occur in a minority of cases (0.5 % of sternal fractures) (Buckman et al. 1987) and have a distinctly different pathogenesis. This rare condition may result from extreme upper body stresses, such as in wrestling (Keating 1987), or due to repetitive hyperflexion of the thorax, as in performing prolonged, strenuous "sit-up" exercises (Robertsen et al. 1996). Sternal stress fractures have also been reported in military recruits performing triceps dips and in a golf player (Barbaix 1996; Hill et al. 1997). Sternal insufficiency fractures occur in patients with risk factors for decreased bone density, such as osteoporosis, and in postmenopausal women. Sternal insufficiency fractures should therefore be considered in the differential diagnosis of chest pain in female athletes at risk for the female athlete triad (eating disorders, amenorrhea/oligomenorrhea, and decreased bone mineral density) (Horikawa et al. 2007; Huang et al. 2012).

The athlete suffering a sternal stress (fatigue and insufficiency) fracture complains of anterior chest pain, usually aggravated by movement and deep breathing.

The onset of complaints may be gradual or sudden. History may reveal a sudden increase in upper body or abdominal training. On physical examination tenderness over the sternum or manubrium on palpation is found, sometimes accompanied by local swelling.

The etiology of sternal stress fractures has not been completely elucidated. Repetitive traction of surrounding muscles is thought to play an important role. The sternocleidomastoid muscle and the pectoralis major are attached anteriorly to the manubrium and sternum, the sternohyoid and sternothyroid muscles are attached to the posterior surface, and the rectus abdominis muscle is attached to the distal end of the sternum. Repetitive traction of these muscles may transmit forces on to the sternum, which eventually exceed the elasticity of the bone resulting in a stress fracture (Gregory et al. 2002).

13.3.4 Sternoclavicular Joint Disorders

The sternoclavicular joint is a diarthrodial, saddle-type joint. It is the only true articulation between the clavicle of the upper extremity and the axial skeleton via the sternum (Spencer et al. 2007). The articular surface of the medial clavicle is significantly larger than the sternal articular surface; less than half of the medial clavicular surface articulates with the upper angle of the sternum. Both articular surfaces in the sternoclavicular joint are covered with fibrocartilage, and between these surfaces an articular disk is interposed. Because of its anatomy, the sternoclavicular joint is characterized by the least bony stability of all major joints in the body (Brukner and Khan 2012; Spencer et al. 2007). The integrity of the joint is provided by the surrounding ligaments: the intra-articular disk ligament, costoclavicular ligament, capsular ligaments, and interclavicular ligament (Fig. 13.2). As a result of this strong stabilization, a large energy vector is required to disrupt the articulation (Martetschläger et al. 2013). Injuries to the sternoclavicular joint in athletes are consequently very rare. The incidence of sternoclavicular injuries in the normal population, based on a report of 1,603 injuries around the shoulder girdle, was 3 % (Bontempo and Mazzocca 2010; Rowe and Marble 1958; Spencer et al. 2007).

Although spontaneous subluxations have been reported, injuries to the sternoclavicular are often caused by a direct trauma or, more commonly, indirectly from a trauma to the shoulder. The most common cause of traumatic subluxations or dislocations of the sternoclavicular joint is traffic accidents. Injuries caused by participation in contact sports are less common (Asplund and Pollard 2004; Marker and Klareskov 1996; Pearsall and Russell 2000; Perron 2003). Simultaneous injuries of the acromioclavicular and sternoclavicular joints are common (Brukner and Khan 2012). Traumatic injuries of the sternoclavicular joint can be divided into mild sprain, moderate sprain (subluxation), or severe sprain (dislocation) and fractures of the medial clavicle physeal growth plate in adolescents and young adults. In a mild sprain the ligaments are intact and the joint remains stable. In a moderate sprain the joint capsule and ligaments may be partially ruptured along with subluxation of the sternoclavicular joint. In a severe sprain there is a disruption of the sternoclavicular

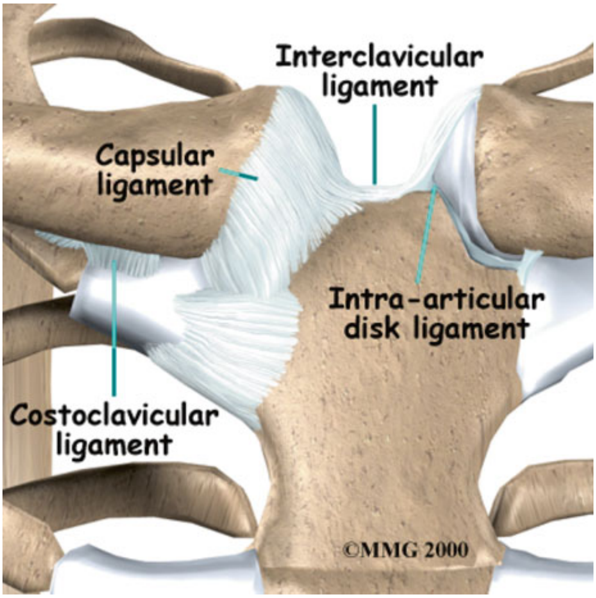

Fig. 13.2 Ligamentous anatomy surrounding the sternoclavicular joint. Courtesy: Medical Multimedia Group LLC

ligaments, caused by dislocation. The majority of the displacements occur in an anterior or posterior direction (Brukner and Khan 2012; Spencer et al. 2007). Anterior displacements are more common; posterior displacements are potentially more dangerous because of the closed proximity of vital structures posterior to the joint, including the subclavian artery and veins, the trachea and esophagus, and the mediastinum (Brukner and Khan 2012).

Subluxation or dislocation of the sternoclavicular joint is also seen without any history of trauma. The vast majority of spontaneous or atraumatic dislocations are anterior. Spontaneous subluxations and dislocations occurring when the patient raises the arms to the overhead position are mostly associated with generalized ligamentous laxity (Spencer et al. 2007).

Another cause of complaints to the sternoclavicular joint is osteoarthritis, for which postmenopausal women, patients with chronic instability, and manual laborers are at a higher risk. Although primary degenerative osteoarthritis of the sternoclavicular joint is common after capsular or ligamentous injuries, moderate to severe changes of the joint were also found in 50 % of individuals aged over 60 years in a postmortem study. It is unknown whether these changes were posttraumatic in nature or resulted from aging (Iannotti and Williams 1999; Martetschläger et al. 2013).

In the assessment of sternoclavicular dislocations beneath 25 years of age, a fracture through the physeal plate should be considered as cause, because the medial clavicular epiphysis is the last epiphysis in the body to ossify (around the 18th to 20th year of life) and fuse (during the 23rd to 25th year) (Brukner and Khan 2012; Franck et al. 2003; Leighton et al. 1989; Lewonowski and Bassett 1992; Sferopoulos 2003; Spencer et al. 2007; Yang et al. 1996; Zaslav et al. 1989).

Depending on the severity of the injury, patients with sprain and displacement of the sternoclavicular joint present with a sharp local pain (particularly with movements of the arm) and swelling. Patients with posterior dislocations have more pain than in an anterior dislocation. The athlete usually supports the injured arm across the trunk with the normal arm. Examination reveals local tenderness with palpation and when the shoulders are pressed together by lateral pressure. In a posterior dislocation the medial end of the clavicle is less prominent and visible and palpable when compared with the normal side. Damage to the underlying vital structures should be considered when a posterior dislocation is suspected (Brukner and Khan 2012; Spencer et al. 2007).

In chronic symptoms of the sternoclavicular joint, Tietze's syndrome, aseptic necrosis of the medial end of the clavicle (Friedrich's disease), SAPHO syndrome, condensing osteitis, and sternocostoclavicular hyperostosis should also be considered (Martetschläger et al. 2013; Spencer et al. 2007).

13.3.5 Costochondritis

Costochondritis is a common but poorly understood condition in athletes (Gregory et al. 2002). It is characterized by pain and tenderness on the costochondral and chondrosternal joints between the sternum and the ribs over one or several segments. Mostly, the 2nd to 5th ribs are involved (Gregory et al. 2002; Grindstaff et al. 2010; Malghem et al. 2001). Costochondritis is considered to be a benign, self-limiting condition, allowing athletes to participate in sports as symptoms allow it. Tietze's syndrome is thought to be a painful inflammation of a single costochondral joint, associated with local swelling, heat, and erythema (Malghem et al. 2001; Mendelson et al. 1997). Tietze's syndrome may be related to seronegative inflammatory disease and may affect the sternoclavicular joint as well (Brukner and Khan 2012). Whether costochondritis and Tietze's syndrome are two separate conditions or maybe have the same underlying pathogenesis remains unclear.

The diagnosis of costochondritis is generally based on clinical findings. There is a history of anterior chest pain, aggravated by activities. Physical examination reveals associated local tenderness on the costochondral or chondrosternal joints of one or more ribs (Malghem et al. 2001; Mendelson et al. 1997). The pain can sometimes be provoked by specific movements such as repetitive arm adduction on the affected side with accompanying rotation of the head to the same side (Fam and Smythe 1985). It is important to distinguish costochondritis from more severe causes of chest pain. Sometimes, additional tests are needed to rule out heart and lung problems.

The exact incidence of costochondritis in athletes is not known. A prevalence of 30 % has been reported among patients presenting with chest pain in the emergency department (Disla et al. 1994). The exact pathogenesis remains also unclear, but several hypotheses have been suggested in literature. Inflammatory conditions are often described as a cause (Disla et al. 1994), supported by reports of positive gallium scans in patients with costochondritis (Ikehira et al. 1999; Miller 1980). There is little

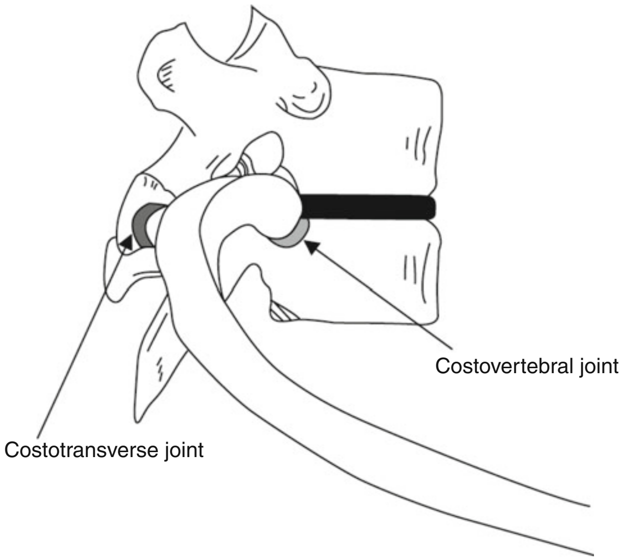

Fig. 13.3 Articulations of a rib with the vertebrae (Illustration from Gregory et al. 2002 © Adis, Springer)

evidence to support the role of infection (Gregory et al. 2002). Another suggestion is neurogenic inflammation or traumatic origin. Pathological abnormalities have not been described however (Fam and Smythe 1985; Ian Rabey 2008). Pull of surrounding musculature and by hypomobility of posterior spinal structures may also lead to costochondritis (Fam and Smythe 1985; Jenkins 1952; Lorentzen and Movin 1976).

13.3.6 Costovertebral and Costotransverse Joint Disorders

Disorders of the costovertebral and costotransverse joints, the joints where the ribs articulate with the vertebrae (Fig. 13.3), include sprains, degenerative changes, and seronegative inflammatory spondyloarthropathies (such as ankylosing spondylitis). Costovertebral and costotransverse joint complaints in athletes, caused by malalignment, are usually amenable to mobilization or manipulation. Costovertebral subluxations have been associated with rowing and butterfly swimming (Thomas 1988). The subluxations may be caused by the forces imposed by the serratus anterior muscle to the ribs to which it attaches during the recovery phase of the rowing or swimming stroke (Gregory et al. 2002).

Costovertebral joint problems usually cause back pain, and the pain may refer to the lateral or anterior chest wall. Complaints may increase by deep inspiration and active movement, as the ribs rotate in a predictable pattern relative of thoracic motion. In physical examination, there is localized tenderness to palpation of the thoracic spine, and there may be restricted mobility of the joints (Brukner and Khan 2012; Gregory et al. 2002; Thomas 1988).

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Radiologic Imaging of Chest Injuries

14

Anouk Marinke Barendregt and Mario Maas

Contents

Abstract

Chest pain is seldom a complaint of athletes. However sports injuries to the chest can be painful and life-threatening. Therefore it is important to choose the most reliable imaging modality to support the clinical diagnosis in the athlete with chest pain. In this chapter the role of radiology in various sports-related chest injuries is described, from the rarely described (but commonly diagnosed) costochondritis and sternal fractures to the more common rib fractures. The chest injury itself will be addressed first and then followed by the appropriate imaging modality and radiologic findings and characteristics. Traumatic as well as overuse injuries to the chest will be discussed. Emphasis will also be placed on ruling out any life-threatening complications by selecting the right imaging modality.

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Abbreviations

ALARA	As low as reasonably achievable
AP	Anterior-to-posterior direction
CT	Computed tomography
ECG	Electrocardiogram
FAT SAT	Fat saturation
IOC	International Olympic Committee
MRI	Magnetic resonance imaging
PA	Posterior-to-anterior direction
PTX	Pneumothorax
SC	Sternoclavicular
STIR	Short-tau inversion recovery
TSE	Turbo spin echo
US	Ultrasound/ultrasonography

14.1 Costochondritis and Tietze's Syndrome

Costochondritis is a benign, self-limiting but painful syndrome of the costochondral cartilage at the costochondral junctions or costosternal joints, mostly at ribs II to V. Deep breathing, coughing or physical exercise can excite the pain. Palpation of the costochondral junction is painful. In 90 % of patients it involves more than one costochondral joint (Proulx and Zryd 2009). Costochondritis does not cause swelling; this is what differentiates costochondritis from Tietze's syndrome, a rare syndrome of the costochondral cartilage that presents with swelling and pain at just one location in 70 % of patients (Proulx and Zryd 2009). Patients older than 35 years or patients with a history of cardiac disease should have an ECG to exclude cardiac pathology. Costochondritis is mostly diagnosed in patients older than 40 years. The condition is known under different names as, for example, anterior chest wall syndrome, costosternal syndrome and parasternal chondrodynia (Proulx and Zryd 2009).

The causes for costochondritis are unknown in most cases (Gregory et al. 2002), but costochondritis is sometimes thought to be caused by sporting activities, especially when the athlete had exercised strenuously in the recent past (Proulx and Zryd 2009). Sports giving rise to costochondritis (as presented in case reports) are rowing (Grindstaff et al. 2010), swimming (Cubos et al. 2010) and volleyball (Aspegren et al. 2007).

Imaging

Imaging is not necessary, since both costochondritis and Tietze's syndrome are clinical diagnoses. Imaging can however be used when there is a need to differentiate between costochondritis/Tietze's syndrome and more severe causes of chest pain like osteomyelitis or bone tumours (Hamburg and Abdelwahab 1987), although differentiation in general is possible combining history and physical examination.

In case distinction is difficult, a CT scan is described as the modality of choice by Hamburg and Abdelwahab (1987) and Proulx and Zryd 2009. On CT, patients with Tietze's syndrome can have findings as focal cartilage enlargement and/or ventral angulation of the rib cartilage (Hamburg and Abdelwahab 1987). Volterrani and colleagues describe MRI superior to CT in a study of 12 patients with Tietze's syndrome. MRI, using FAT SAT, STIR and TSE T2-weighted sequences, detects increased signal intensity of the cartilage and thickening of the involved cartilage (Volterrani et al. 2008). Next to these two imaging characteristics, bone marrow oedema in adjacent subchondral bone (using T2-weighted sequences/STIR) and increased uptake of gadolinium contrast in the area of interest can also point to Tietze's syndrome or costochondritis.

If patients present themselves with fever and/or cough, a chest X-ray could be performed to evaluate if a respiratory cause for the symptoms of pain can be found (Proulx and Zryd 2009).

14.2 Costovertebral and Costotransverse Joint Disorders

Disorders in the costovertebral and costotransverse joints are rare since these joints are stabilised by their tight articulations and ligaments (Little and Adam 2011). The ribs articulate posteriorly with the vertebrae twice. The head of the ribs 2 to 9/10 is attached to the vertebral body of two thoracic vertebrae in the costovertebral joint, stabilised by the radiate ligament and the intra-articular ligament. The head of the first, eleventh and twelfth rib (sometimes also tenth rib) only articulates with the same-numbered vertebrae; therefore, there is no intra-articular ligament in these joints. The neck of ribs one to ten is connected through the rib tubercle to the transverse process of their vertebrae and fixated by several ligaments and the articular capsule. Ribs 11 and 12 do not articulate with the transverse process.

Costovertebral joint (sub)luxation has been described in, for example, rowers and swimmers, in particular during breaststroke (Rumball et al. 2005). This injury can originate especially in the recovery phase between strokes in rowing or swimming when the arms of the athlete unexpectedly hit water or a rough object as, for example, a buoy (Thomas 1988). It is thought that, during the recovery phase, the serratus anterior muscle contracts, resulting in lateroflexion of the scapula. When an unexpected force then is transmitted through the arms, the serratus anterior muscle can transmit this force to the ribs inducing a forceful movement (Thomas 1988) that can result in a traumatic (sub)luxation of a costovertebral joint.

Imaging of Costovertebral or Costotransverse Subluxation

Imaging of subluxation can include PA and lateral X-rays, especially when trauma to the vertebral body or other causes for the pain should be ruled out (Mulder et al. 2012), but in general costovertebral subluxation is a clinical diagnosis. Subluxation on PA X-ray can be seen as left-right asymmetry: compare the affected joint with its healthy counterpart. On lateral X-rays it is important to assess the (mis)alignment of the rib to the vertebral and transverse processes.

Imaging of Joint Stiffness and Hyperostosis
Joint stiffness of the costovertebral and costotransverse joints is thought to be a contributor in the complex origin of rib stress fractures in athletes (Rumball et al. 2005; Warden et al. 2002). When forces are applied to the ribs, proper movement in the costovertebral and costotransverse joints allows these forces to be conducted to the thoracic spine. Hypomobility, due to stiffened costovertebral and costotransverse joints, can result in increased rib loading and therefore injury to the ribs (Warden et al. 2002). Imaging of joint stiffness is difficult. Hyperostosis of the posterior ribs and transverse process can be seen on PA and lateral X-rays (Macones et al. 1989) or CT, and ultrasound of soft tissue structures can display thickening. Nevertheless, those findings are difficult to relate to the degree of joint hypomobility since hyperostosis is also present in asymptomatic employees whose job involves heavy lifting (Macones et al. 1989). Therefore, X-rays and ultrasound are not used in daily practice to evaluate athletes for costovertebral or costotransverse joint stiffness.

Capture

ALARA in chest injuries

For radiography, CT and nuclear imaging of the chest, it is important to pay attention to the ALARA (as low as reasonably achievable) concept. In general athletes are of young age, and the thorax contains organs that are sensitive for radiation damage, as, for example, the lungs, bone marrow and (maturing) bony tissue. Therefore care should be taken in avoiding unnecessary radiation doses in this young population.

14.3 Fracture of the Sternum

A forceful blunt trauma, as, for example, the blow of the sternum against the steering wheel in a motor vehicle accident, can cause a sternal fracture. In most sports injuries of the chest, lower forces are applied compared to (motor) vehicle accidents; therefore, fracture or other injuries of the sternum due to direct sports-related forces are rarely seen in athletes. If the sternum is fractured due to such a high-energy accident, it is often associated with cardiac (life-threatening commotio cordis) or pulmonary injury as well (Mulder et al. 2012). Next to a fracture resulting from direct force to the chest, the sternum can fracture when extreme flexion-rotation or flexion-compression of the cervicothoracic spine takes place or when falling on the shoulder or head results in compression of the thorax (Raghunathan and Porter 2011). This injury mechanism can occur during sports trauma, especially in contact sports and high-energy sports (motor racing), but can also result from strong muscular contraction as seen in, for example, gymnastics and weightlifting (Raghunathan and Porter 2011). Other thoracic structures as the ribs, vertebrae or internal organs can be injured, sometimes resulting in vertebral and/or rib fractures or intrathoracic injury (Raghunathan and Porter 2011).

Next to these compression traumas, a transversal sternal fracture can result from overuse microtrauma leading to stress fractures, as proposed in a body builder who transversally fractured his manubrium sterni when performing sit-ups extensively for weeks (Robertsen et al. 1996). Stress fracture of the sternum has also occurred in athletes who make triceps dips (Hill et al. 1997) and in a wrestler and golfer (Keating 1987; Barbaix 1996). Sternal fractures in children do occur but are uncommon due to the elasticity of the chest. When children fracture their sternum, the injury mechanisms are similar to those observed in adults (Raghunathan and Porter 2011).

Imaging

For imaging of sternal fractures, lateral and AP radiographs are taken first (Raghunathan and Porter 2011). Other authors prefer PA radiographs. There is no consensus on the most suitable view. The fracture is frequently missed on AP and PA radiography, but lateral radiographs often reveal the fracture: a cortical interruption points to a fracture (Perron 2003). If a widened mediastinum is present on AP radiography or the patient has been involved in a high-energy accident, CT or MRI has to be carried out to assess the patient for intrathoracic injury (Perron 2003; Mulder et al. 2012). Ultrasound can also be used to detect fractures; again, a break in the cortex is indicative for a fracture. Ultrasound is as good as or even better in detecting sternal fractures as compared to radiography (Mahlfeld et al. 2001; Jin et al. 2006; Engin et al. 2000), but a disadvantage is the impossibility to image the grade of displacement (Engin et al. 2000) and/or a widened mediastinum. Therefore ultrasound is often followed by CT scanning. Ultrasound is preferable if rapid evaluation of the sternum is needed in, for example, trauma care or if a nonionising technique is required. If a fracture cannot be found on ultrasound or X-ray but the patient is still suspected for fracture of the sternum, a CT scan can be used to evaluate the sternum for cortical interruptions. A CT scan also has to be made when costal or vertebral injury is suspected. Lastly, if CT scan is not able to detect sternal fracture or when a stress fracture might be present, a bone scintigraphy might identify locally active bone because of increased osteoblast activity and thus provide the diagnosis (Raghunathan and Porter 2011). If a fracture is diagnosed, an ECG should be made to evaluate the patient for cardiac arrhythmia (Raghunathan and Porter 2011).

14.3.1 Manubriosternal Dislocation

Manubriosternal joint dislocation type 1 (posterior dislocation of the sternum) or type 2 (anterior dislocation of the sternum) can result from extreme hyperflexion of the thoracic spine (Lyons et al. 2010) or a direct force to the sternum (Lyons et al. 2010; Van Veen and Klaase 2011). The type of manubriosternal joint dislocation depends on the impact location: when a direct force hits the sternum caudally from the manubriosternal joint, a type 1 dislocation is most likely. Type 2 is mostly seen in hyperflexion of the thorax. Type 2 dislocation can be the result of extreme muscle contraction needed to create this hyperflexion. Also, compression during hyperflexion is thought

Fig. 14.1 Lateral chest CT scan showing posterior dislocation of the sternum (Courtesy of Elsevier: Lyons et al. 2010)

to dislocate the manubrium sterni posteriorly. Posterior dislocation of the manubrium sterni can also be the result of direct forceful contact between the chin and manubrium as, for example, in frontal crash accidents (motor racing).

Manubriosternal dislocation can be imaged on lateral X-ray or CT: a shift of the manubrium and/or sternum in a sagittal plane reveals the presence of a dislocation (Fig. 14.1).

14.4 Pneumothorax

Pneumothorax is a possible life-threatening condition and should therefore be diagnosed and treated rapidly (Putukian 2004). Pneumothorax (PTX) is seldom a result of sporting activity, although it may not always be diagnosed correctly by emergency physicians, and thus the incidence might be higher than the literature suggests (Karnik 2001). Due to the high level of fitness of athletes, symptoms might remain unattended or be perceived as not significant, resulting in a delay of diagnosis (Soundappan et al. 2005; Pfeiffer and Young 1980).

Sports-related pneumothorax can be subdivided in spontaneous PTX and traumatic PTX. Traumatic PTX is associated with blunt trauma as well as pulmonary barotrauma.

Case reports of spontaneous pneumothorax indicate an association with sports activities like scuba diving (Harker et al. 1993), weightlifting (Marnejon et al. 1995), jogging (Pfeiffer and Young 1980; Kizer and MacQuarrie 1999), athletics (track running, Davis 2002) and basketball (Curtin et al. 2000). Incorrect breathing techniques or Valsalva manoeuvres might play a role in the onset of spontaneous pneumothorax in these sporting activities (Marnejon et al. 1995). Spontaneous pneumothorax occurs more frequently in tall and thin young males (Mulder et al. 2012).

Traumatic PTX can occur during sports activity. Blunt trauma during contact sports (football, ice hockey (Curtin et al. 2000; Partridge et al. 1997)) and noncontact sports (skiing, snowboarding, hiking, bicycling (Kizer and MacQuarrie 1999)) can lead to traumatic PTX. Blunt trauma can also lead to fractures of thoracic structures; sharp fracture fragments can perforate the parietal pleura and may lead to a traumatic pneumothorax. This injury mechanism is described in rib (Partridge et al. 1997) and clavicle (Dugdale and Fulkerson 1987) fractures. Children also can develop a traumatic pneumothorax after high-energy collisions during sports, as presented in case reports from patients playing rugby, football and bicycling (Soundappan et al. 2005).

Another injury mechanism for pneumothorax during sports is observed in scuba divers. Pulmonary barotrauma of ascent can result from scuba diving (Russi 1998; Buzzacott 2012). During the ascent the pressure of surrounding water to the body is decreased, leading to expansion of air inside the lungs and thus to expansion of the lungs through distention of the alveoli (Salahuddin et al. 2011). The overinflated lungs can get damaged on alveolar level if the diver does not exhale sufficiently when ascending. In this situation the alveoli may rupture, and air will enter the perivascular sheath that surrounds the alveoli, giving rise to interstitial emphysema. This interstitial emphysema can result in mediastinal emphysema (if perivascular sheaths are ruptured), arterial gas embolism (if pulmonary capillaries are ruptured) and pneumothorax (if the visceral pleura is ruptured) (Russi 1998; Salahuddin et al. 2011).

Imaging

If pneumothorax (and/or pneumomediastinum) is suspected, standard PA and lateral radiography should be performed (Partridge et al. 1997; MacDuff et al. 2010). Displacement of the pleural line and absence of lung markings are diagnostic for the (partial) collapse of the lung (MacDuff et al. 2010). PA and lateral X-rays in inspiration increase the sensitivity for minor pneumothorax by increasing the relative size of the affected area. CT scanning is the gold standard test if an exact estimation of the collapsed part is necessary or if standard radiography was not able to demonstrate pneumothorax in clinical suspected cases. Due to its low density, air is black on CT, and therefore a clear distinction between PTX (black) and lung tissue is seen when lung window is used (MacDuff et al. 2010; Perron 2003).

14.5 Rib Contusion, Fracture and Costochondral Separations

Rib fractures are the most common injury of the chest, especially in high-energy sports (Gielen et al. 2007; Mulder et al. 2012).

Middle (5–10) and lower ribs (11 and 12) are more frequently fractured than ribs 1–4 (Gielen et al. 2007). Fracture of one or more ribs during sports activity can be due to blunt trauma, compression trauma or other direct or indirect external forces.

The fracture is mostly situated at the site of impact, but direct force to a small area coming from anterior can also fracture a rib at lateral position (Perron 2003). It is also possible that the costochondral junction is injured in this situation. Rib fractures are observed in both adults and children but occur more commonly in adults (Perron 2003; Miles and Barrett 1991).

Fractures can also be due to internal forces: locally violent muscle contraction in a different direction of pull can give rise to a typical athletes' avulsion fracture. The insertion of the scalenus anterior muscle on the relatively flat and weak scalene tubercle at the first rib is a known avulsion fracture site (Sakellaridis et al. 2004). When the scalenus anterior contracts, for example, while playing tennis or throwing, the scalene tubercle can fracture, especially when the serratus anterior muscle also contracts pulling the first rib in caudal direction (Sakellaridis et al. 2004). These avulsion fractures have only been reported in the first and floating ribs (Miles and Barrett 1991). In the floating ribs it is the powerful contraction of the external or internal oblique, latissimus dorsi or serratus posterior muscles that can fracture the 11th or 12th rib(s) at the origin of these muscles.

Complicated rib fractures in athletes consist of multiple fracture sites (occurring, e.g. when the thorax is compressed), fractures resulting in flail chest and fractures in the first four and last two ribs (Miles and Barrett 1991). Flail chest can occur when multiple ribs are fractured at more than one site per rib, giving rise to a paradoxically moving rib cage segment. Flail chest, when not timely diagnosed, can result in respiratory insufficiency. Fractures in the first four and last two ribs can be dangerous since there might be a loose bone fragment present. Sharp fragments of these ribs can possibly damage important intrathoracic or intra-abdominal structures. A bone fragment can, for example, perforate the parietal pleura, causing a traumatic pneumothorax. Fracture of the first rib can result in neurovascular complications by injuring the subclavian artery and/or the brachial plexus (Phillips et al. 1981). When one of the lower ribs is involved, a bone fragment can result in hepatic, splenic or renal injury (Gielen et al. 2007; Al-Hassani et al. 2010).

Imaging

Imaging is unnecessary only if just one rib fracture is suspected and there are no other complications present (Mulder et al. 2012). If this is not the case, imaging starts with standard chest and rib radiographs, especially evaluating the region where the trauma took place (Perron 2003). Any visible cortical interruption points to a rib fracture. Costovertebral dislocation might also be identified on radiographs. Moreover, pneumothorax can be excluded using standard radiographs. However ultrasound is more sensitive for rib fractures, especially if the fracture is situated close to the costochondral junction and the trauma mechanism is mild to moderate (Turk et al. 2010). The fracture will be seen as an interruption of the anterior echogenic margin (Turk et al. 2010). Additionally ultrasound can be used to examine the patient for costochondral lesions and costochondral separations (Gielen et al. 2007; Turk et al. 2010). Using ultrasound, dynamic movement of involved structures can be seen during inspiration and expiration. A costochondral lesion presents itself with a non-gradually movement at the painful area and again a noncontinuous

Fig. 14.2 Axial CT scan of a right fifth-rib fracture in a 29-year-old elite rower. Chronic phase with reparative callus bridging the fracture line. Window settings: W 1,600, C 400, slice thickness 2 mm

anterior echogenic margin (Gielen et al. 2007; Turk et al. 2010). A drawback of ultrasound is that it is highly dependent on operator experience and that some areas of the ribs are not accessible by ultrasound due to the overlying clavicle or scapula. CT can be used (Fig. 14.2) when X-ray and ultrasound of chest were negative but rib fracture is still considered presumable. In case of complicated rib fractures, additional imaging techniques such as angiography (suspected injury to subclavian artery) or CT abdomen should be considered.

Caption

A professional sidecar motocross racer injured during the world championship race in 2013 demonstrated multiple rib fractures with serious injury. During the crash the driver fell below the sidecar. The clavicle and 12 ribs fractured; the racer was in the intensive care unit for 5 days.

14.6 Rib Stress Fracture

In a healthy subject, the bone is constantly remodelling, adapting to new or different loads the body puts on the skeleton. On the tissue level osteoblasts constantly produce lamellar bone. Osteoclasts enzymatically destruct bone and then resorb the damaged bony tissue.

When disbalance between osteoclastic bone resorption and osteoblastic bone production is present, bone gets weak and is vulnerable for microdamage, which can result in stress fractures (Anderson 2006). Different mechanisms play a role in the genesis of disbalance. In athletes, especially in beginners or when training is intensified, repetitive motion locally stimulates osteoclasts to resorb bone.

Osteoblasts are also activated, but in the first weeks these cells are unable to keep up with the increased osteoclastic activity (Anderson 2006). During the first few weeks after beginning a sport or changing training or equipment, bone is more vulnerable for stress fractures (Anderson 2006).

An analysis of 263 Japanese athletes with a stress fracture showed that 14.1 % of all stress fractures in athletes occur in the ribs: only a stress fracture of the tibia is more often seen (Iwamoto et al. 2011). Of course this percentage is largely dependent on the type of sports that these athletes perform.

Rib stress fractures are associated with different sports, among others golf (Lord et al. 1996), canoeing (Maffulli and Pintore 1990), swimming (Taimela et al. 1995) and squash (Orava et al. 1991). Stress fractures of the middle ribs (5–9) are described extensively in rowers (Warden et al. 2002; Karlson 1998; Iwamoto et al. 2011). Repetitive contraction of the rectus abdominis, obliquus externus and/or serratus anterior muscle in rowing weakens the bone of the middle ribs and can result in a stress fracture, especially at the lateral part of the ribs where the muscles insert (Connolly and Connolly 2004; Karlson 1998; Rumball et al. 2005).

Stress fracture of the first rib has also been described but is more rare. In these fractures, the repeated pull from the scalenus anterior muscle (helping the thorax and shoulder girdle to retract the arms and paddle) and the serratus anterior muscle is thought to be the cause of first-rib stress fracture (Anderson 2006; Connolly and Connolly 2004). Sports/activities associated with first-rib stress fractures are basketball (Sacchetti et al. 1983), baseball pitching, weightlifting, volleyball and soccer (Matsumoto et al. 2003). Male ballet dancers who prepare for partner lifting with weight training are described to suffer from first-rib stress fractures (Prisk and Hamilton 2008); female ballet dancers are thought to be at risk for posterior lower rib stress fractures due to compression during the uplifting by their male partners (Bar-Sever et al. 1997).

Imaging

To identify stress fractures, a bone scintigraphy is described superior to standard X-rays and CT scan (Anderson 2006). The labelled diphosphonates show uptake where active bone turnover takes place, showing a ‘hot spot’ on bone scintigraphy scanning. Both the American College of Radiology in its Appropriateness Criteria and the IOC Manual of Sports Injuries point to a nuclear bone scan as the gold standard for diagnosing rib stress fractures (Mohammed et al. 1995; Mulder et al. 2012).

However, Anderson claims that MRI is as sensitive as bone scintigraphy. On MRI, bone marrow oedema and periosteal fluid are indicative for a stress fracture, and sometimes a thin fracture line can be seen. However caution should be taken, since asymptomatic persons may also show bone marrow oedema on MRI (Navas and Kassarjian 2011). Therefore, a precise history and clinical examination should precede MRI.

14.7 Sternoclavicular Joint Disorders

The sternoclavicular (SC) joint articulates using a small fibrocartilaginous disc. The SC joint is remarkably stable because of the tight capsular and ligamentous structures (Brys and Geusens 2007; Wirth and Rockwood 1996): three ligaments connect the sternum and clavicle directly to each other (interclavicular ligament, anterior SC ligament, posterior SC ligament). The costoclavicular ligament stabilises the joint by connecting the first rib to the rhomboid fossa of the clavicle (located posteriorly). Because of these structures, a dislocation of the SC joint is very rare: just 2–3 % of dislocations in the shoulder girdle are located at the sternoclavicular joint (Brys and Geusens 2007; Restrepo et al. 2009).

If a dislocation occurs, it involves anterior dislocation of the SC joint in the majority of patients (Restrepo et al. 2009). However in athletes who perform contact sports or high-energy sports, a posterior dislocation can be present. Anterior dislocation (or presternal dislocation) can be expected when a direct force hits the lateral part of the clavicle, pressing the sternal part of the clavicle forward/in ventral direction (Sakellaridis et al. 2004).

A forceful lateroposterior blow to the shoulder forces the lateral clavicle anteriorly, imposing a backward force at the sternoclavicular joint eventually leading to posterior dislocation of the sternal part of the clavicle (Buckley and Hayden 2008; Brys and Geusens 2007). An anteriorly directed force to the sternomedial part of the clavicle can also give rise to a posterior (or retrosternal) dislocation, but this is not often the case (Buckley and Hayden 2008). Contact sports as American football (Brys and Geusens 2007), rugby (Brys and Geusens 2007; Laffosse et al. 2010; Blakeley et al. 2011), judo and wrestling (Laffosse et al. 2010) and high-speed sports as motorcycling (Brys and Geusens 2007), skiing and equitation (Laffosse et al. 2010) are most often the cause of sports-related posterior sternoclavicular joint dislocation (Brys and Geusens 2007).

Posterior sternoclavicular dislocation can be dangerous since vital structures as the trachea, larynx, oesophagus, brachial plexus, recurrent laryngeal nerve, lungs, venous or arterial vessels and even the aorta can be compressed and/or ruptured (Buckley and Hayden 2008; Chaudhry et al. 2011). This may result in potentially life-threatening vascular and respiratory complications as laceration or occlusion of major vessels, pneumothorax and/or respiratory insufficiency.

Diagnosing sternoclavicular injuries in children and young adults can be difficult due to the late fusion of the medial epiphysis of the clavicle. This epiphysis ossifies at the age of 18–20, and only at age 23–25, it fuses with the clavicle shaft (Groh and Wirth 2011). Therefore in these patients, a physeal injury (Salter-Harris type 1 and 2 fractures) can be mistaken for a SC joint dislocation (Wirth and Rockwood 1996; Macdonald and Lapointe 2008).

14.7.1 Atraumatic Sternoclavicular Joint Disorders

Next to the traumatic sternoclavicular dislocation, athletes can suffer from sternoclavicular subluxation, which can be provoked by overuse. Cases from an adolescent female swimmer (Echlin and Michaelson 2006) and a military who was repetitively making heavy lifting and overhead movements (Gleason 2006) demonstrate the occurrence of overuse injury to the sternoclavicular joint.

Other atraumatic sternoclavicular joint disorders that might be important to consider for differential diagnosis of a swollen or painful SC joint are condensing osteitis, sternocostoclavicular hyperostosis and Friedreich's disease (aseptic necrosis of medial clavicle), although they are not reported to have a direct relation with sporting activities (Carroll 2011; Hiramuro-Shoji et al. 2003). A thorough description of these rare conditions (including radiological findings) was made by Hiramuro-Shoji and colleagues (Hiramuro-Shoji et al. 2003).

Imaging

Sternoclavicular dislocation and subluxation is difficult to identify on AP and lateral radiographs. The so-called serendipity view (40° cephalic tilt view in AP) yields a somewhat better view of the SC joints (Wirth and Rockwood 1996). Another disadvantage of radiography is the impossibility to detect any intrathoracic complications. Cross-sectional imaging is advised in order to assess the joint and evaluate for asymmetry. In children and young adults, MRI is preferable because injury to the epiphysis is visible only on MRI, and this injury can then be differentiated from SC dislocation (Groh and Wirth 2011). Also, intrathoracic damage can be imaged using MRI.

In cases where rapid evaluation is necessary or when it involves an older adult, CT is the best imaging modality (Brys and Geusens 2007; Groh and Wirth 2011). Especially when CT angiography is performed, injury of the great vessels can be made visible next to the imaging of the SC joint.

14.8 Pectoralis Major Muscle Rupture

Partial or total pectoralis major muscle ruptures are relatively rare injuries that can result from an unsuspected fall or blow but also from eccentric muscle contraction as in heavy lifting (Provencher et al. 2010). The latter injury mechanism is observed more often in the last decades, accompanied by an increased rate of physical activity involving bench press and other muscle exercise/work-out in the gym. According to a systematic review by ElMaraghy, 48 % of all cases of muscle injury to the pectoralis major can be accounted for by the deep part of the lift in a bench press manoeuvre (ElMaraghy and Devereaux 2012). This also explains why case reports about men are more predominant than reports describing women with this particular muscle injury (Provencher et al. 2010).

Sports-related cases of pectoralis major rupture other than the gym include among others boxing, jiu-jitsu, windsurfing, soccer, skateboarding, Olympic gymnastics (De Castro Pochini et al. 2010), American football, rugby, ice hockey (Mulder et al. 2012) and steer wrestling (Wheat Hozack et al. 2013).

The complex anatomy of the pectoralis major muscle poses difficulties for both diagnosing and treating these injuries. The pectoralis major muscle is the major muscle in adduction, anteflexion and endorotation of the arm. The muscle can be divided in two parts: the clavicular head and the sternal head (ElMaraghy and Devereaux 2012). The sternal head is subdivided in 6–7 muscle segments. The sixth and seventh segment attach at the cartilage of (floating) ribs six and seven rather than at the costosternal border (ElMaraghy and Devereaux 2012). The most inferior

Fig. 14.3 Ecchymosis in the right arm caused by pectoralis major rupture in a 27-year-old body builder (acute phase). Also notice the left-right asymmetry of the nipples and pectoralis major contour (Courtesy of NtvG, H.W. Bouma and R.G.H.H. Nelissen, 2012)

part of the pectoralis major muscle is also called the sternoabdominal part and is different from the other parts due its steeper pennation angle (Elmaraghy and Devereaux 2012).

The clavicular and costosternal head insert at the lateral lip of the bicipital groove of the humerus (Rehman and Robinson 2005) in two layers: a 2 mm anterior tendon layer which is continuous caudally with the posterior 2 mm tendon layer (ElMaraghy and Devereaux 2012).

Tears of the pectoralis major muscle occur most frequently at the insertion of the tendon to the humerus or at the musculotendinous junction: these two locations account for 67 % of the reported cases (ElMaraghy and Devereaux 2012). The muscle belly or muscle origin at the clavicular or costosternal parts can also rupture, but this is observed infrequently. Additionally, bony avulsions can be seen, but this is a rarity: in only 5 out of 365 injuries to the pectoralis major, avulsion of the humerus was reported (ElMaraghy and Devereaux 2012).

Diagnosing a pectoralis major rupture involves a thorough physical examination. In the acute setting, swelling and ecchymosis can be observed (Fig. 14.3). The patient complains of pain and loss of function over the pectoralis muscle. A tear at the musculotendinous junction or enthesis often can be observed directly (depending on the amount of swelling) or later on in the more chronic setting due to the absent or smaller preaxillary fold, especially when the physician compares the injured side to the healthy axilla on the other side of the body (Provencher et al. 2010).

Imaging

For classification of the pectoralis major injury and treatment planning (surgical or nonsurgical approach), it is important to determine the precise anatomic location and severity of the injury. A more detailed method for classification has recently be proposed by ElMaraghy and Deveraux, taking into account the anatomic location, timing and extent of injury (ElMaraghy and Devereaux 2012). Several imaging methods may add to the evaluation of pectoralis major injury.

Plain radiographs can be helpful if a bony avulsion is suspected (Provencher et al. 2010). Ultrasonography and MRI are the imaging modalities that can provide more detailed information concerning the location and classification of the injury (Gielen et al. 2007). In the acute phase swelling and ecchymosis can limit the

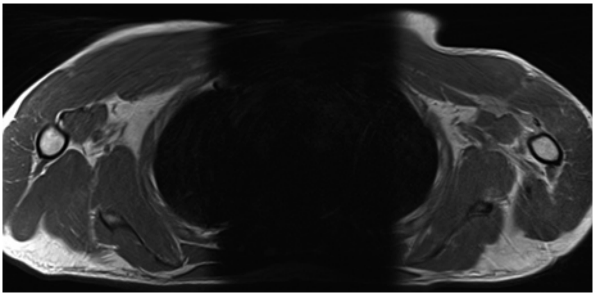

Fig. 14.4 Axial MRI of a subtotal pectoralis major tear (*left*) at the musculotendinous junction. Note the intermediate signal intensity in the distal part of the pectoralis major muscle, suggestive of haematoma. Proton density-weighted image, slice thickness 3 mm

visibility of the injury, and thus it is advised to evaluate the patient with MRI only after the swelling has resolved.

When evaluating a patient with MRI, the fibres of the two parts of the pectoralis muscle are best visualised using an oblique coronal MRI (Connell 1999). With this oblique view, it is possible to estimate the amount of fibres that is ruptured and thus if the pectoralis muscle is injured totally or only partially and to what extent (Connell 1999). Muscle contusion and oedema in and around the muscle, which often accompany the pectoralis tear, are found as areas of high signal intensity in or around the muscle on T2-weighted MRI, STIR and FAT SAT. The pectoralis major tendon is best imaged on an axial T2-weighted MRI. The tendon forms a small linear area of low intensity (Connell 1999) starting at the lateral lip of the bicipital groove at the humerus, continuing just ventrally from the coracobrachialis and biceps brachii muscle and ending in the musculotendinous junction. If a complete rupture of the tendon or musculotendinous junction is present, the tendon and muscle fibres will retract (Ohashi 1996). The torn tendon can involute, leading to a distinct MR image in which the tendon is discontinuous (Fig. 14.4).

Both ultrasonography and MRI pose difficulties in reliably evaluating if only one tendon layer is damaged or if the bilaminar tendon in its whole is affected due to the small size of the anterior and posterior tendon layer (together they are only 4 mm in size) (Provencher et al. 2010; ElMaraghy and Devereaux 2012). It is described that at this moment, only at surgery a precise distinction concerning the involvement of the tendon layers and exact width and thickness of injury can be made (Provencher et al. 2010; ElMaraghy and Devereaux 2012).

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Nuclear Medicine Imaging of Thoracic Sports Injuries

15

K.P. Koopmans

Contents

Abstract

Nuclear medicine imaging of the thorax may be helpful to the clinician to assess sports-related trauma. For this purpose bone scintigraphy, in combination with a SPECT-CT, can help the physician examine bone injuries with a high sensitivity such as fractures, stress fractures, and bone bruise. A new technique which needs further investigation is the use of sodium fluoride (NaF) PET scanning.

Thus far, lung scintigraphy has not been proven to be of use in assessing sports-related injuries to the lungs.

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15.1 Introduction

Chest pain is a common phenomenon in athletes. It may arise from several conditions which involve all structures of the chest wall and the intrathoracic organs (Gregory et al. 2002). Nuclear medicine is able to play an important role in the examination of sports-related chest pain in addition to the radiological techniques. For several acute problems, e.g., vascular ruptures and pneumothorax, radiological techniques are the only suitable imaging techniques. However, for the assessment of skeletal (chronic) trauma, cardiac problems, and lung problems, nuclear medicine can be very beneficial. Furthermore, research in sports physiology has proven nuclear medicine to be of great value (Marabotti et al. 2007; Kitada et al. 2008; Laaksonen et al. 2010; Seccombe et al. 2010).

In this chapter, nuclear medicine applications for the bony thorax, consisting of the sternum, ribs, and lungs, are addressed. The heart will be discussed in detail in Chap. 44.

15.2 Bone Injuries

Bone scintigraphy has already proven to be of great value for the examination of the thoracic skeleton. However, a new development is the application of sodium fluoride (NaF) PET with [^{18}F] NaF as tracer for the detection of (micro-)damage to the bone (Drubach et al. 2010; Li et al. 2011). NaF PET is a 3D imaging technique which yields superior resolution compared to conventional bone scintigraphy, with or without SPECT, and makes it possible to quantify uptake. Therefore this technique may become the method of choice to evaluate the athletes' thoracic pain.

In this chapter, nuclear medicine applications for imaging the clavicle, sternum, and ribs will be described. From a medicolegal point of view, the use of bone scintigraphy may be useful to exclude fractures (2012). The high forces which may occur during training on the thoracic cage can, due to their repetitive nature, result in overuse injuries of the bones and joints. Although upper extremity and thoracic stress fractures are less common than lower extremity stress fractures, they can have an enormous impact on the athlete due to the resulting chronic pain. However, these painful chest wall conditions are not limited to athletes; these syndromes apply to the general population as well (Gregory et al. 2002). Regarding the diagnosis of these stress fractures, bone scintigraphy is able to play an important role by finding the cause to these complaints when initial radiographs are negative or inconclusive (Anderson 2006; Jones 2006; Miller and Kaeding 2012).

15.2.1 Sports Injury to the Ribs

15.2.1.1 Rib Contusions

Bone bruises in sports arise together with soft tissue injuries after blunt contact trauma and are usually presented as bleedings, edemas, or infarctions. Bone bruises are characterized by microtrabecular fractures which leave the bone itself

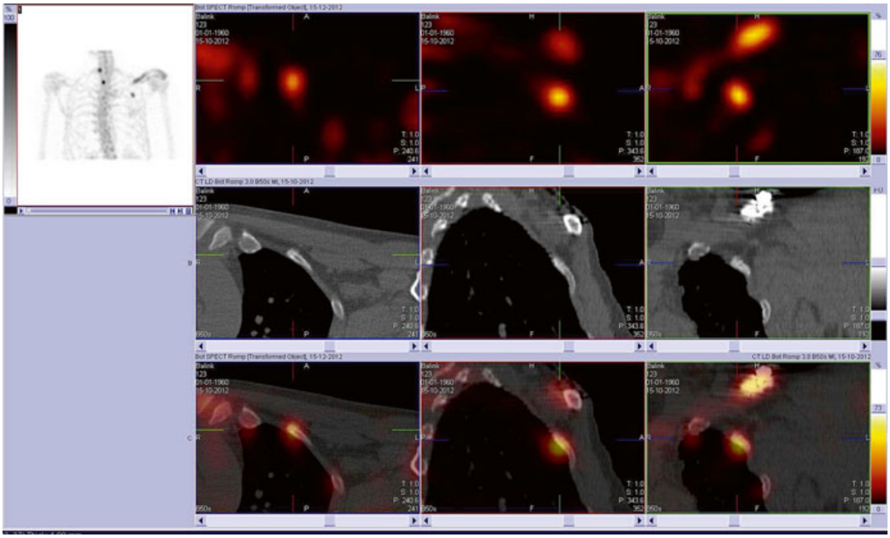

Fig. 15.1 A 52-year-old amateur cyclist was admitted to the hospital after a cycling accident while cycling 35 km/h. He presented with pain between the scapulae, in the lower neck, and in his thorax. The initially performed CT only showed a fracture of the left clavicle. Due to the continuing pain complaints, a bone scintigraphy with SPECT-CT was performed. This revealed a rib fracture of the 3rd rib on the right side, a fracture of the right processus spinosus of the 1st thoracic vertebra, and a fracture of the processus spinosus of the 4th rib (Courtesy of H. Balink, Department of nuclear medicine, Medical Centre Leeuwarden)

macroscopically intact (Rangger et al. 1998). MRI has already, early after recognition of this disease entity, played an important role in diagnosis of bone bruises since it provides the clinician with a clear insight into the extent and severity of the bone lesion (Ucar et al. 2012). Historically, nuclear medicine has not played an important role in the detection of bone bruises. Bone scintigraphy is able to detect bone lesions but with a lower sensitivity and specificity than MRI (Soudry and Mannting 1995; Even-Sapir et al. 2002). In bone scintigraphy, bone bruises are characterized by focal increased osseous uptake. The intensity of uptake might relate to the extent of microfractures, i.e., more microfractures lead to an increased uptake. In combination with a SPECT/CT camera system or with NaF PET, bone scintigraphy can possibly be used as a total body screening method for bone bruises (Fig. 15.1).

15.2.1.2 Acute Rib Fractures

Diagnosis of rib fractures may be difficult. Identification of rib fractures by plain radiography can be challenging, but plain radiographs are very helpful in detecting additional disease such as hemothorax or pneumothorax. After the acute phase, bone scintigraphy with SPECT/CT can be performed to examine the presence of rib fractures (Erhan et al. 2001). Nevertheless, not only plain radiographs are limited in detection of rib fractures, but this also applies to CT. In a recent study involving 130 patients suffering from blunt chest trauma, 52 rib fractures were missed on CT reconstructions (Cho et al. 2012). In these cases the combination of a SPECT and CT will likely give a higher sensitivity and specificity for the detection of rib fractures. Moreover, bone bruising can be distinguished from fractures using the CT and thereby increases the diagnostic advantage of bone SPECT-CT for the clinician.

15.2.1.3 Rib Stress Fractures

A stress fracture can be defined as a partial or complete bone fracture resulting from repetitive stress, stress milder than required in order to fracture the bone in a single loading. Stress fractures occur when the remodeling and repair capabilities of the bone are exceeded by the continuously occurring microfractures during repetitive exercise (Bennell et al. 1996).

The most common stress fracture occurs in the first rib. Nevertheless, many fractured first ribs remain asymptomatic and are coincidentally found. In sports involving overhead activity, the repetitive contractions of the scalene muscles produce bending forces which may finally result in a fracture (Connolly and Connolly 2004). Pain can be located in the shoulder, be linked to inspiration, or be tenderness in the neck. In these cases chest radiographs are of limited help, and bone scintigraphy, CT, and MRI are more sensitive. Generally, MRI has the advantage of being able to exclude other pathologies without radiation risk, whereas bone scintigraphy is better in excluding osseous pathology (Dobrindt et al. 2012).

In golf players and elite rowers, fractures of other ribs are more common. These fractures are as well often difficult to ascertain on plain radiographs, and for the diagnosis of these fractures, bone scintigraphy and possibly NaF PET are required (Maffulli and Pintore 1990; Karlson 1998; Gregory et al. 2002). However, NaF PET is likely to have a superior sensitivity in the detection of (impending) stress fractures compared to bone scintigraphy, but its value has to be ascertained (Drubach et al. 2010; Li et al. 2011; Iagaru et al. 2012).

15.2.2 Sternum Fractures

Only 0.5 % of all sternum fractures are sports-related stress fractures, usually occurring in sports requiring extreme upper body stresses, e.g., wrestling, strenuous abdominal muscle training, and even golfing (Keating 1987; Barbaix 1996; Gregory et al. 2002). The subsequent pain is generally gradual or sudden in onset, is located in the anterior chest, and increases with deep breathing. For the diagnosis of sternal fractures, ultrasound, plain radiographs, or CT can be applied. For the detection of sternal fractures in the early phase, both ultrasound and bone scintigraphy can be used (Erhan et al. 2001; Jin et al. 2006). However, as with rib fractures, NaF PET may be more sensitive than bone scintigraphy (Drubach et al. 2010; Li et al. 2011).

15.2.3 Costochondritis

Costochondritis is a poorly understood condition (Proulx and Zryd 2009), characterized by tenderness and pain on the costochondral and costosternal joints, though without swelling of the involved joints. Costochondritis has a higher prevalence in both athletic young females as in young females in the general population. Regarding sports, this syndrome is most common in young female rowing athletes (Grindstaff et al. 2010). Bone scintigraphy in patients with costochondritis generally shows an increased uptake in costochondral joints, but this finding is not specific for this condition (Mendelson et al. 1997). Nonetheless, bone scintigraphy may have additional value in combination with CT and plain radiographs.

15.3 Lung Injuries

15.3.1 Pneumothorax and Tension Pneumothorax

Pneumothorax is a common complication following blunt chest wall trauma. Generally plain PA chest radiographs are acquired for the diagnosis of pneumothorax. Traditionally, nuclear medicine is not used in the diagnosis of pneumothorax (Omar et al. 2011).

However, ventilation perfusion scintigraphy can be used to examine impairment of regional or overall lung function. In patients diagnosed with pneumothorax, impaired ventilation and perfusion was found in the apical regions of the lungs where the pneumothorax had occurred (Bense et al. 1986). In a published case report, lung ventilation and perfusion scintigraphy contributed to the diagnosis of an unsuspected pneumothorax (Lee et al. 1984). Whereas lung perfusion scintigraphy, with or without SPECT/CT, has no place in routine evaluation of pneumothorax, it might nevertheless be of use in localizing the air leaks responsible for pneumothorax (Ceulemans et al. 2012).

Conclusion

Due to the low incidence of traumatic sports and stress injuries to the thorax, only scarce research data exists about the use of nuclear medicine imaging techniques in this part of the musculoskeletal system. However, the use of NaF PET might be beneficial for the detection of traumatic ossal injuries to the thorax. Further research and experience with this technique for this application is warranted.

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Part V

The Musculoskeletal System Topographically: The Shoulder

Sport-Specific Shoulder Injuries

16

Ann Cools

Contents

Abstract

In this chapter, shoulder injuries, related to sports performance, are described. Shoulder injuries are multifactorial due to the presence of several synovial and functional joints (glenohumeral, sternoclavicular, acromioclavicular, scapulothoracic,

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and coracoacromial arch) that might be injured. Acute shoulder injuries can occur as a result of a traumatic event in any sport, whereas chronic shoulder pain is often attributed to the high demands of the overhead throwing movement. Functional impingement and pain during throwing activities is the most frequent clinical finding in overhead athletes. During the clinical examination of the athlete, the clinician aims to identify the specific location and cause of impingement, the presence of rotator cuff pathology, biceps-related pathology, labral tears, instability, range of motion deficits, and scapular dysfunction.

16.1 Introduction

Most athletic shoulder injuries are the result of one of two mechanisms: (1) an acute external force applied on the shoulder complex (macrotrauma) or (2) repetitive overhead activity and overuse (microtraumata). The shoulder is susceptible to traumatic injuries such as dislocations, subluxations, acromioclavicular joint sprains, and soft tissue injuries, in particular in collision and contact sports. However, most of the injuries result from repetitive overuse mechanisms, due to overload, aberrant overhead throwing biomechanics, and dysfunctional adaptations to the sport, leading to chronic symptoms like impingement and bursitis (Ellenbecker and Cools 2010). Moreover the shoulder is predisposed to athletic injury because of the large amount of mobility of the glenohumeral joint, allowing powerful throwing and smashing but putting the shoulder at risk for injury due to the inherently poor glenohumeral instability. Incidence rates of shoulder injuries vary depending on the specific sports, with up to 20 % of acute shoulder injuries in ice hockey (Bahr et al. 2012). Chronic shoulder pain conditions caused by overuse and instability are the predominant injuries in sports demanding high loads on the shoulder such as baseball, tennis, and swimming, with an incidence of between 17 and 26 % (Bahr et al. 2012). The purpose of this chapter is to give an overview of functional shoulder anatomy and biomechanics and discuss common injuries of the shoulder complex in the overhead athlete.

16.2 Functional Anatomy and Biomechanics

The shoulder complex is composed of three synovial joints (sternoclavicular, acromioclavicular, and glenohumeral) and one physiologic articulation (scapulothoracic joint). These four articulations, together with the ligaments, the rotator cuff muscles, and the prime movers (deltoid, pectoralis major, and latissimus dorsi) of the shoulder, provide the necessary stability and power during various shoulder movements, in particular the overhead throwing movement. Dysfunction in any of these structures can result in limited performance of the entire upper limb.

16.2.1 Sternoclavicular Joint

The sternoclavicular joint provides the only real articular connection (synovial joint) between the shoulder complex and the axial skeleton. It is by nature a very stable saddle joint, stabilized by several ligaments, of which the most important one is the costoclavicular ligament. This ligament mainly controls anterior and posterior translations of the clavicular head on the sternum (Wilk et al. 2009b). The sternoclavicular joint is reinforced by the intra-articular disk, absorbing centrally directed forces and improving the congruence of the articular surfaces, thus avoiding dislocations of the clavicula. During arm elevation, the clavicula moves into elevation, long-axis rotation, and depending on the plane of the movement retraction or protraction (Ludewig et al. 2009).

16.2.2 Acromioclavicular Joint

The acromioclavicular (AC) joint is a synovial plane joint, allowing limited motion, and protected by two major ligament complexes. Some variations in size and shape of the articular surfaces need to be noted. In some cases they are separated by a meniscus attached to the superior acromioclavicular ligament. This meniscus may be a blade of fibrocartilage that extends nearly halfway into the joint, or it may form a complete disk that divides the joint into two parts. In other joints no synovial joint is present with the joint being made by a pad of fibrous tissue attached to the outer end of the clavicle, and no articular cavity. The acromioclavicular joint fulfills an important role with respect to shoulder mobility maintaining an appropriate scapular position during the early phases of elevation and assisting acromial elevation during elevation of the arm above shoulder height (Ludewig and Reynolds 2009). Functionally, the two main movements at the AC joint are anteroposterior gliding movement during shoulder flexion and extension and elevation-depression during glenohumeral abduction.

16.2.3 Glenohumeral Joint

The glenohumeral (GH) joint is the most mobile joint of the human body. In particular, overhead athletes place tremendous stress on the soft tissue and osseous structures of the GH joint (Ellenbecker and Cools 2010). Because of the lack of congruency between the humeral head and the glenoid, the shoulder has to rely upon the structural quality and functional capacities of the ligaments, the labrum, and the stabilizing muscles. Anatomically, the labrum serves as the glenoid attachment for the GH ligaments and the long head of the biceps. Biomechanically the main function of the labrum is to deepen the glenoid fossa, thus increasing the surface area of contact with the humeral head and avoiding excessive translation of the humeral head relative to the glenoid fossa (Wilk et al. 2009b). The anterosuperior part of the labrum has poor blood supply, making it susceptible for overload injury

(Cooper et al. 1992). Moreover vascularity decreases with age, and mechanoreceptors seem to be absent in the labrum, possibly influencing proprioceptive quality of the GH joint. Free nerve endings, however, were found in the fibrocartilaginous tissue of the labrum, the biceps insertions, and the connecting tissue around the labrum (Vangsness et al. 1995).

The shoulder joint capsule and the GH ligaments are loose and redundant, allowing a large range of motion. In particular the inferior GH ligament protects the shoulder from uncontrolled translations inferiorly and anteriorly during the combined motion of abduction and external rotation (Wilk et al. 2009b). Normally the capsule of the GH joint is sealed airtight and contains a very small amount of fluid. This results in a negative intra-articular joint pressure, leading to joint cohesion, thus contributing to passive joint stability (Alexander et al. 2012).

Beside the static constraints, the shoulder relies upon its active stabilizers, mainly the rotator cuff, during daily activities and specifically during overhead movements, to maintain functional stability. The rotator cuff muscles reinforce the shoulder in several ways. By contracting as a balanced force couple, the humeral head is sucked into the glenoid; however, the rotator cuff also strengthens the capsule through blending of the cuff tendons into the shoulder capsule. Making the capsule "stiffer" increases the GH stability, tightening the GH ligaments and thereby centering the humeral head into the glenoid fossa (Ellenbecker and Cools 2010; Nimura et al. 2012).

16.2.4 Scapulothoracic Joint

The scapulothoracic joint comprises the physiologic joint of the scapula floating on the thoracic wall, with very little ligamentous constraints, and mainly depending upon the quality of optimal recruitment of the scapular muscles to maintain a functional position with respect of the thorax and the shoulder. The ultimate function of the scapula is to provide a stable base for the GH joint by orienting the glenoid fossa for optimal contact with the humeral head (Kibler 1998). Whereas the trapezius muscle and the serratus anterior muscle actively control scapular movement through dynamic contractions, the pectoralis minor, rhomboid, and levator scapulae muscles have a more passive role, providing postural control to the scapula and keeping the scapula steady on the trunk during dynamic arm movements (Cools et al. 2008b; Ellenbecker and Cools 2010; Ludewig and Reynolds 2009).

The trapezius and serratus anterior muscles work as a force couple on the scapula, resulting in the necessary rotations and translational movements to guarantee proper scapular positioning and movement. The primary condition for an optimally working force couple is muscle balance, meaning that all muscles must be activated in the right amount and at the appropriate time. Disturbances in any of these variables may lead to scapular dyskinesia and possibly to chronic overload shoulder pain.

16.2.5 Coracoacromial Arch

The coracoacromial arch of the subacromial space is often considered as a physiologic joint of the shoulder complex, in which the bursa has an important role based on good gliding capacity and its protective function against direct trauma. The roof of the subacromial space is composed by the acromion, the AC joint, the coracoacromial ligament, and the coracoid process. The space within the arch or the coracohumeral distance depends upon arm position and decreases with arm elevation (Maenhout et al. 2012; Seitz and Michener 2011). It has been shown that the acromiohumeral distance is reduced in overhead athletes with an internal rotation range of motion deficit, possibly increasing the risk for impingement symptoms in this population (Cools et al. 2008b; Maenhout et al. 2012).

16.3 Etiology and Injury Mechanism

16.3.1 The Overhead Throwing Motion

Of all phases of overhead throwing, the cocking (just prior to the acceleration phase) and deceleration (final stage of throwing) phases are considered to be the most stressful and demanding for the glenohumeral joint.

During the cocking phase, the shoulder is put into a position of maximal external rotation, maximal horizontal abduction, and depending upon the specific sport a certain amount of abduction. As an example, during baseball throwing, the shoulder is in approximately 90° of abduction, whereas during the tennis serve or the volleyball smash, the degree of abduction is between 140° and 180° (Elliott 2006; Escamilla and Andrews 2009; Reeser et al. 2012). In particular the anterior part of the GH joint is at risk for being "stretched" out and needs to be protected by optimal concentric and eccentric rotator cuff activity to stabilize the humeral head into the glenoid fossa. In addition the labrum is highly stressed in this extreme external rotation position (Ellenbecker and Cools 2010).

The scapula plays an important role in the cocking phase. In order to keep optimal GH stability, the scapula has to move into upward rotation, posterior tilting, and maximal retraction (Kibler 1998). This movement results in proper alignment of the scapula along the axis of the humeral shaft. If the scapula is not able to perform this movement because of a lack of muscle strength or flexibility, "hyperangulation" will occur, meaning there is an angle between the plane of the scapula and the plane of the moving humerus, possibly leading to internal impingement (see Sect. 16.5.1) (Wilk et al. 2009a).

During the deceleration phase, the ball is released and the arm and shoulder decelerated. The shoulder joint moves into internal rotation, and the elbow extends rapidly. The deceleration forces are approximately twice as high compared to the acceleration forces, but for a shorter period (Escamilla and Andrews 2009). Tremendous eccentric activity is needed from the biceps, posterior cuff muscles, and scapular retractors. This demanding muscular activation puts the shoulder at risk for overuse lesions of the rotator cuff and labral tears at the attachment of the long head of the biceps (superior labrum from anterior to posterior or SLAP lesions) (Burkhart et al. 2003b, c). As a result of repetitive overhead throwing, the posterior shoulder structures (capsule and rotator cuff) tend to functionally adapt, leading to posterior shoulder stiffness and reduced internal rotation range of motion. This reduced range of motion has been associated with scapular dyskinesis, reduced acromiohumeral distance, and symptoms of subacromial impingement (Borich et al. 2006; Maenhout et al. 2012; Tyler et al. 2010).

In summary, overhead throwing is a very demanding movement for the shoulder complex, in which optimal biomechanics, neuromuscular coordination, and strength of the surrounding muscles are needed. Anterior instability, subacromial and internal impingement, tensile overload of the rotator cuff, and labral tears are possible injuries that might occur in case of aberrant throwing technique or overload.

16.4 Injuries

16.4.1 Acute Shoulder Injuries

Most common acute shoulder injuries in overhead athletes are anterior shoulder dislocation, AC joint injury, and clavicular fractures (Bahr et al.2012). Rotator cuff ruptures, fractures, sternoclavicular joint dislocations, posterior shoulder dislocations, and plexus and vascular injuries are less common but should not be overlooked. For the scope of this chapter, only the most common acute injuries are further described.

Dislocations

Dislocations occur more in men than in women, with high recurrence rate in young patients after a first episode of acute dislocation (Boone and Arciero 2010). Due to the acute traumatic event, they are very frequently accompanied by structural damage at the glenohumeral joint. Most injuries are located at the anterior capsulolabral complex (Bankart lesion) and at the posterior aspect of the humeral head (Hill-Sachs lesion). It is important to determine the injury mechanism, the direction of the force, and the amount of force that caused the event. Shoulder dislocations may be the result of a direct fall on the outstretched arm but also of an excessive high force applied to the shoulder in the abduction – external rotation position, for instance, by falling during downhill skiing or by being tackled by the opponent in team handball when shooting a ball (Bahr et al. 2012). Changes in the contour of the shoulder under the deltoid and inability to move the arm are typical signs of an anterior dislocation.

Fractures of the Clavicula

Clavicular fractures are extremely common in children and adolescents who fall on their shoulder or on an outstretched arm (Pandya et al. 2012). In some sports, in which the risk of falling is larger, for instance, in cycling or mountain biking, the prevalence of clavicular fractures is very high (22 % of all traumatic injuries in top-level road cyclists) (Bahr et al. 2012; De Bernardo et al. 2012). It can however also occur as a result of a direct impact on the shoulder, for instance, in contact sports such as rugby. The injuries are divided into medial and lateral fractures, depending on the location of the fracture with respect to the coracoclavicular ligamentary complex. Clavicular fractures lead to local swelling and malalignment that can easily be detected on inspection.

AC Joint Injuries

AC joint injuries are the result of a fall on the shoulder or a direct blow on the lateral side of the shoulder. If the trauma comes directly from the lateral side, the AC joint is compressed, often leading to structural damage to the intra-articular disk. If the impact comes from the front or the back, this may lead to AC dislocation and rupture of the coracoclavicular and acromioclavicular ligaments. AC joint injuries are classified into 6 grades, depending on the degree and direction of the malalignment (Bahr et al. 2012; Reid et al. 2012). Grades I and II comprise injury to the AC joint without dislocation. Grade III is a total dislocation with rupture of the coracoclavicular ligament. Grades IV to VI are total dislocations of the AC joint in posterior (IV), cranial (V), or caudal (VI) direction (Fig. 16.1). Initial diagnosis is based on swelling, pain, and visible displacement of the distal portion of the clavicula with respect to the acromion.

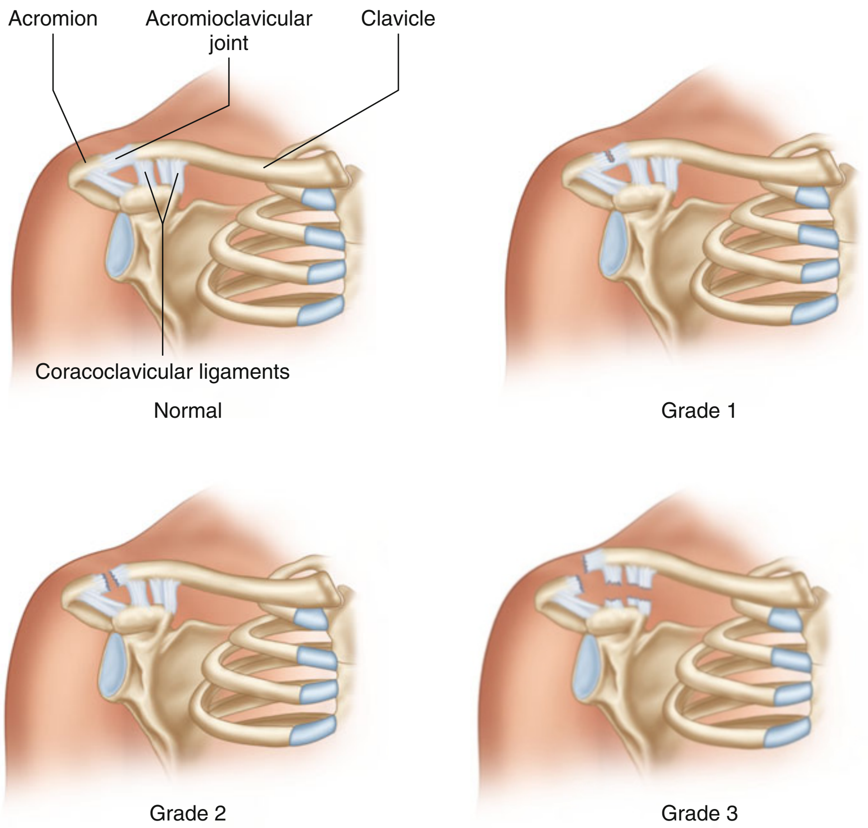

Fig. 16.1 Grading AC joint injuries *grade 1* to *3* (Bahr et al. 2012)

16.4.2 Chronic Shoulder Pain

Chronic shoulder pain is probably the most common arm problem in recreational and competitive overhead athletes. Throwing athletes need full, unrestricted arm function to optimally perform in their sport. Nontraumatic shoulder pain in the overhead athlete is a diagnostic challenge. The causes of chronic shoulder pain are numerous but often difficult to identify and diagnose. Research indicates that shoulder impingement is the most common cause of shoulder pain in overhead athletes (Cools et al. 2008b). In recent literature, impingement has been described as a group of symptoms rather than a specific diagnosis (Cools et al. 2008a). In this current opinion, it is thought that numerous underlying pathologies may cause impingement symptoms. Glenohumeral instability, rotator cuff or biceps pathology, scapular dyskinesis, and glenohumeral internal rotation deficit have been associated with impingement symptoms in clinical literature (Cools et al. 2008a; Kibler 1998). Various anatomical structures can be impinged internally or externally, probably depending on the motion and loading put on the shoulder during the pain-provoking activity. However, a possible instability in the shoulder is often "silent" and difficult to show by ordinary tests and has therefore by some been termed "functional instability" (Castagna et al. 2010; Jobe et al. 1989). It is now thought that functional instability in the shoulder may lead to a vicious circle involving microtrauma and secondary impingement and may eventually lead to chronic shoulder pain. Since the first paper, published by Walch et al. (1992), describing a new site of impingement between the humeral head and the posterosuperior rim of the glenoid, internal superior glenoid-type impingement has been suggested to be a common cause of chronic shoulder disorder in overhead athletes. This type of impingement occurs in the cocking position of throwing, with the glenohumeral joint in maximal external rotation, in maximum horizontal abduction, and, depending on the sport, in abduction or forward flexion (Cools et al. 2008b). In general, overhead athletes with internal impingement have posterior shoulder pain and tenderness of the infraspinatus tendon on palpation. Internal superior glenoid impingement particularly occurs when the humeral shaft goes beyond the plane of the body of the scapula during the cocking position of throwing (Wilk et al. 2009a). Under normal circumstances, the scapula goes into retraction simultaneously with the horizontal abduction movement of the humerus. When the body of the scapula and the humeral shaft fail to remain in the same plane of movement during the cocking phase of throwing, encroachment of the rotator cuff tendons between the humeral head and the glenoid rim may cause internal impingement symptoms. This phenomenon is called "hyperangulation." However, in spite of the documented structural pathology and cuff lesions (Walch et al. 1992), shown by several groups to be related to internal superior glenoid impingement symptoms, it is suggested that functional disturbances, such as subtle glenohumeral instability, glenohumeral range of motion (ROM) restrictions, scapular dysfunction, and muscle stiffness, are often associated with internal impingement symptoms, rather than structural deficits and pathologies (Cools et al. 2008b; Tyler et al. 2010). Another type of impingement, subcoracoid impingement, has been described related to anterior shoulder pain and subscapularis tendon tears.

However, the pathogenesis has still not been explained properly. Subcoracoid stenosis and anterosuperior translations of the humeral head, both resulting in narrowing of the coracohumeral space, may lead to anterosuperior tears of the cuff including the subscapularis tendon. Symptoms particularly occur during the deceleration and follow-through phases of throwing.

16.5 Examination

In view of the assumption that impingement symptoms may be the result of various underlying pathologies, it is important to understand the biomechanical relationship between these symptoms and shoulder diagnoses. Since functional deficits rather than structural pathology often are the underlying cause of chronic shoulder pain in the overhead athlete, the clinical examination of the patient is very important.

The physical examination of the overhead athlete consists initially of a thorough history (or subjective assessment); inspection; active, passive, and resistance tests; and pre- and post-examination palpation. During the physical examination of the athlete with shoulder pain, it is imperative that the investigator examines what kind of impingement the patient suffers from and what the underlying pathology might be. Several papers offer the clinician an approach to specific tests that can be used when screening the athlete's shoulder for impingement-related shoulder problems (Cools et al. 2008a; Hegedus et al. 2012). All the clinical tests described in the following paragraphs are summarized in Table 16.1.

16.5.1 Impingement Tests

Of the various provocative impingement tests, the most popular are the Jobe, Hawkins, and Neer tests. These tests show high sensitivity, however questionable specificity, and should therefore only be used as a first screening tool to confirm the presence of impingement-related shoulder pain. Besides these impingement tests, very often, instability tests (apprehension, relocation, release) are used as provocation tests for impingement, interpreting them with respect to pain rather than instability symptoms, to further define the cause of impingement. In general it is suggested that at least three tests should be positive to draw conclusions regarding impingement symptoms (Cools et al. 2008a; Hegedus et al. 2012; Meister et al. 2004).

16.5.2 Rotator Cuff Tests

To define the involvement of rotator cuff pathology in the impingement symptoms, a modified version of the Jobe test is a valuable tool (Tennent et al. 2003). Indeed originally the test was described to investigate the integrity of the rotator cuff muscles, particularly the supraspinatus. However, based on this test, one cannot define

Table 16.1 Summary of clinical tests of the shoulder (Cools et al. 2008a)

Impingement	Neer	Forced passive forward flexion with the arm internally rotated and caudal pressure on the acromion
	Hawkins	Passive internal rotation from a 90° forward flexed position
	Jobe	Resisted elevation in the scapular plane with the shoulder in maximal internal rotation
Rotator cuff	Full can	Resisted elevation in the scapular plane with the shoulder in external rotation (thumbs up)
	External rotation lag sign	Arm in slight elevation and external rotation: patient is asked to keep this position against gravity
	Hornblower's sign	An inability to externally rotate the elevated arm
	Lift-off test	Arm in full internal rotation on the back, patient is asked to lift off his/her hand from the back
	Belly-press test	Patient is asked to push his/her hand into his/her belly with the elbow aside, inability to keep the elbow steady
Scapular involvement	Scapular assistance test	Patient performs active elevation while examiner manually assists scapular upward rotation and posterior tilting
	Scapular retraction test	Patient performs Jobe test while examiner manually stabilizes the scapula into retraction against the thoracic wall
Instability	Apprehension	Patient exhibits apprehensive muscle tension during the position of 90° abduction-90° external rotation
	Relocation	Dorsal pressure on humeral head in the apprehension position gives symptom relief
	Release	Symptoms of instability when hand is released from the patient's shoulder after the relocation test
	Load and shift	Passive anterior translation of the humeral head with respect to the glenoid results in subluxation
	Sulcus	Examiner induces caudal translation on the humeral head by pulling on the elbow down; this results in a sulcus at the level of the glenohumeral joint
	Posterior subluxation test	Performing a dorsal pressure while the shoulder is in horizontal adduction results in posterior subluxation
	Hyperabduction test	Examiner performs abduction >90° while fixing the acromion and the clavicle caudally

(continued)

Table 16.1 (continued)

SLAP and biceps pathology	O'Brien test	Resisted elevation in two positions: 10° horizontal adduction thumb down (1) and thumb up (2), pain only during first position
	Biceps load II test	Resisted elbow flexion while shoulder is in 120° abduction, external rotation, elbow 90° flexed and full supination
	Yergason test	Resisted supination results in pain in bicipital groove
	Dynamic labral shear test	Examiner applies a shear load to the joint by maintaining external rotation and horizontal abduction and lowering the arm from 120° to 60° abduction
GIRD	ROM measurement	Left-right comparison of internal rotation with the arm 90° abducted in the frontal plane

whether a painful test is the result of functional impingement rather than rotator cuff muscle dysfunction. Therefore, the examiner can perform the full-can test, in which the rotation position is changed from internal (thumbs down) into external rotation (thumbs up). In addition, specific tests can be used to identify a rupture of the infraspinatus (external rotation lag sign, hornblower's sign) and subscapularis (lift-off test, belly-press test) (Cools et al. 2008a; Tennent et al. 2003).

16.5.3 Scapular Involvement Tests

Scapular involvement in impingement-related shoulder pain may be examined by the scapular assistance test (SAT) and the scapular retraction test (SRT) (Burkhart et al. 2003a; Cools et al. 2008a; Kibler et al. 2006). The SAT, in which scapular movement quality is examined, consists of manual assistance of correct scapular movement during elevation of the arm. In the SRT, in which scapular stability is examined, the empty-can test is performed while the examiner stabilizes the patient's scapula and shoulder in a position of retraction by placing the forearm along the medial border of the scapula. These tests are positive for scapular involvement if patients feel symptom relief compared to the original provocative test or movement.

16.5.4 Instability Tests

The clinical tests to examine shoulder instability can be divided in provocative tests and laxity tests. Commonly used provocative tests for instability are the apprehension and relocation tests. In case of instability, patients will exhibit instability symptoms, such as apprehensive muscle tension and subluxation, rather than pain. Distinct from the provocative tests, the laxity tests are assessing humeral translation with respect to the glenoid fossa. Commonly used laxity tests are the load and shift test (anterior laxity), sulcus sign (inferior laxity), posterior subluxation test (posterior laxity), and hyperabduction test (general laxity) (Cools et al. 2008a; Hegedus et al. 2012).

16.5.5 Biceps Pathology and SLAP Lesion Tests

Currently SLAP lesion tests are under debate (Hegedus et al. 2012). In general no test is found to be sensitive as well as specific. Therefore, it is suggested to use clusters of at least three SLAP lesion tests, in which apprehension test, O'Brien test, biceps load II test, Yergason test, and dynamic labral shear test may help in the evaluation of SLAP lesions.

16.5.6 Clinical Evaluation of GIRD

The assessment of GIRD is performed by measuring glenohumeral internal rotation range of motion, preferable in supine position with the shoulder abducted 90° and the scapula stabilized against the bench. A side difference of 20° is considered to be positive for GIRD ((Ellenbecker and Cools 2010; Borstad and Dashottar 2011).

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Shoulder Imaging

17

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Abstract

The shoulder girdle is frequently involved in acute trauma and overuse in sports. Imaging has an important role in diagnosis and follow-up of articular and extra-articular shoulder lesions. The volume of this chapter is too short to provide in-depth discussion; it has the intention to give a basic and concise overview of the techniques, indications, and diagnosis with focus on staging and novel developments.

Radiographic evaluation remains the cornerstone of primary imaging of the shoulder. Conventional magnetic resonance imaging (C-MRI), MR arthrography (MRA), and ultrasound (US) are increasingly being used to assess presence rotator cuff tears and their extent, and to assist in planning surgical treatment. MRA (direct and indirect) is the most accurate and sensitive available imaging method for the detection of labral tears (glenoid labrum, Bankart and SLAP lesions). Indirect MRA (I-MRA) is more and more regarded as a standard practice in patients with shoulder instability due to suspected labral pathology where further investigative imaging is indicated. CT arthrography (CTA) may be used as an alternative for direct MRA in cases of contraindication for MRI.

Abbreviations

ABER	Abduction and external rotation
AC	Acromioclavicular (joint)
ADIR	Adduction and internal rotation
AIGHL	(Floating) Avulsion of the humeral and glenoid attachment of the IGHL
AIOS	Acquired instability overuse surgical repair
ALPSA	Anterior labroligamentous periosteal sleeve avulsion
ALIPSA	Anterior ligamentous periosteal sleeve avulsion
AMBRII	Atraumatic, multidirectional, bilateral, responds to rehabilitation, inferior capsular shift, interval closure
AS	Anterosuperior
ASI	Anterosuperior impingement
BHAGL	Bony HAGL
BLC	Biceps-labral complex
BPHAGL	Bony posterior HAGL
BT	Biceps tendon
CC	Coracoclavicular ligament
CHL	Coracohumeral ligament
C-MRI	Conventional MRI (without arthrography)
CTA	CT arthrography

D-GEMRIC	Delayed gadolinium-enhanced magnetic resonance of cartilage
D-MRA	Direct MR arthrography
DCO	Distal clavicular osteolysis
FADIR	Flexion adduction and internal rotation
FOV	Field of view
FS	Fat saturated
FTT	Full-thickness tear
GARD	Glenoid articular rim divot
GAGL	Glenoid avulsion posterior band of the IGHL
Gd	Gadolinium
GE	Gradient echo (MRI sequence)
GH	Glenohumeral
GLAD	Glenolabral articular disruption
GLOM	Glenoid labrum ovoid mass
GRID	Glenoid internal rotation deficit
GT	Greater tuberosity
HADD	Hydroxy apatite deposition disease
HAGL	Humeral avulsion of the inferior glenohumeral ligament
IA	Intraarticular
IV	Intravenous
IGHM	Inferior glenohumeral ligament
I-MRA	Indirect MR arthrography
ISP	Infraspinatus
LHB (T)	Long head of the biceps (tendon)
LT	Lesser tuberosity
MGHL	Middle glenohumeral ligament
MR (I)	Magnetic resonance (imaging)
MRA	MR arthrography
MVA	Motor vehicle accident
NPV	Negative predictive value
OA	Osteoarthritis
OCD	Osteochondral disease
PASTA	Periarticular articular sided SSP tendon avulsion
PD	Proton density
PGLAD	Posterior GLAD
PHAGL	Posterior HAGL
PNT	Percutaneous needle tenotomy
POLPSA	Posterior labroligamentous periosteal sleeve avulsion
PPV	Positive predictive value
PRP	Platelet-rich plasma
PTT	Partial-thickness tear
RC	Rotator cuff
RI	Rotator interval
SGHL	Superior glenohumeral ligament
SA-SD	Subacromio-subdeltoid bursa
SE	Spin echo
SI	Signal intensity

SLAC	Superior labrum anterior cuff
SLAP	Superior labrum anterior to posterior (tear)
SNR	Signal to noise ratio
SSC	Subscapularis
SSP	Supraspinatus
STIR	Short tau inversion recovery
T	Tesla
TE	Echo time
TL	Transverse ligament
TR	Repetition time
TSE	Turbo spin echo (FSE, fast spin echo)
TUBS	Traumatic unidirectional instability after Bankart surgery

17.1 Imaging of the Shoulder Girdle

The shoulder girdle is frequently involved in acute trauma and overuse in sports. Imaging has an important role in diagnosis and follow-up of articular and extra-articular shoulder lesions. The volume of this chapter is too short to provide in-depth discussion; it has the intention to give a basic and concise overview of the techniques, indications, and diagnosis with focus on novel findings.

Radiographic evaluation remains the cornerstone of primary imaging of the shoulder girdle in case of acute trauma (glenohumeral and AC dislocation, fractures, strain) and chronic overuse with impingement.

Conventional magnetic resonance imaging (C-MRI), MR arthrography (MRA), and ultrasound (US) are increasingly being used to assess the presence and size of rotator cuff tears to assist in planning surgical treatment (Lenza et al. 2013). C-MRI, MRA, and US have good diagnostic accuracy, and any of these tests could equally be used for detection of full-thickness tears in people with shoulder pain for whom surgery is being considered. MRA (direct and indirect) is the most accurate and sensitive available imaging method for the detection of labral tears (glenoid labrum, Bankart and SLAP lesions). Indirect MRA (I-MRA) is more and more regarded as a standard practice in patients with shoulder instability due to suspected labral pathology where further investigative imaging is indicated (Fallahi et al. 2013). CT arthrography (CTA) may be used as an alternative for direct MRA (D-MRA) in cases of contraindication for MRI.

17.1.1 Radiography and CT

Radiographic examination remains the mainstay and primary imaging examination of the shoulder girdle in case of trauma, glenohumeral and acromioclavicular joint complaints, subacromial impingement, and mass lesions. Radiographic examination of the shoulder includes multiple views to investigate the

Table 17.1 Radiographic examination of the shoulder girdle, series tailored on clinical finding

Clinical question	Radiograph 1	Radiograph 2	Radiograph 3	Alternative
AC dislocation	AC joint at rest	AC joint standing with weight 10 kg in the hand	Scapular Y view	Alternative US without and with cross arm test
Clavicula fracture Sternoclavicular joint	Clavicula PA	Clavicula AP caudocranial tilted 15°	Clavicula AP craniocaudoal tilted 15°	CT better evaluation of sternoclavicular joint
Glenohumeral joint dislocation, (osteo) arthritis, proximal humerus (stress) fracture	Glenohumeral joint standing ¾ rotated to the joint	Scapula standing axial view (scapular Y view) 90 % rotated in comparison with radiograph 1	Glenoid: post reduction: axial view prone for detection of bony Bankart	CT: better detection of bony Bankart
Scapula	Scapula AP	Scapula standing axial view with elevation of humerus		CT: no superposition of ribcage
Subacromial impingement	Glenohumeral joint standing ¾ rotated to the joint	Axial view of the scapula (scapular Y view) 90 % rotated in comparison with radiograph 1	Glenohumeral joint, AP view prone: evaluation of subacromial space	MRA-MRI: bone and tendon evaluation
Sternum	Lateral view			CT

glenohumeral and acromioclavicular (AC) joint, manubrioclavicular joint, scapula, clavicula, and humerus (Table 17.1) (White et al. 2008). Radiographs are tailored on the clinical findings and questions. Specific trauma series of the glenohumeral joint, AC joint, clavicula, and scapula are performed to document dislocations and fractures (Table 17.1) (Smekal et al. 2008; Schnabel et al. 2004; Philipp et al. 2004). Also specific series with images in prone and standing positions are made in case of glenohumeral joint disease (degenerative or inflammatory) and subacromial impingement complaints (Fig. 17.1a–c) (Table 17.1). Subacromial impingement series include axial images of the scapula (scapular Y view) to describe acromion types according to Bigliani and Gagey (Natsis et al. 2007). Generally radiographic examination is reduced to 2 or 3 views; specific views are avoided and substituted by non-enhanced reduced radiation dose volume CT with two-dimensional and three-dimensional multiplanar reconstructions (Kuhlman et al. 1988). Radiographs are indicated for postoperative evaluation and follow-up of osteosynthesis and prosthesis.

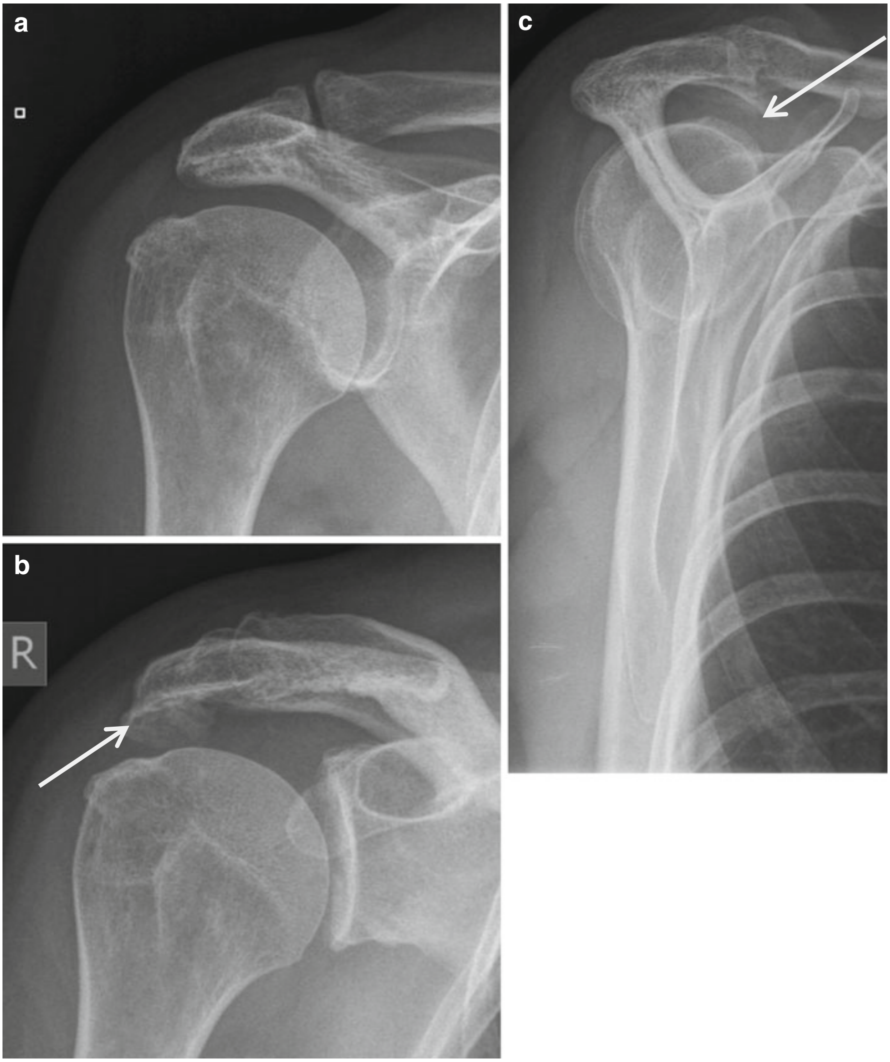


Fig. 17.1 (**a**–**c**) Radiograph of the glenohumeral joint, subacromial impingement series, including AP view (**a**) in prone position for evaluation of the subacromial space and AC joint, standing ¾ view of the glenohumeral joint (**b**) and standing scapular Y view for evaluation of subacromial spur (*arrow*) and acromion shape type 2 (*curved*) according to Bigliani

17.1.2 Ultrasound

Ultrasound is a cost-effective and accurate examination for the evaluation of the RC, SA-SD bursa, the AC joint, extra-articular and rotator interval (RI) part of the CL biceps, and other shoulder girdle muscles except for the SSC. Rutten compared the performance of US, 1.5 T C-MRI, and 1.5 T D-MRA (Rutten et al. 2010). He concluded that following US of the shoulder performed by a dedicated radiologist, MRI offers little additional value, with regard to the detection of rotator cuff tears. Personal expertise plays a crucial role in choosing which imaging technique will be used (Rutten et al. 2010) (Table 17.1). As a result of the low therapeutic consequence of non-detection of low-grade partial-thickness RC tears, US is regarded as the primary investigation tool. Advantage of US over MRI is the dynamic evaluation of impingement during elevation or endorotation. The long head tendon of the biceps (LHB) in its extra-articular course and the peripheral part of the biceps pulley and interval area is accurately demonstrated. Acromioclavicular joint capsule integrity and dislocation is evaluated in rest and dynamically during cross arm test or by compression of the lateral half of the clavicula. The glenohumeral joint is not documented on US examinations except for the joint cavity on posterior cranial approach.

17.1.3 MRI Examination Procedure

MRI is the only technique that covers all anatomic areas, including bony and soft tissue structures of the shoulder girdle.

MRA is the best technique to study the glenohumeral joint. In direct MRA (D-MRA) the shoulder joint can be approached from anterior and posterior. The posterior approach has the advantage that contrast extravasation in the anterior structures and erroneous interpretation are avoided. A small amount of iodinated contrast radioscopically to prove intraarticular needle position is followed by 10 ml Gd 1/200 solution; ready-to-use diluted Gd-DOTA solutions are commercially available (Artirem®).

I-MRA is an MR technique improving articular and periarticular contrast compared to D-MRI. It is achieved by injection of paramagnetic MR contrast media intravenously (IV). After the IV injection, exercising the joint for an average of 15 min. results in considerable signal intensity increase within the joint cavity and in pathologic tissue. The method is less invasive than D-MRA.

FS MR sequences yield arthrographic images (Figs. 17.2a–c, e and 17.3a–d). Three to the glenoid orthogonal imaging planes are used in neutral arm position (Fig. 17.3a–d and Table 17.2). ABER position (abduction and external rotation) is described by Tirman to improve detection of lesions of the anterior-inferior labral pathology, articular sided tears of the infraspinatus, and posterior impingement lesions (Fig. 17.11) (Tirman et al. 1994a, b; Cvitanic et al. 1997). Other positions may be used as there are ADIR (adduction and internal rotation) or FADIR (flexion adduction and internal rotation). FADIR positioning appears to be a useful adjunct in evaluating patients with equivocal or subtle posteroinferior labral abnormalities on conventional MRA sequences (Chiavaras et al. 2010).

It is expected that with use of 3 T MRI or higher magnetic fields the increased contrast and spatial resolution on T2 or intermediate TE WI FS will lead to better evaluation even without gadolinium administration (Fig. 17.21a, b).

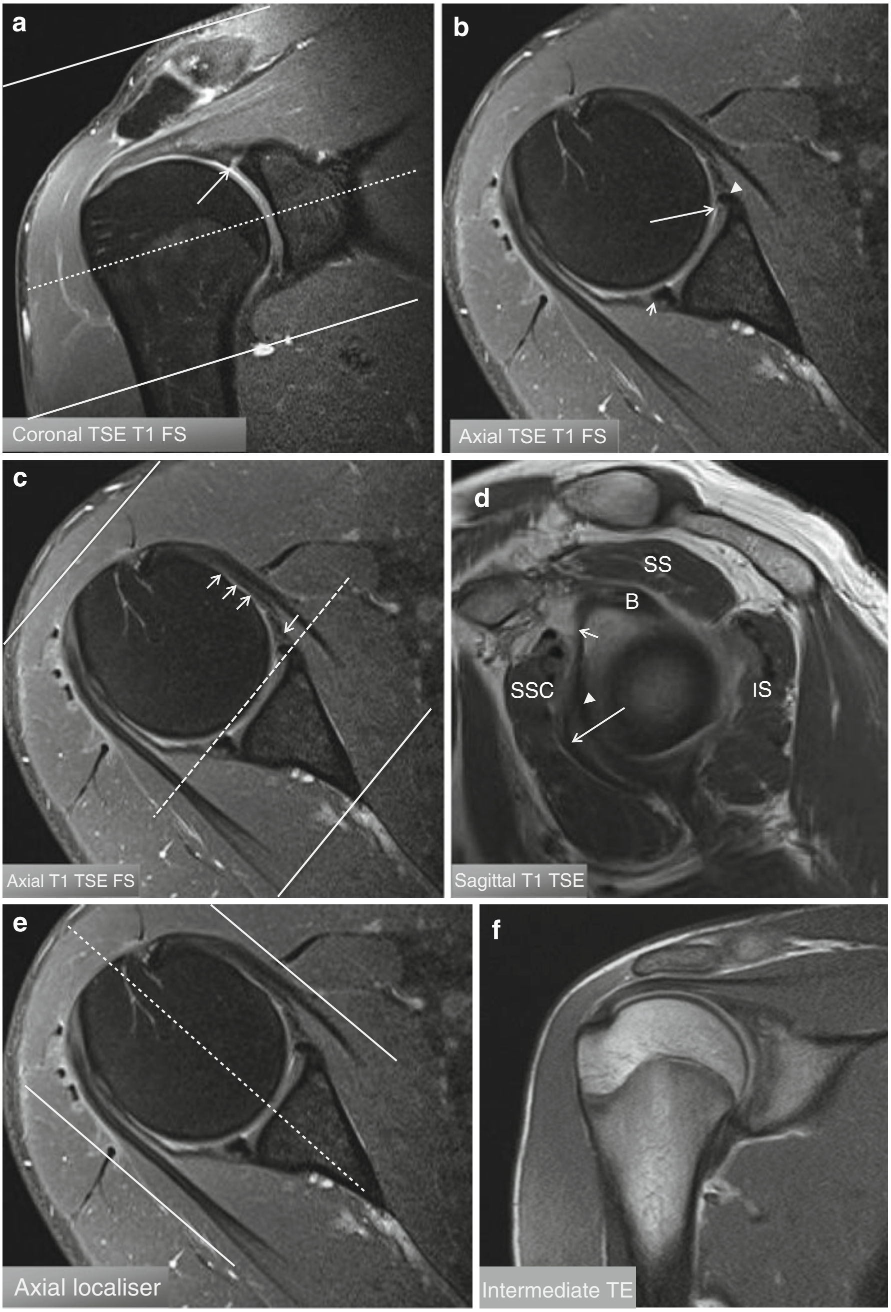


Fig. 17.2 (**a**–**f**) Three imaging planes orthogonal to the glenoid articular surface. (**a**) Mid-glenoid coronal image with demonstration of axial imaging plane and imaging volume perpendicular to the glenoid articular surface. (**b**) Axial imaging plane at the *dotted line* in (**a**). (**c**) Mid-glenoid axial image with demonstration of sagittal imaging plane and imaging volume parallel with the glenoid articular surface. *Arrow*: middle glenohumeral ligament. *Short arrow*: superior glenohumeral ligament. *Arrowhead*: anterior labrum. (**d**) Sagittal imaging plane at the *dotted line* in (**c**). (**e**) Mid-glenoid axial image with demonstration of coronal imaging plane and imaging volume parallel with the glenoid articular surface. (**f**) Coronal imaging plane at the *dotted line* in (**c**)

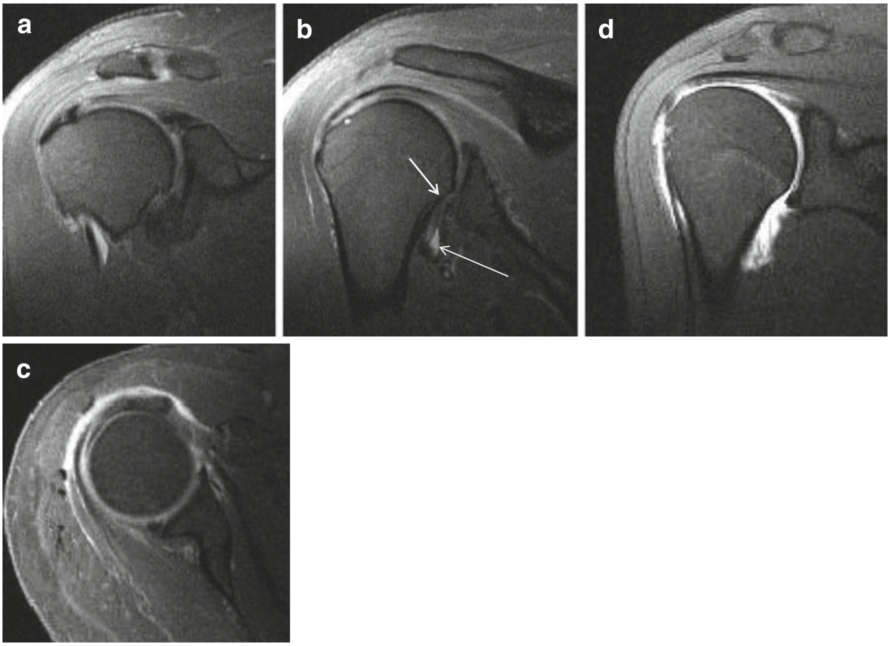


Fig. 17.3 (**a**–**d**) Comparison of 1.5 T I-MRA and 1.5 T D-MRA on T1-WI with FS in a normal shoulder joint. (**a**–**c**) I-MRA in coronal (**a, b**) and axial (**c**): gadolinium enhancement at the AC joint, glenohumeral joint with tendon sheath of CL, and SA-SD bursa. (**d**) D-MRA in coronal imaging plane: gadolinium enhancement at the glenohumeral joint only, axillary joint capsule insertion on humerus (*b short arrow*), axillary pouch of joint recess filled with gadolinium (*b long arrow*)

Table 17.2 Imaging sequences MRA of the shoulder

1. T1 FS para-axial slice thickness 3 mm
2. T1 FS paracoronal slice thickness 3 mm
3. T1 FS parasagittal slice thickness 3 mm
4. PD and T2 FS paracoronal slice thickness 3 mm
5. T1 parasagittal thickness slice 4 mm

17.1.4 CT Arthrography

CTA generally is substituted by MRA (D-MRA or I-MRA). For cartilage lesions and intraarticular lesions of the biceps, an improved detection of lesions is reported. Omoumi et al. compared CTA and D-MRA with arthroscopy prospectively for hyaline cartilage lesions (Fig. 17.4a, b). They found only moderate diagnostic performance for both techniques, although better for CTA (sens 46.4–82.4 %; spec 89.0–95.9 %) compared to D-MRA (sens 31.9–66.2 %; spec 91.1–97.5 %) (Omoumi et al. 2014).

17.2 Normal Anatomy and Variants

Normal anatomical variants have to be recognized and discriminated from relevant pathology. Variant anatomy may have a role in symptomatic shoulder complaints (Zhang et al. 2014).

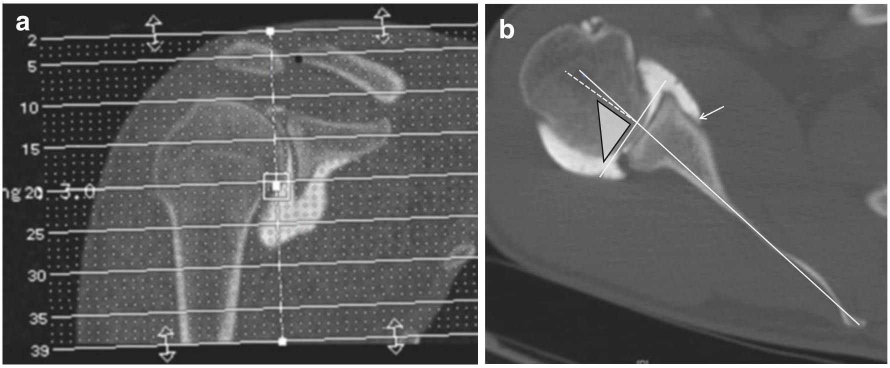


Fig. 17.4 (**a**, **b**) Glenoid version. Glenoid version is calculated on axial reconstructed multiplanar images perpendicular to the glenoid articular surface in the coronal and axial imaging plane; this is the true glenoid axial plane (**a**). The image inferior to the base of the coracoid process is selected (**b**). Tangent line to the lateral margin of the labrum is drawn, and the axis of the scapula is defined and drawn (**b**). A line perpendicular to the glenoid tangent is drawn (**b** *dotted line*). In retroversion negative version angles are calculated. In calculation of glenoid version. Anterior glenoid capsule insertion (*b arrow*)

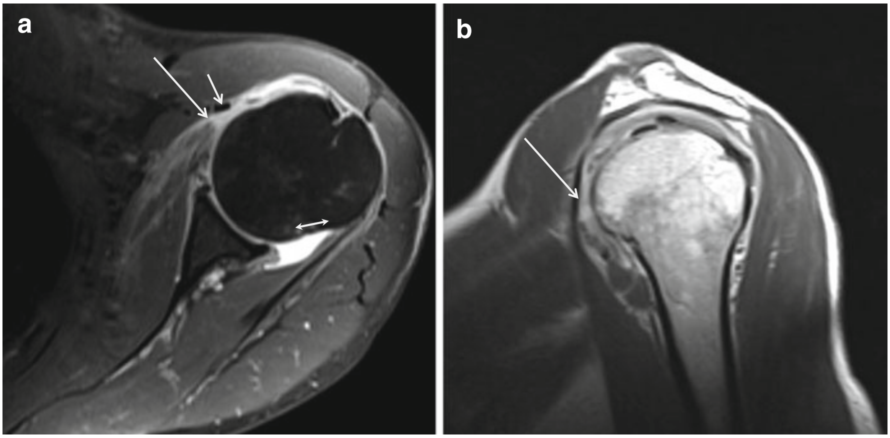


Fig. 17.5 (**a**, **b**) A 3 T I-MRA of left shoulder in patient with complaints of subcoracoidal impingement. (**a**) Axial T1-WI FS. (**b**) Sagittal T2-WI. Major expansion of the synovial space related to increased amount of synovial fluid demonstrated on (**a**). Bare area posterior (**a** *double headed arrow*) medial to capsular insertion not covered with hyaline cartilage. Complete SSC tendon tear (**a**, **b** *arrow*) with retraction medial tot the coracobrachial tendon (**a** *short arrow*)

17.2.1 Cartilage and Glenoid Variants

Humeral head cartilage is thicker centrally; a bare area, not covered with cartilage, is located posterior cranial at the humeral head at the junction of joint capsule and articular cartilage (Fig. 17.5a). This bare area should be discriminated

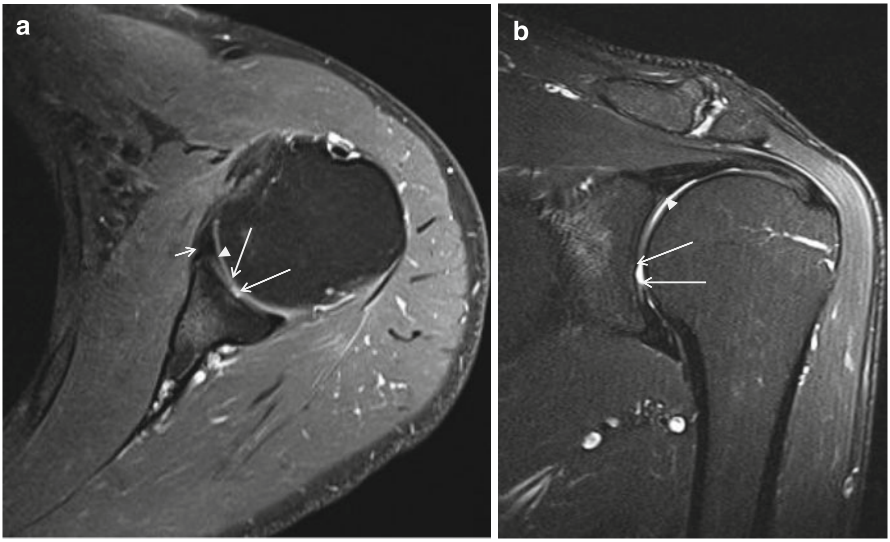


Fig. 17.6 (**a**, **b**) Normal variant, bare area humeral head, 3 T I-MRA, TSE T1-WI with FS. (**a**) Axial and (**b**) coronal mid-glenoidal imaging planes with centrally located defect at the hyaline cartilage (margins of the defect are marked with *long arrows*), labrum (*short arrow a*), labrocartilaginous junction (*arrowhead b*)

from Hill-Sachs impact. Hill-Sachs lesion starts more superiorly above the level of the coracoid process on axial images. An additional bare area has been described between the supraspinatus insertion on the greater tuberosity and the adjacent articular cartilage. Failure to recognize and account for these bare areas at imaging may lead to erroneous diagnosis or overestimation of SSP partial-thickness tears (PTT).

The glenoid articular surface is located in 7° retroversion if calculated in the true glenoid axial plane (Rouleau et al. 2010). Glenoid retroversion should be calculated orthogonal to the glenoid articular surface; this is called the true glenoid axial plane. This true glenoid axial plane includes reconstructed multiplanar images with inclination in the axial and coronal imaging plane (Fig. 17.4a). If a strict axial imaging plane is chosen, retroversion is overestimated. Optimally the lateral labral margin has to be included in the glenoid tangent (this implies MRI or CTA) (Fig. 17.4a, b). Decreased retroversion leads to increased risk of anterior dislocation. The most frequent cause of reduced retroversion is Bankart lesion with or without bony fragment.

The cartilage of the glenoid is thinner centrally. The tubercle of Assaki is a central thickening of subchondral bone at the level of this cartilage thinning (De Wilde et al. 2004). Infrequently a bare spot of focal well-demarcated articular cartilage defect at the central aspect of the glenoid is present (Fig. 17.6a, b); this condition is less frequent in children.

The glenoid can be shallow or hypoplastic predisposing to instability.

17.2.2 Labral Variants

The glenoid labrum is a ring of fibrocartilaginous tissue that surrounds the glenoid rim (Fig. 17.2d). The labrum increases the depth of the glenoid cavity, functions as a pressure seal (negative pressure) during motion, and provides stability and shock absorption to the shoulder joint. Transverse sections of the labrum reveal commonly a triangular shape (anterior 64 %; posterior 47 %) (Figs. 17.2b and 17.6a short arrows); it may be rounded (anterior 17 %; posterior 33 %) (Fig. 17.2b arrowhead) or rarely flat, cleaved, notched, or even absent (Figs. 17.7 and 17.8 arrows). The size has a broad variation from 2 to 14 mm leaving size criteria of little diagnostic use. Also the SI of the labrum is variable (Loredo et al. 1995). Initially the labrum was considered to be of low SI on all MR pulse sequences.

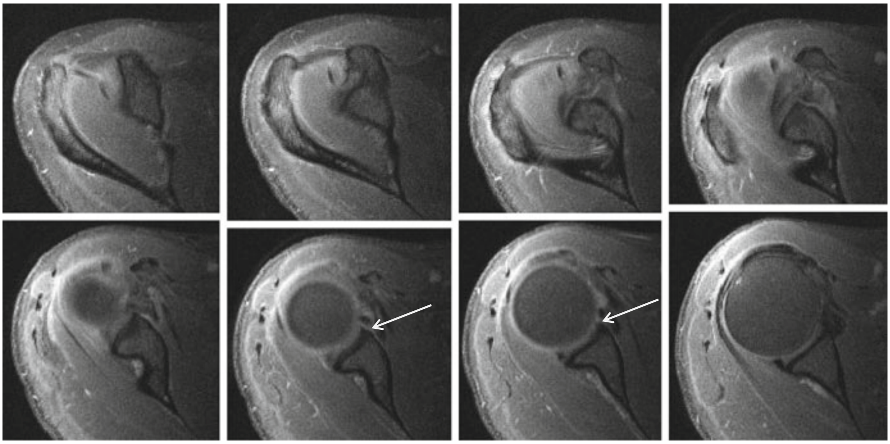


Fig. 17.7 Anterior labral variants: sublabral foramen documented on 3 T I-MRA. I-MRA with series of axial images superior to the glenoid up to the middle third of the glenoid. Sublabral foramen (*arrow*) is detected at the anterior half of the glenoid

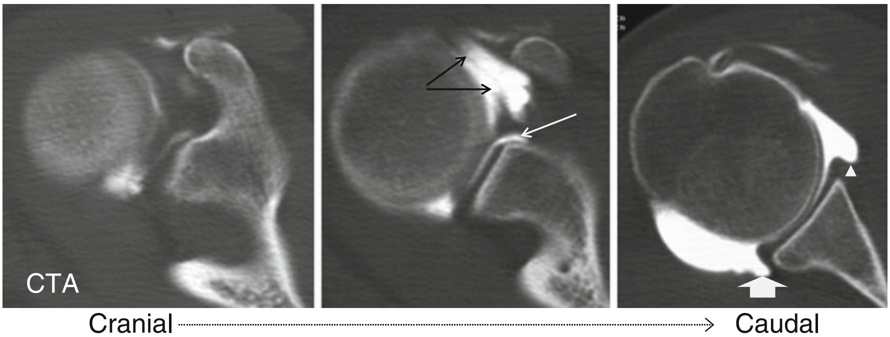


Fig. 17.8 Anterior labral variants: sublabral foramen documented on CTA. CTA with axial images, sublabral foramen (*arrow*)

Table 17.3 Variability of SI of the glenoid labrum

Diffuse low
Central round high SI
Diffuse high SI
Transverse linear high SI
Longitudinal linear high SI
Triangular high SI

Table 17.4 Bicipitolabral complex (BLC)

Type I BLC Labrum is firmly attached to the glenoid rim. No intervening cartilage or central free edge (Fig. 17.6b arrowhead)
Type II BLC attachment of BLC to the glenoid occurs more medially. Continuation of the hyaline cartilage under the labrum. Accompanied by a small synovial-lined sulcus between the labral free edge and the cartilage (Fig. 17.2a arrow)
Type III BLC prominent triangular meniscoid labrum. Deep recess that may be continuous with a sublabral foramen (Fig. 17.8)

More recent studies have identified areas of increased linear or globular signal intensity in nearly a third of arthroscopically normal labrum tissue (Table 17.3). Posterosuperior labrum increased signal is possibly related to magic angle phenomenon (B0 of 55° on 1.5 T).

The superior portion of the labrum can be mobile and lax, a variant that is recognizable with arthroscopy.

The superior and anterosuperior regions of the labrum have the poorest blood supply, which slows the healing process of SLAP tears in this location.

The labrocartilaginous transition may present as an abrupt transition with the labrum demonstrating a free edge margin (type A attachment) (Fig. 17.2b, arrow) or the transition zone may blend with the hyaline cartilage (type B attachment) (Fig. 17.6a arrowhead) (Dunham et al. 2012).

17.2.2.1 Superior Labrum Variants

Fifty percent of the biceps tendon fibers arise from the superior glenoid labrum and the remainder from the supraglenoid tubercle. Three distinct types of biceps-labral complex (BLC) are recognized (Table 17.4) (Figs. 17.6b arrow and 17.2a arrow). A bicipital labral sulcus is a cleft between the labrum and the biceps.

17.2.2.2 Anterosuperior Labrum Variants

Sublabral recess, sublabral foramen, and Buford complex are frequent variants of the anterior labrum (Kreitner et al. 1998).

- *Sublabral recess* (type II and III BLC) represents the most frequent normal anatomic variant of the anterior superior labrum. A recess deeper than 2 mm is present in 39 % of specimens. It follows the contour of glenoid cartilage and is smooth, with 1–2 mm width, and has no extension to superior labrum. A perilabral cyst is

Table 17.5 Three classic key features to differentiate a sublabral recess from a SLAP tear

Location: sulcus typically extends only to the most posterior insertion point of the biceps tendon attachment to the labrum and glenoid
Contour: smooth margins: more likely sulcus. Irregularity in the contour: suspicious for SLAP tear
Orientation: extension laterally more likely tear

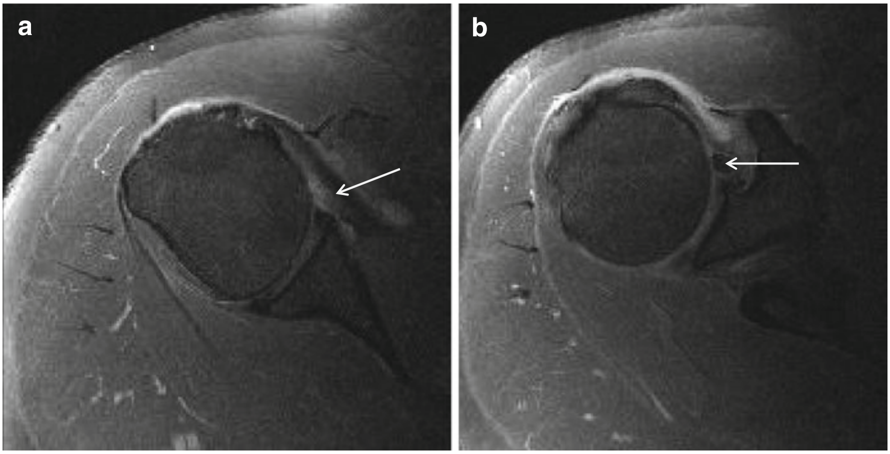


Fig. 17.9 (**a**, **b**) Anterior labral variants: Buford complex demonstrated on 3 T I-MRA. I-MRA with axial T1 FS images in middle third (**a**) and at the cranial third of the glenoid (**b**) demonstrating absent anterior labrum A and thick middle glenohumeral ligament (Buford complex) (*arrow* **a**, **b**)

not present. The recess can extend posterior from the biceps tendon. Three classic key features differentiate recess from a SLAP tear (Table 17.5).

- A *sublabral foramen* is detected in 10–15 % of arthroscopies and located between 1 and 3 o'clock. An associated osseous indentation is possible (Figs. 17.7 and 17.8). It should not extend below the level of the mid-glenoid notch. It can be attached to the anterior-inferior labrum through a "labral slip": a communication between the glenohumeral joint and the subscapularis recess is found. Seventy-five percent are associated with cordlike MGHL (Buford), and a sublabral foramen may coexist with a sublabral recess. A foramen is differentiated from a labral tear or loosening based on the smooth margins of the foramen, the lack of associated traumatic injuries in the adjacent capsuloligamentous structures, and absence of significant displacement (<1–2 mm) of the detached labrum. Joint fluid that accesses to the subscapularis recess through the sublabral foramen should not be misinterpreted as a type II SLAP tear with associated paralabral cyst.
- In *Buford complex*, which is found in 6 % of shoulder arthroscopies, the antero-superior labrum is absent with thickening of middle glenohumeral ligament (MGHL) (Figs. 17.9a, b and 17.10a, b). If the cordlike structure is followed on consecutive axial images, the superior origin and distal capsular merge is demonstrated. An increased association of Buford complex and sublabral foramen

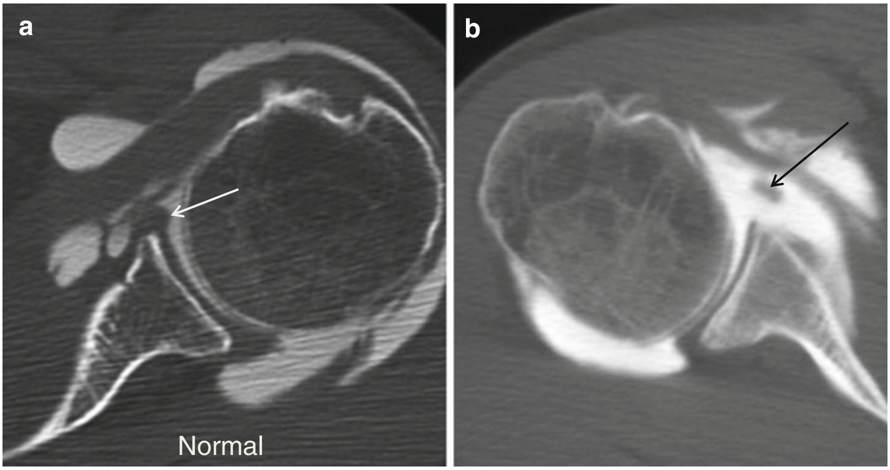


Fig. 17.10 (**a**, **b**) Anterior labral variants: Buford complex demonstrated on CTA. Axial mid-glenoidal image of left normal shoulder (**a**) demonstrating normal anterior labrum (**a** *arrow*) and axial mid-glenoidal image of right shoulder (**b**) demonstrating thick middle glenohumeral ligament (**b** *arrow*) an (**d**) absent labrum in Buford complex

with SLAP lesions is reported in literature. The presence of anterosuperior labral variant anatomy may result in higher stress on the superior BLC, predisposing to injury.

17.2.3 Glenohumeral Ligaments and Variants

- The *SGHL* is nearly invariably present, in 97 % at arthroscopy. Variants include a common origin with the MGHL and/or direct origin from the biceps tendon. A rare variant is a SGHL origin from the posterior labrum with a course overriding the biceps tendon origin without attaching to the anterior labrum or MGHL. Normally the SGHL is rather thin but may be thickened in patients with an underdeveloped or absent MGHL. Distally the SGHL merges with the coracohumeral ligament (CHL) to form the CL biceps pulley (Fig. 17.2d small arrow). Distally the CL biceps pulley fuses with the anterior part of the SS and inserts on the greater and minor humeral tubercle and thus acts as a stabilizer of the CL biceps at the entrance of the intertubercular sulcus.
- The *MGHL* has a variable origin, merges with the anterior capsule along SSC, and inserts on the lesser tubercle (Fig. 17.2d long arrow and c short arrows). The structure is well demonstrated if followed on continuous axial slices. It is redundant in internal rotation and stretched in external rotation and limits anterior translation in 60–90° shoulder abduction. The MGHL has a variable origin, either on labrum (Fig. 17.2c medial short arrow) or medial to the labrum (Fig. 17.4b arrow); it may have a common origin with the SGHL and biceps

tendon or have a conjoined origin with the biceps tendon alone or on the IGHL. The MGHL is absent in 1/3th of the shoulders; this finding is associated with prominent subscapular recess. It may be cordlike in Buford complex with absent AS labrum (Figs. 17.9a, b and 17.1a, b). Longitudinal splitting or duplication of the MGHL has been reported as a normal variant or a partially healed longitudinal split tear of the MGHL. The foramen of Weitbrecht is located between the SGHL and MGHL (Fig. 17.8 black arrow). If the MGHL is absent, a single large communication with a redundant subscapular recess is present. A thickened and high riding MGHL may lead to narrow the foramen. A sublabral foramen may present as a pseudoparalabral cyst. The foramen of Rouvière is located between the MGHL and IGHL.

- The *IGHL* is composed of an anterior band ("U shape"), and between those posterior band the axillary recess. It represents a fibrous thickening of the shoulder capsule and is the most consistently present and the most important stabilizator of GH joint. The anterior band runs from the mid-glenoid notch, between 2 o'clock and 4 o'clock, and is thicker than the posterior band. In ABER position (Fig. 17.11a–c arrows), the anterior band of the IGHL becomes taut and is well visualized along its entire course. A high origin anterior band should not be mistaken for an anterior labral tear on MRA. The posterior band has its origin between 7 o'clock and 9 o'clock. Two distinct patterns of humeral insertion are recognized: (1) collar-like attachment in which the entire IGHL inserts slightly inferior to the articular edge of the humeral head (Fig. 17.3b arrow) and (2) a V-shaped attachment in which the anterior and posterior bands of the IGHL attach adjacent to the articular edge of the humeral head. The axillary pouch attaches at the apex of the V distal to the articular edge.
- Variant origin of the anterior band of the IGHL from the MGHL is described; also a high origin anterior band is described and could be mistaken for an anterior labral tear on MRA. The insertion of the inferior glenohumeral ligamentous complex on the surgical neck of the humerus frequently results in a jagged appearance on axial images. The posterior band may be thicker than the anterior band. A band of connective tissue also called "the periarticular fiber system" attaches the IGHL to the SGHL (Huber and Putz 1997).
- A *spiral GHL* arises from the axillary component of the IGHL and the infraglenoid tubercle and courses laterally to fuse with the MGHL and may be demonstrated on axial and oblique sagittal MRA planes (Merila et al. 2004).

17.2.4 Capsular Insertions

Three types of anterior capsule insertion are recognized. Type I with insertion at the glenoid margin (Fig. 17.2c medial arrow), type II inserts at the glenoid neck (Fig. 17.8 arrowhead), and type III inserts more medially along the scapula (may predispose to instability) (Fig. 17.4b arrow). Do not misinterpret over-distension of

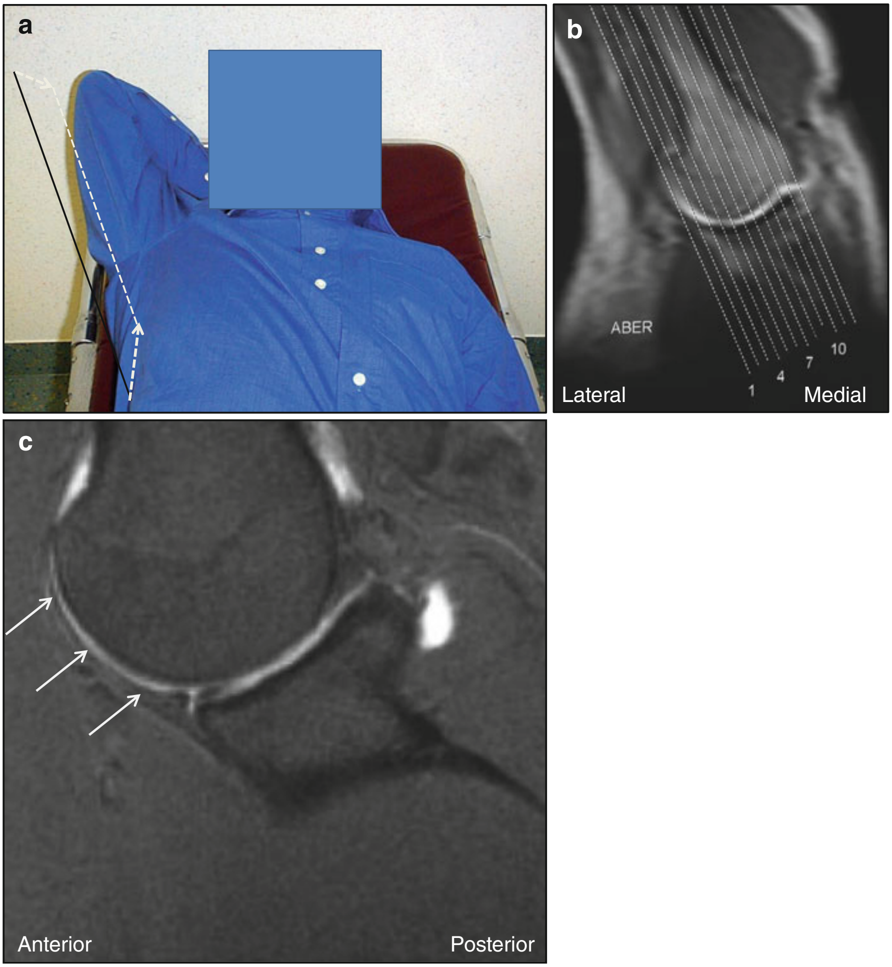


Fig. 17.11 (**a**–**c**) MRI in ABER position. (**a**) Prone position with shoulder in abduction and external rotation; imaging plane C is drawn. (**b**) Localizer image in to the glenoid coronal plane. This plane is used to plan the to the glenoid sagittal imaging plane C. (**b**) 1,4,7,10 slice positions in glenoid coronal plane

the joint capsule as a type III capsular insertion. The posterior capsule should always insert on the glenoid rim (Fig. 17.8 thick arrow)!

17.2.5 Biceps Pulleys and Rotator Interval

The biceps pulleys are the coracohumeral ligament (CHL), SGHL, and transverse ligament (TL) (Fig. 17.12a–c).

RI is the triangular space at the anteriosuperior aspect of the glenohumeral joint between the SSP and SSC tendons, the coracoid process as its base, the superior

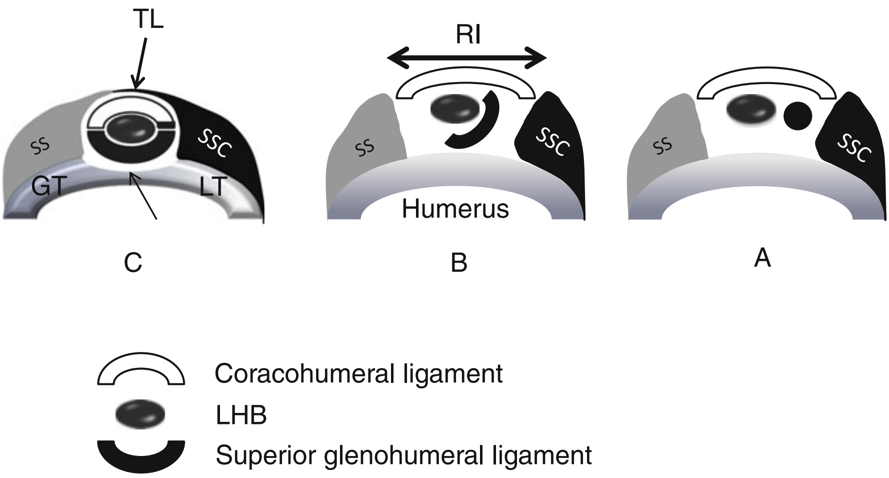


Fig. 17.12 (**a**–**c**) Schematic drawings of transverse cuts of the biceps pulley. (**a**) Near the origin of the ligaments at the base of the coracoid process. (**b**) Middle third of rotator interval (*RI*). (**c**) Lateral at the entrance of the LHB in the intertubercular groove (*thin arrow*), the LHB is covered by the transverse ligament (*TL*) that is anatomically an extension of the SSC tendon. Medially (**a**) the SGHL and GHL are distinct structures with separate origin at the base of the coracoid process. Centrally (**b**) the superior glenohumeral ligament and coracohumeral ligament fuse anteromedially to form a pulley that most laterally (**c**) fuses anteriorly with the minor tubercle and SSC and latero-superior to the SSC and greater tubercle of the humerus. In this area the pulley is covered by the TL

aspect of the intertubercular groove as its apex. The CHL is sometimes described as a capsular fold rather than a true ligament located at the superficial (bursal) aspect of the glenohumeral joint capsule in the RI. The lateral band (largest) inserts on the greater tubercle and merges with the SSP; the medial band (smallest) merges with the SGHL and inserts on the lesser tubercle and SSC. The SGHL runs over the scapular neck, and glenoid parallels intraarticular the course of the LHB tendon. Together with CHL it forms a U-shaped anterior sling extending along the LHB tendon that limits medial subluxation of the intraarticular LHB tendon over the edge of the lesser tuberosity (Fig. 17.12a–c) (Ho 1999; Weishaupt et al. 1999; Schaeffeler et al. 2012; Nakata et al. 2011; Tagliafico et al. 2014; Zanetti and Pfirrmann 2004).

17.2.6 Long Head of the Biceps

The presence of one or more supernumerary heads of the LHB tendon is described. The prevalence of a three-headed biceps brachii is estimated to be 10–20 %. The origin is located at the supraglenoid tubercle and superior labrum, the second slip adjacent to the LHB tendon origin and at the

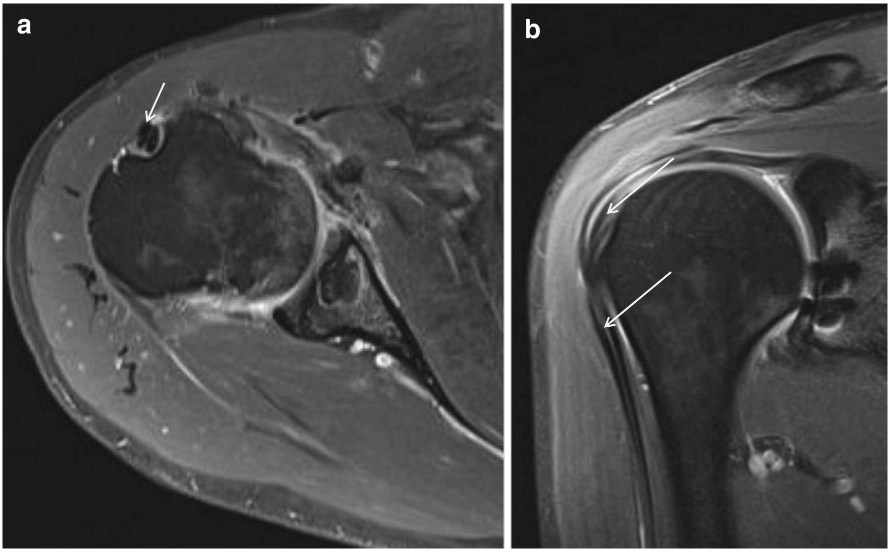


Fig. 17.13 Split long head of the biceps tendon, 3 T I-MRA. Axial T1-WI FS (**a**) and coronal T1-WI FS (**b**) showing two LHB tendons (*arrows*) at intertubercular groove (**a**, **b**) and superior to the groove (**b**)

glenohumeral joint capsule, and the third slip at the margin of the greater or lesser tuberosity at the proximal aspect intertubercular groove (Vinson et al. 2012). Two separate tendons are visible in the intertubercular groove (Fig. 17.13a, b). The accessory tendon is often flat in appearance (Fig. 17.13a arrow), the adjacent LHB tendon more rounded. It is difficult or impossible to distinguish between an accessory tendon and a longitudinal tear. Features that favor an accessory tendon are the flattened appearance and most important the separate site of origin for the accessory tendon.

A complete absence of the intraarticular portion of the tendon is very rare.

Variants at the anchor and proximal IA LHB variants are also known. In the absence of the normal glenoid origin, the tendon is adherent to or incorporated within the superior joint capsule. A “bifurcate” or “Y-shaped origin” of the LHB tendon is described with two separate origins that merge together before exiting the joint as a single tendon (one from glenoid, one from rotator cable or superior capsule) (Wittstein et al. 2012). Prevalence is about 2 %.

Aberrant intraarticular origin of the LHBT from the anterior edge of the supraspinatus tendon may contribute to symptomatic concomitant rotator cuff pathology; these patients are treated with tenodesis of the LHBT to relieve symptoms (Zhang et al. 2014). Possible lack of extension of intraarticular contrast material into the intertubercular groove is mostly misinterpreted as biceps tear. The clue to the diagnosis is the absence of such features as a tendon stump, tendon degeneration, and retracted distal tendon.

17.3 Pathology

17.3.1 Clavicle, AC, and Sternoclavicular Joint

Clavicle fracture and AC instability are frequent findings in contact sports and fall of bikers. Acute sternoclavicular joint subluxation/dislocation is a rare finding.

Radiography is useful for the initial assessment of suspected disorders of the clavicle, sternoclavicular, and acromioclavicular joints.

Radiographically two AP views for the clavicle and AP and scapular Y views for the AC joint are made (Table 17.1).

US has been described as a screening tool to assess possible sternoclavicular joint dislocation; however, it is usually used only if CT and MRI are not readily available.

AC joint instability is graded by Tossy-Rockwood in six types (Table 17.6). US to grade AC joint instability is as reliable as radiographic measurement (Kock et al. 1994; Heers and Hedtmann 2005, Tossy et al. 1963; Rockwood et al. 1996). Disrupted deltoid and trapezius insertion and common fascia were demonstrated on US in all patients classified according to Rockwood's classification as type V, half of the patients classified as type IV, about a quarter of patients classified as type III, and only in a minority type II injuries (Table 17.6).

Although US is increasingly used as a primary investigation tool to demonstrate AC dislocation in a dynamic way (during cross arm test or with compression of the clavicle), it has a limited role in the evaluation of the AC joint itself, where it is most useful to exclude the presence of joint inflammation with increased joint fluid and Doppler signal (Heers and Hedtmann 2005; Matter et al. 1995). If joint fluid is detected on US, it is considered a nonspecific finding, which could represent active inflammation or simply joint effusion due to degenerative osteoarthritis.

CT allows excellent visualization of the articular surfaces, osseous changes, subtle or complex fractures, and joint malalignment, with a rapid scan time, making it particularly helpful in the workup of trauma patients. With its multiplanar capabilities and superior soft tissue resolution, MRI is a very effective modality for characterizing soft tissue injuries, inclusive of ligamentous tears and cartilaginous injuries. In the specific case of posterior sternoclavicular dislocations, both CT and MR angiography can be very helpful in elucidating occult associated vascular injury (Ernberg and Potter 2003).

Radiographs, CT, US, and MRI may show widening of the AC joint space in painful traumatic and even atraumatic stress-induced distal clavicular osteolysis (DCO). Cutoff width of the normal AC joint is <5 mm; right and left differ by no more than 2–3 mm. Atraumatic DCO has been described in adult athletics. The combination of weightlifting and overhead activity (basketball, volleyball, tennis, swimming) is a risk factor for atraumatic DCO. Long-term sequelae DCO include widening of the AC joint and AC joint osteoarthritis. About 80 % of patients present with flattening of the distal clavicle and interval widening of the AC joint to a mean of 5.0 mm (Cahill 1982; de la Puente et al. 1999; Kaplan and Resnick 1986; Murphy et al. 1975; Levine et al. 1976; Roedl et al. 2015). Posttraumatic and stress-induced

Table 17.6 Tossy-Rockwood classification AC instability

	Type I	Type II	Type III	Type IV	Type V	Type VI (rare)
AC ligament	I–II	III	III	III	III	III
CC ligament	0	I–II	III	III	III	III
Joint capsule	0	III	III	III	III	III
Deltoid muscle detachment	0	II	III	III	III	III
Trapezius muscle detachment	0	II	III	III	III	III
Clavicle (radiograph, US)	Not elevated with respect to acromion	Minor elevation with respect to acromion	Elevation of one clavicula height with respect to acromion	Clavicle displaced posteriorly into trapezius	Coracoclavicular distance more than double than normal (>25 mm)	Clavicle inferiorly displaced behind coracobrachialis and biceps tendons

CC coracoclavicular ligament, *I-II-III* capsule or ligament grade sprain, muscle sprain grade I – II and III, *0* normal

DCO have similar appearances on MR imaging, the most common and conspicuous MR imaging feature being increased T2 signal intensity in the distal clavicle (Kaplan and Resnick 1986).

17.3.2 Glenohumeral Instability, Microinstability, and Internal and External Impingement

17.3.2.1 Labral Pathology

Labral pathology is found in athletes with instability and in repetitive microtrauma and trauma and related to aging and degeneration. Degenerative labrum lesions are characterized by mucoïd degeneration, calcifications, synovialization with alterations in morphology, and SI of the labrum (Loredo et al. 1995). The abnormal morphology should be described with possible fraying, absence, detachment, displacement, fragmentation, deformity, or flap tear.

17.3.2.2 Shoulder Instability

The shoulder joint is the most unstable joint. The etiology of instability can be traumatic or atraumatic. Instability is classified according to the severity (microinstability, subluxation, and dislocation) and according to the direction (unidirectional–multidirectional).

Macroinstability is most often anterior (90 %) and much less frequent posterior (5 %), rarely inferior (luxatio erecta) or superior. Superior dislocation resembles RC rupture. Associated fractures and labroligemantous lesions should be excluded. After traumatic shoulder dislocation (treated non-operatively), the likelihood of repeat dislocation depends on patient age and the date of the initial injury. Patients younger than 20 years have a higher risk of recurrent dislocation (>90 % when subluxation events are included) than those older than 40 years (<10 %).

Multiple categories of microinstability are described. AMBRII (atraumatic, multidirectional, bilateral, responds to rehabilitation, inferior capsular shift, interval closure) is found in young females and present with capsular laxity or hypoplastic glenoid labrum. TUBS is traumatic unidirectional instability after Bankart surgery. AIOS is acquired instability related to overuse with surgical repair and often found in athletes doing throwing sports or swimming.

Shoulder dislocation is primarily investigated with radiographs and trauma series (Fig. 17.14a, b and Table 17.1). Secondarily MRA or CTA is performed for the evaluation of labrum, ligaments, tendons, and cartilage.

17.3.2.3 Anterior-Inferior Labrum Lesions

Anterior-inferior capsuloligamentous, labrum, and glenoid lesions are related to anterior shoulder dislocation and may lead to habitual dislocation and shoulder instability.

- *Bankart* lesion is a detachment of anteroinferior labrum and IGHL from the glenoid rim with rupture of the periosteum but no cartilage damage (Fig. 17.15).

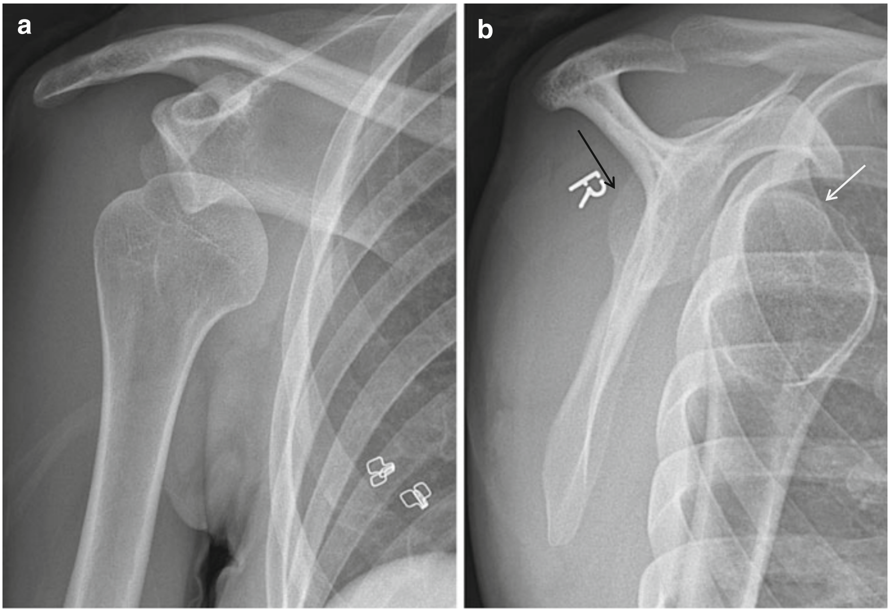


Fig. 17.14 (**a**, **b**) Acute right anterior shoulder dislocation in a 30-year-old female patient. Radiographic evaluation with trauma series (same patient of Fig. 17.15). (**a**) ¾ view axial to the glenoid demonstrating inferior medial dislocation of the humerus head. (**b**) Scapular Y view with anterior dislocation of the humerus (*white arrow*) relative to the glenoid (*black arrow*)

- In *bony Bankart* lesion a bone fracture fragment at the anterior-inferior part of the glenoid is present (Fig. 17.16). The size of the fracture fragment defines the grade of instability; fracture fragments involving 1/3th or more of the AP diameter of the glenoid are at risk for development of habitual dislocation and need Bankart repair surgery, The diameter of the bone fragment is best evaluated on CT(CTA).
- Multiple acronyms are known to describe *non-bony Bankart*-type lesions of the anterior-inferior labrum related to anterior traumatic shoulder dislocation. For some surgeons differentiating the lesions is important to plan therapy and to prepare surgical intervention.
- Glenoid labrum ovoid mass (*GLOM*) is defined as a detached labrum that floated upward in the region of the coracoid process. GLOM may simulate another lesion, biceps dislocation, loose body, air, cordlike MGHL, or SLAP. In the differential diagnosis the detection of an anterior-inferior labrum lesion is important.
- *Perthes* lesion is defined as an avulsion of the IGHL and labrum with intact periosteum; the intact but stripped periosteum connects to the IGHL (Fig. 17.17a, b). Perthes lesions are better visualized in ABER position.
- Anterior labroligamentous periosteal sleeve avulsion (*ALPSA*) is described by Neviaser (1993); an avulsion of the IGHL complex from glenoid with intact

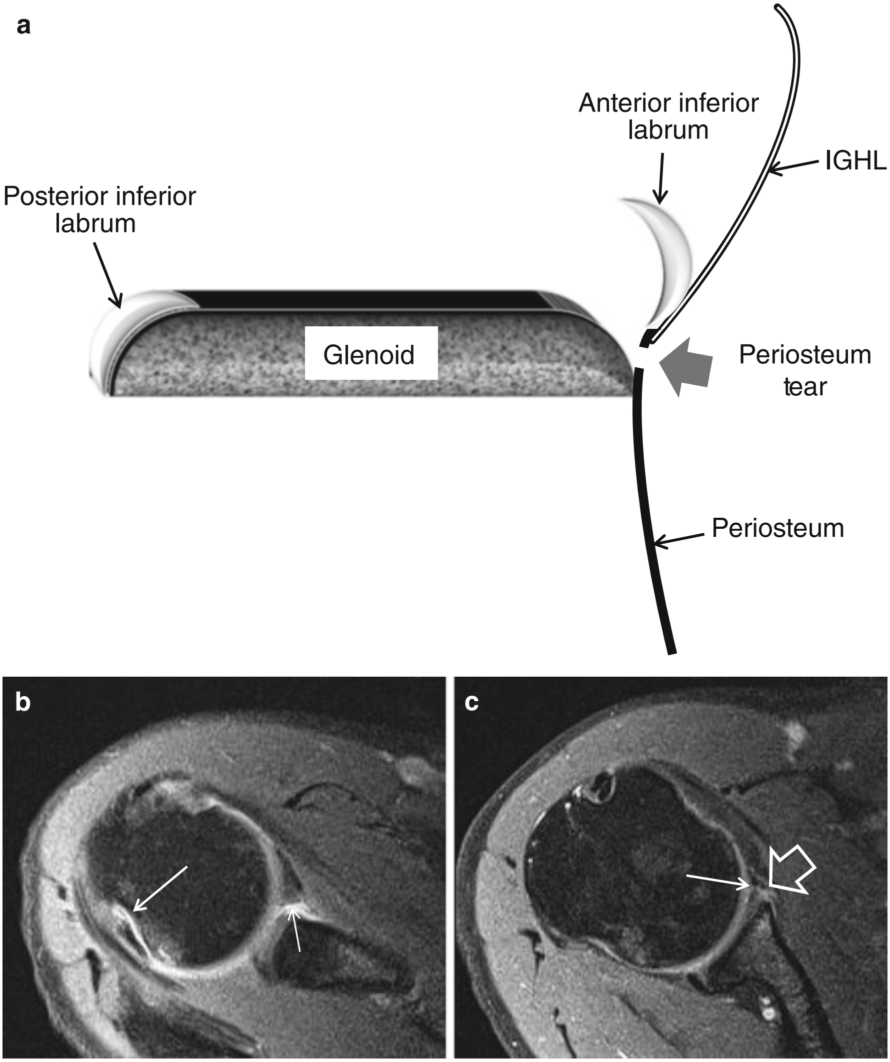


Fig. 17.15 (**a**–**c**) Bankart lesion in a 30-year-old female patient with traumatic right shoulder dislocation (same patient of Fig. 17.14). (**a**) Schematic drawing of axial slice through the inferior third of the glenoid with Bankart lesion. Displacement of anterior-inferior part of the glenoid labrum with disruption (*thick arrow*) of the periosteum connecting the labrum with the glenoid. Normal IGHL connection to the labrum and periosteum. (**b**) Axial 3 T I-MRA T1-WI FS at the level of the tip coracoid process with Hill-Sachs depression (*arrow*) (sublabral foramen *thin arrow*). (**c**) Bankart lesion with gadolinium enhancement between labrum and hyaline (*arrow*) cartilage extending lateral to the labrum with infiltration of extra periosteal area (*arrowhead*)

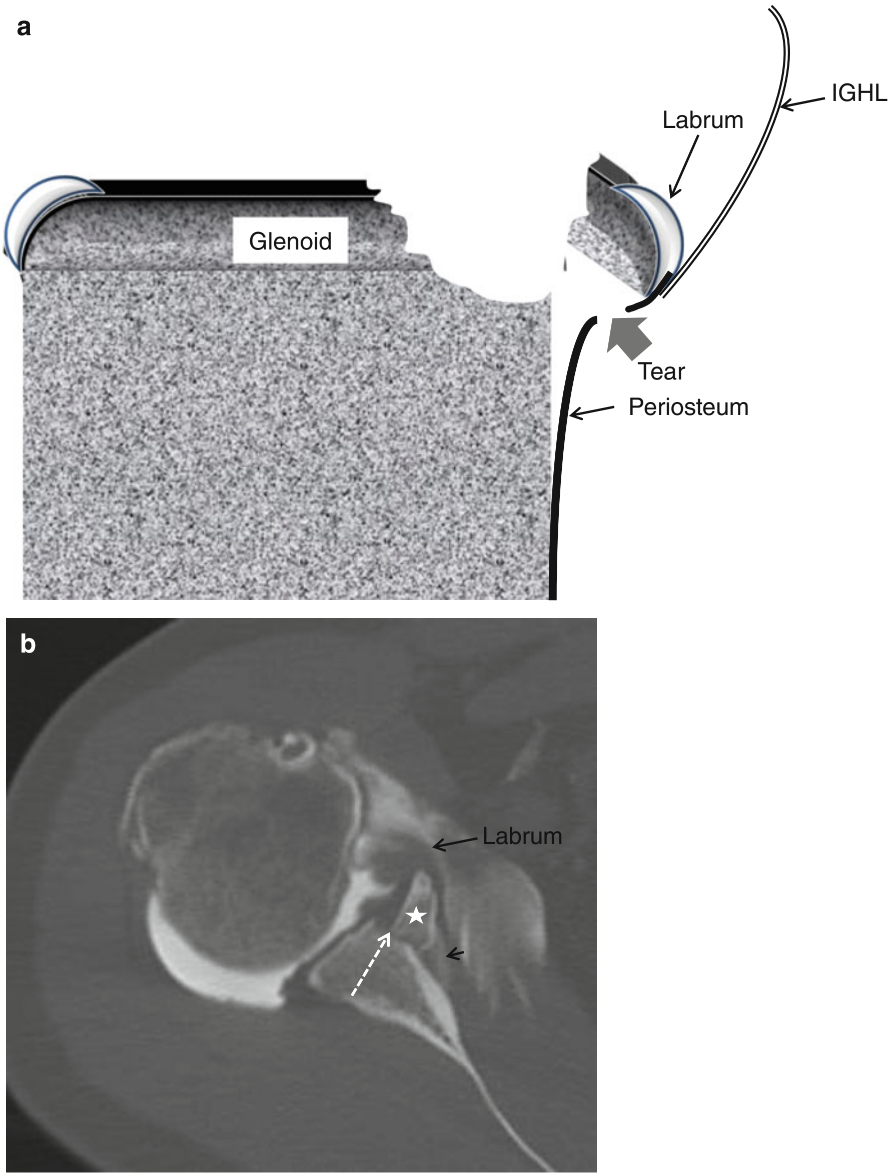


Fig. 17.16 Bony Bankart lesion in a 35-year-old male patient with history of acute right shoulder dislocation. (**a**) schematic drawing of axial slice through the inferior third of the glenoid with bony Bankart lesion. Demonstration of loose bony fragment and torn and partially stripped periosteum. (**b**) Axial CTA image at the level of the inferior third of the glenoid. Fracture line at the glenoid with step of at the subchondral bone (*dotted arrow*) and medial displacement of the fracture fragment (*star*) including the labrum (*arrow*). Contrast enhancement of the periosteum related to disruption of the periosteum (*short arrow*)

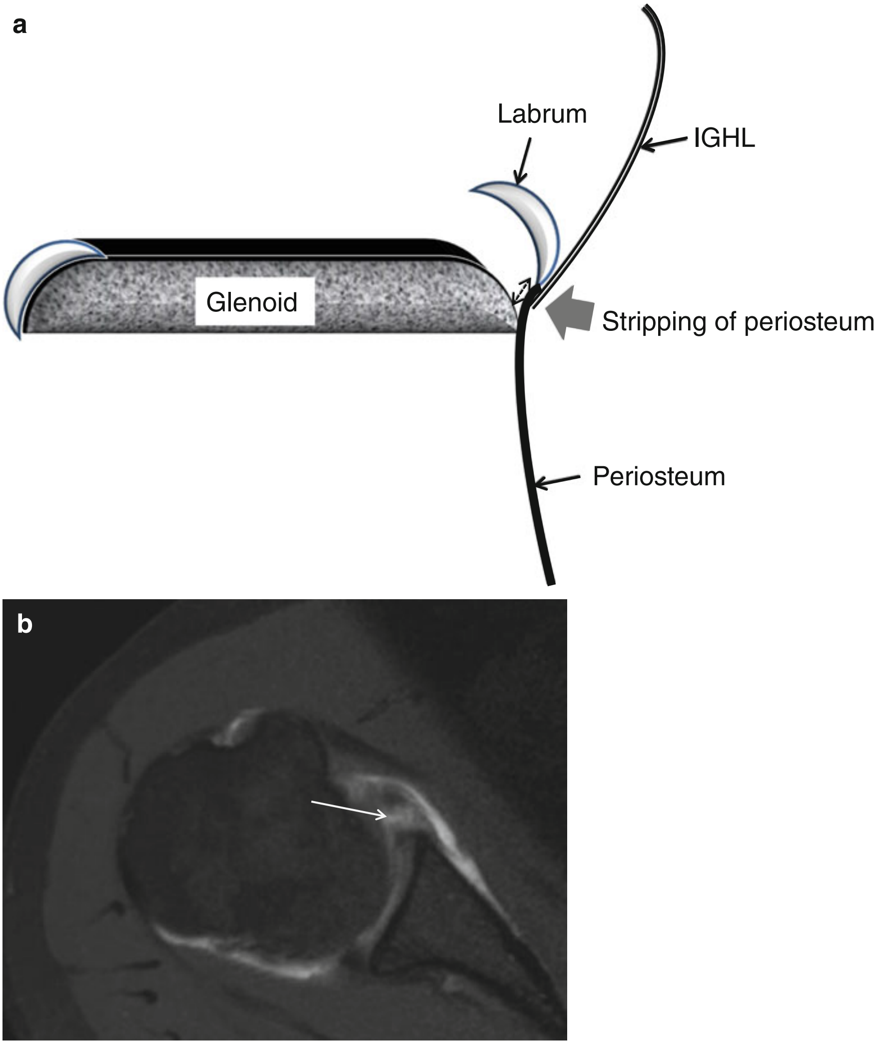


Fig. 17.17 (**a**, **b**) Perthes lesion schematic drawing and 1 T D-MRA axial T1-WI. Displacement of the anterior-inferior labrum continuous with the IGHL and stripped periosteum (*double-sided dotted arrow*) but no disruption of the periosteum. Gadolinium enhancement between hyaline cartilage and labrum without disruption of the periosteum (*arrow*). Anterior extra-articular location of gadolinium related to anterior capsule tear

periosteum is found. The avulsed labrum is medially displaced and inferiorly rotated (Fig. 17.18a, b). If the lesion heals in this position with synovialization, a mass is created and recurrent anterior instability is characteristic. In chronic cases the surgeon has to dissect the lesion from the scapular neck to relocate the labrum on the glenoid rim. ALPSA can also be found at 6 o'clock.

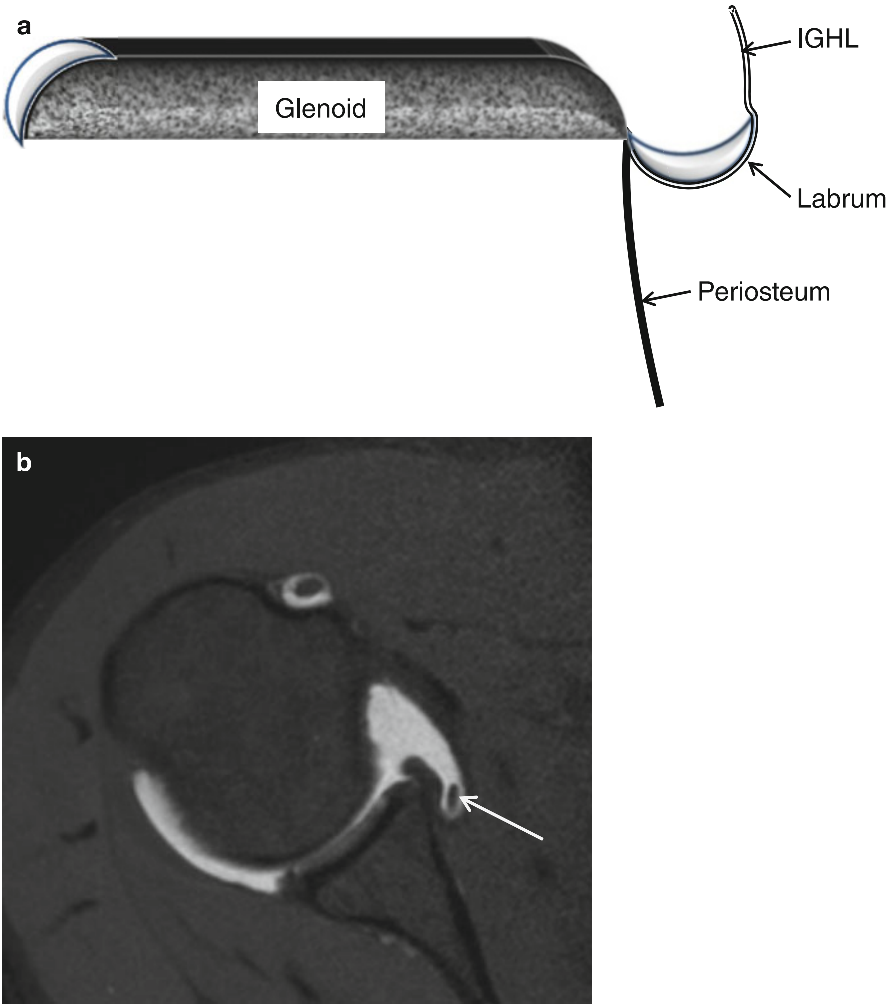


Fig. 17.18 (**a**, **b**) ALPSA lesion schematic drawing and 1 T D-MRA axial T1-WI. Avulsion of the inferior glenohumeral ligament complex from the glenoid with intact periosteum and medially displaced and inferiorly rotated labrum (**b** *arrow*)

- In anterior ligamentous periosteal sleeve avulsion (*ALIPSA*), the IGHL is partially disrupted from the labrum without labrum displacement (Fig. 17.19).
- Glenolabral articular disruption (*GLAD*) is a non-displaced superficial tear of the anterior-inferior labram with fibrillation (flap) or erosion (defect) of the adjacent articular cartilage (Fig. 17.20a–c thin arrows). Usually no associated dislocation nor anterior instability is present (anterior fibers of IGHL not disrupted, labrum not displaced). This type can progress to rapid degenerative joint disease and intraarticular bodies. Treatment is debridement of the labrum and cartilage lesion without stabilization procedure.

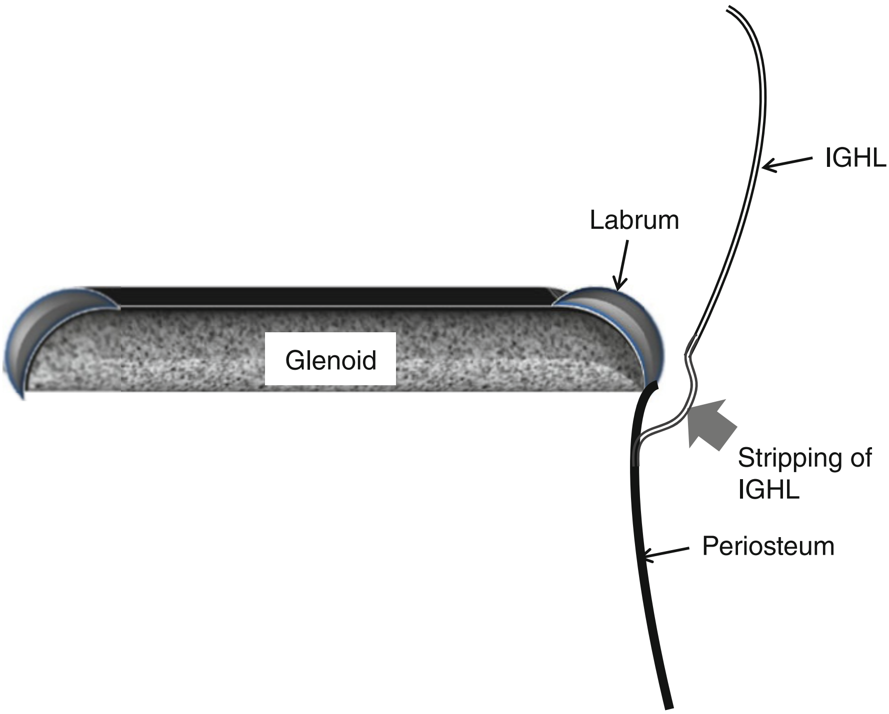


Fig. 17.19 ALIPSA lesion schematic drawing

- In humeral avulsion of the IGHL (*HAGL*) the normal U shape (Fig. 17.3b thin arrow) of the anterior band of the IGHL becomes J-shaped (Fig. 17.21a, b). A not-recognized HAGL is a cause of a failed Bankart repair.
- In 20 % of cases bony avulsion of humerus is present; these lesions are given the acronym *BHAGL*.
- Glenoid articular rim disruption (*GARD*) (divot) is a chondral or osteochondral lesion adjacent to a labral tear (Bankart, Perthes, ALPSA, etc.) with associated dislocation and instability on clinical examination (Fig. 17.22a–c). The lesion is treated with labroligamentous repair.
- Lesions may deteriorate in time. Perthes can change in Bankart or ALPSA. Labral lesions associated with inferior glenohumeral ligament complex lesions cause major instability (HAGL and BHAGL).
- Glenoid avulsion of the IGHL (*GAGL*) is rare; characteristic is the inverted J sign.
- In floating *AIGHL* and avulsion of the humeral and glenoid, attachment of the IGHL is present. The condition is more frequent in younger patients and coincides with Hill-Sachs lesion.

Midportion capsular tear accounts for 35 % of capsular tears and is located more posterior and often found after initial dislocation without labral tear. The lesion can be confused with contrast extravasation.

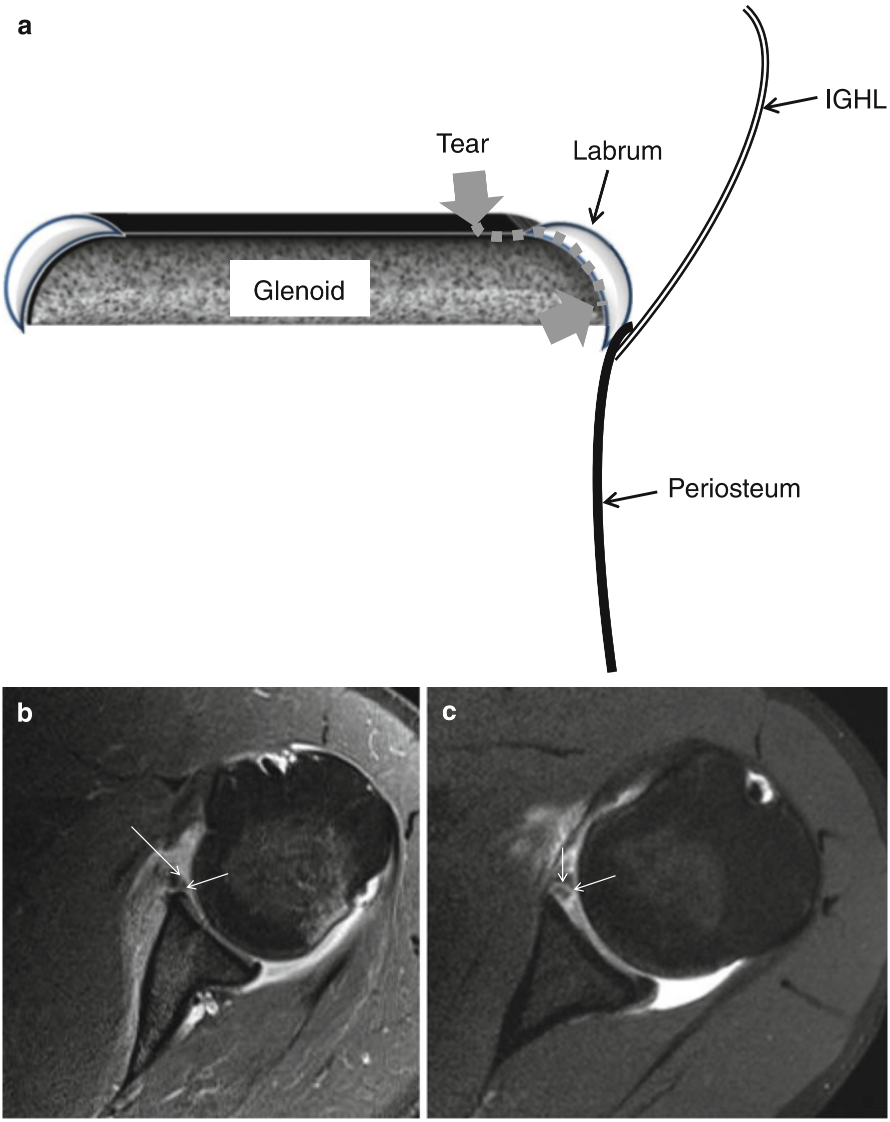


Fig. 17.20 (**a**–**c**) GLAD schematic drawing and 3 T I-MRA of left shoulder in a 19-year-old male patient, for comparison 1 T D-MRA. (**b**) Axial T1-FS 3 T I-MRA and (**c**) axial T1-FS 1 T D-MRA image demonstrating gadolinium enhancement at the hyaline cartilage (*arrow*) continuous within the labrum. No dislocation of the labrum

17.3.2.4 Adhesive Capsulitis

Adhesive capsulitis (frozen shoulder) is a clinical syndrome predominantly found in middle-aged females (40–60 years). The lesion is frequently underdiagnosed. Corticosteroid injections offer rapid pain relief in the short term (particularly in the first 6 weeks) for adhesive capsulitis. Long-term outcomes seem to be similar to

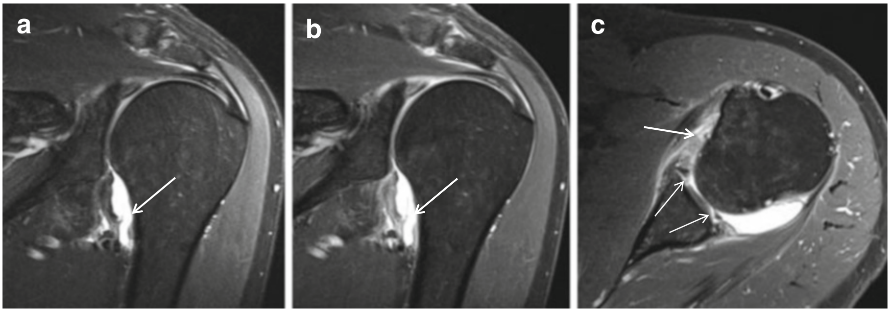


Fig. 17.21 (**a**–**c**) A 3 T I-MRA of HAGL lesion in a 44-year-old male patient after trauma of the left shoulder. (**a**) Coronal intermediate TE WI FS, (**b**) coronal T1-WI FS, and (**c**) axial T1-WI FS demonstrating J aspect of axillary pouch on coronal imaging signifying loosening of the humeral insertion of the inferior glenohumeral ligament (*arrows*). Associated extensive labral lesion is depicted with GLAD morphology anteriorly and posteriorly (PGLAD) (**c** *thin arrows*). Demonstration of interchangeable images with equal spatial resolution and contrast on intermediate FS (**a**) and T1 FS (**b**)

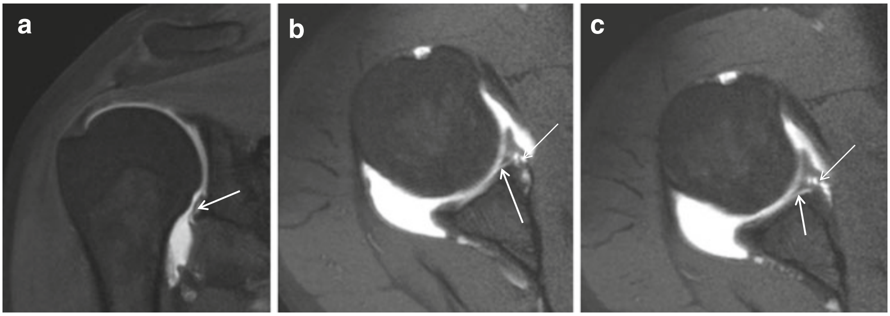


Fig. 17.22 GARD lesion on 1 T D-MRA T1 FS. (**a**) Coronal and (**b**, **c**) axial images. Hyaline cartilage lesion (*arrows*) with Perthes lesion (*thin arrows*) demonstrated on axial images

other treatments, including placebo (Song et al. 2014). On MRI, I-MRA, and D-MRA the axillary pouch is small with thickening (>4 mm) of the capsule and IGHL and enhancement after IV Gd (Figs. 17.23 and 17.24). Due to capsule enhancement I-MRA offers increased conspicuity of thickening of the axillary capsule and IGHL compared to D-MRA and MRI. Real-time and dynamic US has a role in diagnosis of retractile capsulitis. Reduced endo- and exorotation capacity of the glenohumeral joint results in constant anterior location of the LHB and the intertubercular groove. Thickening and power Doppler signal of the synovium and capsule may be present at the LHB tendon sheath or at the RI (Corazza et al. 2015). Therapeutic imaging (US or CTA) guided joint distention with corticosteroid may be performed.

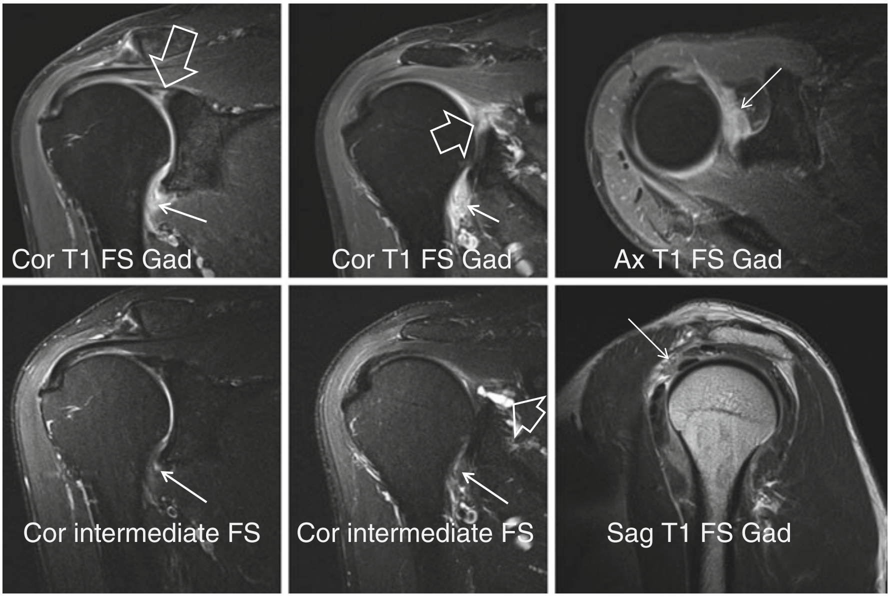


Fig. 17.23 Adhesive capsulitis, 3 T I-MRA in a 67-year-old male patient. SLAP VIII lesion. Demonstration of thickening of the axillary capsule-IGHL (*arrows*) and rotator interval (*thin arrow*). Better demonstration on T1-FS compared to intermediate FS images. SLAP VIII lesion is demonstrated with paralabral cyst (*thick arrows*)

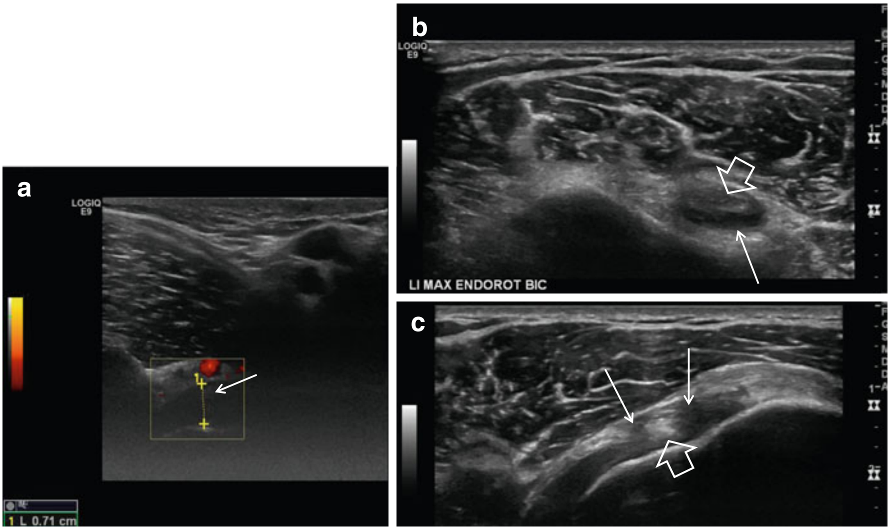


Fig. 17.24 Adhesive capsulitis, US in a 48-year-old female. (**a**) Axillary image with shoulder elevation, (**b**) axial slice at the level of the LHB tendon sheath, and (**c**) axial image at the RI with maximal endorotation. Thickening of the capsule and synovium (*arrows*) with anterior location of the LHB (*thick arrow*) on maximal endorotation position

17.3.2.5 Posterior Instability

Posterior instability accounts for 5 % of instabilities. It is characteristic non-traumatic event that may cause recurrent posterior instability. The instability is multidirectional and related to seizures, electric shock, or adduction, flexion, and internal rotation movement. In 60 % labral lesions are present. Posterior labral tears greater than 15 mm are significantly associated with posterior instability. Posterior capsular laxity is the most common abnormality (Schwartz et al. 1987).

- The dislocation may result in *reversed Bankart* lesion with labral tear and periosteal rupture but without cartilage lesion. Bone fracture fragment may be present as well as a *reversed Hill-Sachs* (McLaughlin). Fluid or contrast may extend behind the glenoid.
- In *Kim* lesion deep intrasubstance incomplete detachment (marginal crack) of the posteroinferior labrum is associated with a defect at the chondrolabral junction. MRI depicts these lesions in a sensitive (85 %) and specific (75 %) way (Smark et al. 2014). This may lead to repetitive posterior instability with subluxation of the humeral head and shear forces between glenoid rim and labrum with failure of the chondrolabral junction. Kim lesion can be concealed at arthroscopy and is treated by converting it to complete tear and suture with an anchor.
- *Reversed or posterior Perthes* (Fig. 17.25) may lead to *POLPSA* or posterior labroligamentous periosteal sleeve avulsion (posterior ALPSA) (when medially displaced) and predisposes to posterior instability (Fig. 17.26). This lesion is treated by reduction of the periosteal sleeve with attachment of the labrum.
- In posterior glenoid labrum articular disruption (*GLAD*), a focal defect in the articular cartilage between 7 and 9 o'clock is present associated with labral tear but no instability.
- *PHAGL* or posterior humeral avulsion of the IGHL is the posterior counterpart of HAGL. In *BPHAGL* associated bony avulsion is present. On MRI typically extra-articular contrast extravasation is detected.
- In *reversed GAGL* glenoid avulsion of the posterior band of the IGHL is present. Bennett lesion is characterized with an enthesophyte that arises from the postero-inferior portion of the glenoid rim, probably from the insertion of the posterior band of the IGHL, and is sometimes associated with labral tears and undersurface RC tears (internal impingement). This lesion is common in baseball pitchers (25 %). Posterior capsular laxity is the most common abnormality seen with posterior instability (Fig. 17.26 thin arrow).

17.3.2.6 Multidirectional Instability

Multidirectional instability is a non-traumatic form of instability in multiple directions resulting from capsuloligamentous laxity related to soft tissue connective disorders (Ehler-Danlos, Marfan). It is found in young females and individuals with capsular laxity or hypoplastic glenoid labrum. The instability is atraumatic or related to a minor event associated with multidirectional laxity and with bilateral

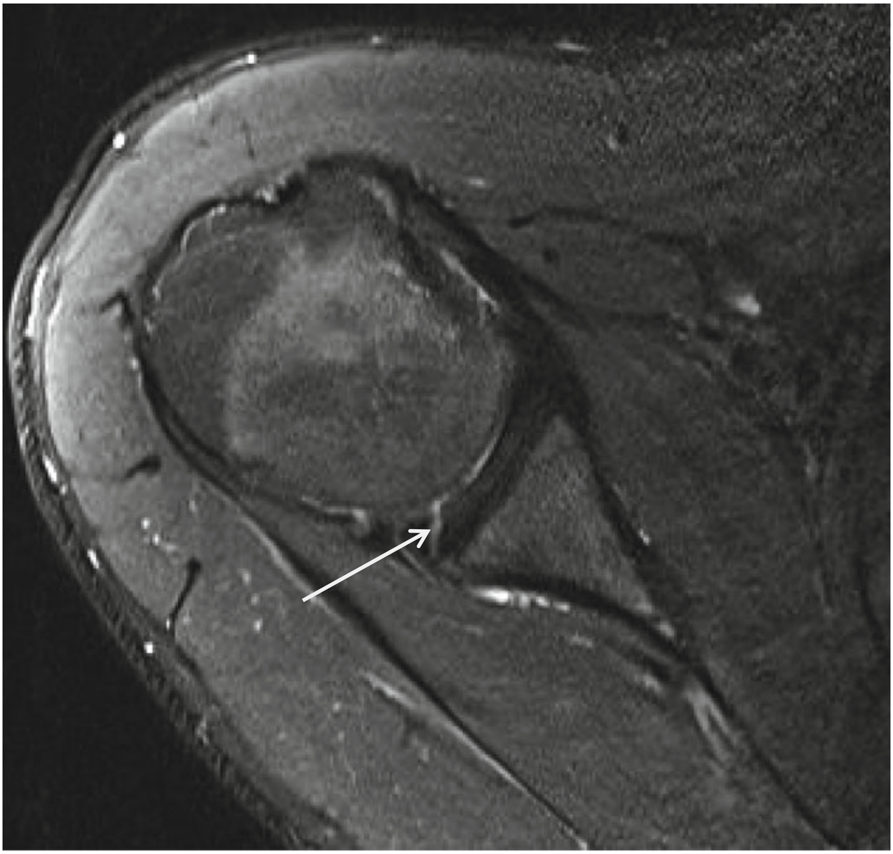


Fig. 17.25 Reversed Perthes lesion, 3 T I-MRA. Axial image demonstrating gadolinium infiltration between posterior inferior labrum and hyaline cartilage (*arrow*). Intact periosteum. For comparison Perthes lesion Figs. 17.22 and 17.17

findings. Treatment is predominantly by rehabilitation directed at restoring optimal neuromuscular control. If surgery is necessary, it needs to include reconstruction of the rotator interval capsule-coracohumeral ligament mechanism and tightening of the inferior capsule (AMBRII (atraumatic, multidirectional, bilateral, responds to rehabilitation, inferior capsular shift, interval closure)). These patients have a lax capsule (difficult to quantify on MRI). Some have arthroscopic and MRA or CTA findings found in other instabilities like Hill-Sachs, greater tuberosity fracture, bony Bankart (indication for open repair), inverted pear-shaped glenoid, reversed Bankart, reversed Hill-Sachs (McLaughlin), and OCD of the glenoid fossa.

17.3.2.7 Instability Associated Bony Lesions

Bony lesions may be present in shoulder instability. Hill-Sachs is found in 75 % of patients with anterior instability. MRI is superior to arthroscopy for detecting

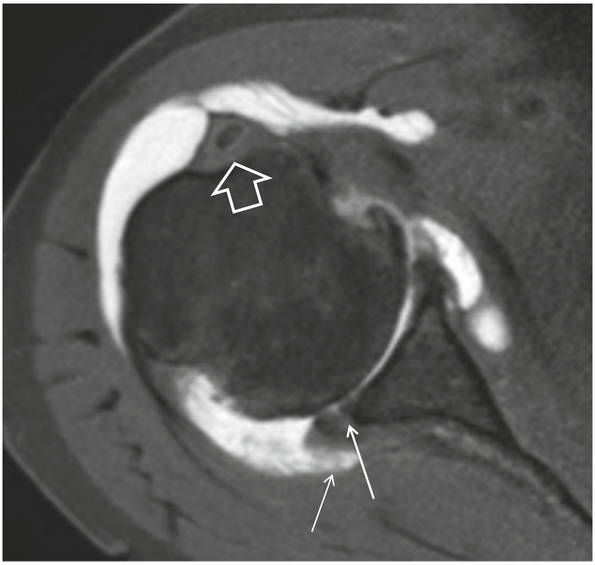


Fig. 17.26 POLPSA 1 T D-MRA, older patient with glenohumeral osteoarthritis. Less conspicuous enhancement at the posterior inferior labrum (*arrow*). Chronic tenosynovitis LHB with stenosis: absence of contrast at tendon sheath, thickening of tendon sheath (*thick arrow*). Posterior capsule insertion (*thin arrow*)

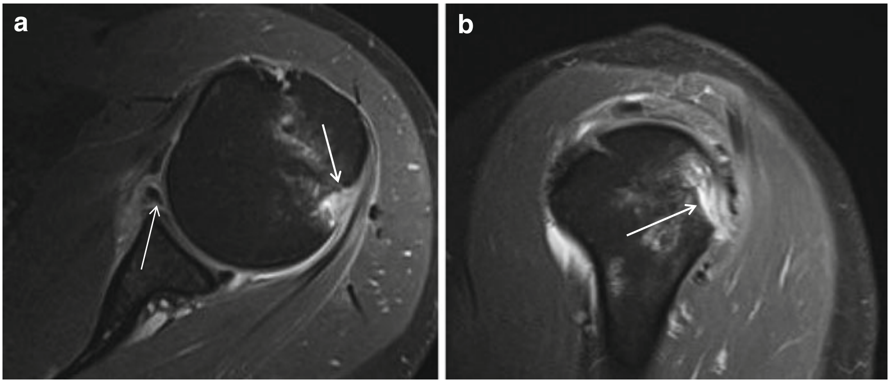


Fig. 17.27 (**a, b**) MRI Male patient with reduction of acute anterior shoulder dislocation, 2 weeks ago, Hill-Sachs defect detected on 3 T I-MRA. (**a**) Axial T1-WI FS and (**b**). sagittal T1-WI FS, bone marrow edema at the greater tuberosity, and humeral epiphysis surrounding depression of the cortical bone and subchondral lamella (*arrows*). Cranial extension of anterior Bankart lesion is depicted (**a** *thin arrow*)

Hill-Sachs lesions (Fig. 17.27a, b). Hill-Sachs is located in the top 2 cm of the humerus and located posterolaterally above or at the level of the coracoid process. Posterolateral depression of the humeral head in the most cranial CT or MR axial slice is most specific. Deep Hill-Sachs defect may elicit recurrent dislocation. This is caused by leverage action of the humeral impression that

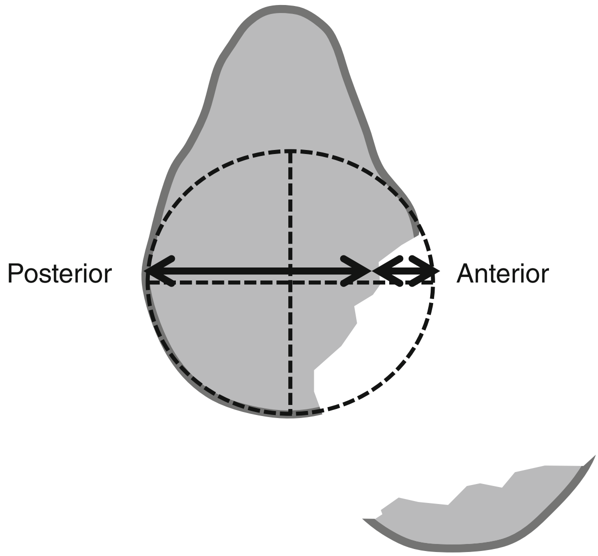


Fig. 17.28 Pear-shaped glenoid. Drawing demonstrating calculation of percentage of bone loss

covers the anterior glenoid in endorotation position. Exorotation movement then results in leverage with dislocation.

Reversed Hill-Sachs has to be differentiated with cystic change or vessels in the “bare area” of the ISP that is a normal anatomic groove posterolaterally (located at long axis of humerus, 2 cm distal to top of humeral head).

Bony Bankart and reversed bony Bankart lesion may result in instability. Anterior bony Bankart fragment over 1/3th of glenoid AP diameter at the level of the center of rotation of the glenoid is associated with habitual dislocation (Figs. 17.16 and 17.28b) (Bhatia et al. 2011). Three-dimensional CT is most accurate to quantify bone deficiency (Griffin and Brockmeier 2015).

17.3.2.8 Microinstability

Microinstability is minor displacement of the humeral head without dislocation. Potential sites of involvement of microinstability are the anterior articular surface of the SSP tendon, the articular surface of the posterior SSP-anterior ISP tendon, the CHL, the intraarticular part of the LHB and biceps pulley, the SGHL, the deep fibers of the SSC tendon, the cranial part of the middle GHL, anterosuperior and posterosuperior part of the labrum, and the origin of LHB. Three different types are described: SLAC, superior labrum anterior cuff; ASI, anterosuperior impingement; and GIRD, glenoid internal rotation deficit. SLAC is defined as anterosuperior subluxation related to repeated overhead activity or related to acute trauma (fall, MVA (strap)). Typical sites of involvement are anterior glenoid, anterior biceps, SGHL (MGHL), and anterior articular PTT of SSP. Treatment is focused on reduction of instability.

17.3.2.9 Impingement

Impingement is subdivided in external (primary intrinsic) and internal (secondary intrinsic). Two types of external impingement are recognized: subacromial and subcoracoidal.

Internal Anterosuperior Impingement

Internal anterosuperior impingement produces pain in *elevation* and *internal rotation*, with impingement of the deep surface of the subscapularis (Gerber and Sebesta 2000; Habermeyer et al. 2004a, b) and a lesion at the biceps pulley resulting in instability of the LHB. The slight anterosuperior humeral head translation impinges on the glenoid with development of SSC/SSP partial articular sided tears and lesions in the anterosuperior portion of the glenoid labrum.

Internal Glenoid Posterosuperior Impingement

The act of overhead throwing causes pain related to impingement of the humeral head with the glenoid rim in *abduction* and *external rotation*. The slight anterior translation of the humerus during this act is the result of anterior capsule failure and causes impaction of GT and glenoid and impingement on the posterior SSP, anterior ISP, and posterosuperior labrum. MRI may reveal tears of the SSP-ISP (anterior infraspinatus partial undersurface tears), labral pathology with fraying, and tears including a variation of the type II superior labrum from anterior to posterior lesion, humeral head GT, and glenoid cystic lesions with cortical bone irregularities communicating with the articular cavity (Tirman et al. 1994a, b; Fessa et al. 2015). MRI in ABER position is useful (as the ABER position is in fact identical to the overhead abduction external rotation position that causes elongation of the anterior capsule IGHL and pain).

Glenoid Internal Rotation Deficit

Glenoid internal rotation deficit (GIRD) is found in throwing athletes. A posterior fibrosing capsulitis with thickening of the posterior band of the IGHL and associated anterior capsule stretching results in a slightly posterosuperior shifted center of rotation. This turns out in increased forces on LHB and anchor and superior labrum and a peel back mechanism with SLAP II lesion. On MRI a posterior capsulitis with thickening of the posterior capsule, a large labrum, SLAP II with extention posterior from the biceps and signs of internal posterior impingement are found. GIRD is treated by stretching of the capsule (conservative) or by arthroscopic repair with release of the posterior capsule.

External Subacromial Impingement

In this (most frequent) type of impingement *abduction elevation* of the shoulder causes progressive painful compression of the SSP, SD-SA bursa, and LHB between the humeral head and coracoacromial arc. Impingement on the tendinous portion of the rotator cuff by the coracoacromial ligament and the anterior third of the acromion is responsible for this frequent and characteristic syndrome of disability of the shoulder. A characteristic proliferative (keel) spur or enthesophyte has been noted

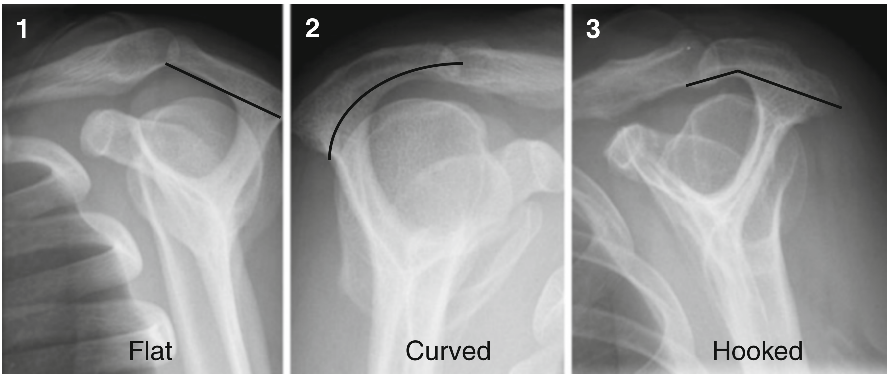


Fig. 17.29 (*1–3*) External subacromial impingement, osseous abnormalities of the acromion, Bigliani types 1, 2, and 3 demonstrated on scapular Y view

Table 17.7 Acromion types of Bigliani (1–3) and Gagey (4)

Type 1: Flat (12 %)
Type 2: Curved (56.5 %)
Type 3: Hooked (29 %)
Type 4: Upward convexity (2.5 %)

Inferior margin of the acromion is evaluated on sagittal MRI or CT images or scapular Y radiograph of the scapula. Figures 17.29 and 17.30

on the anterior lip and undersurface of the anterior process of the acromion (Fig. 17.1b, c arrow); this area may also show erosion and eburnation. The impingement may also involve the tendon of the LHB, and if it does, it is best to decompress the tendon and remove any osteophytes which may be in its groove. Hypertrophic osteophytosis at the AC joint may impinge on the SSP tendon when the arm is in abduction (Neer 2005). According to Neer 95 % of RC tears at the level of its enthesis at the GT are the result of chronic subacromial impingement leading to tendinopathy and tears (Fig. 17.63). Clinical diagnosis is made by the Neer and Hawkins test. Osseous abnormalities are present at the level of the acromion: enthesophytes, anterior hooking (type 3 Bigliani Fig. 17.29. 3, Table 17.7), anterolateral inferior downsloping, and low position to distal clavicula. Also os acromiale (Fig. 17.31) and M. Paget (acromion or clavicle) are associated with subacromial impingement. At the level of the GT fracture with displacement or remodeling may cause a prominent GT resulting in subacromial impingement. Secondary soft tissue abnormalities are found in the SSP and LHB with tendinosis, PTT or FTT, thickened or ossified coracoacromial ligament, subacromial bursal thickening, and hypertrophied SSP muscle (Fig. 17.19). Calcifications at the SSP may be the result and increase the thickness of the tendon amplifying subacromial impingement. Three acromial types are described by Bigliani in 1986; type 3 is associated with impingement and RC tears (Fig. 17.29 and Table 17.7). Gagey added type 4 in 1993 (Fig. 17.30a, b)

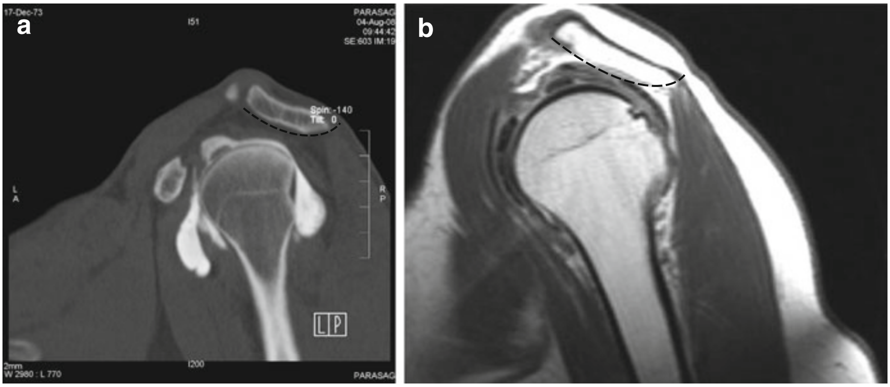


Fig. 17.30 (**a, b**) Type 4 acromion according to Gagey. (**a**) Sagittal CTA and (**b**) sagittal T1

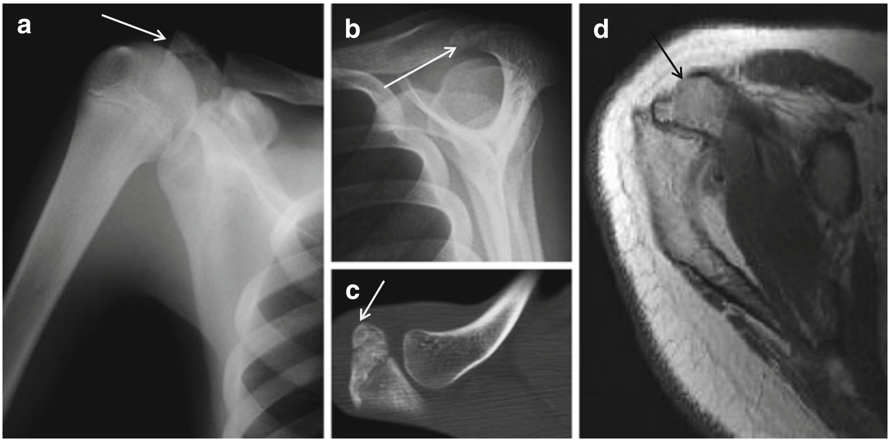


Fig. 17.31 Os acromiale. Radiographic demonstration of os acromiale (*arrows*) on AP view (**a**) and (**b**) scapular Y view. CT (**c**) and MRI (**d**) demonstration on axial slice

(Natsis et al. 2007). The acromion types are described on sagittal CT or MRI slices or scapular Y radiographs of the scapula (Figs. 17.29 and 17.30).

The types of acromial shape with the existence of enthesophytes together comprise two important parameters for subacromial impingement syndrome and rotator cuff tears. Enthesophytes were found mostly in type 2 (7.9 %) and type 3 (37.7 %) acromion (Fig. 17.29.1 and 2). The enthesophytes are localized at the site of the coracoacromial ligament insertion on the acromion (Fig. 17.1b, c). Enthesophytes were significantly more common in type 3 acromions, and this combination is particularly associated with subacromial impingement syndrome and rotator cuff tears (Natsis et al. 2007). Hooked acromion (type 3) may be congenital or acquired due to aging related to degeneration of the origin of the CHL; it is more common in males and mostly symmetric. Lateral downsloping acromion is related to impingement on the SSP in critical zone, also possibly on the SSC. Low lying acromion relative to the distal clavicula is present in os acromiale, which is a not fused accessory ossification center (junction of meta-, meso-, and preacromion). It may be the cause of shoulder pain itself; the contraction of the deltoid muscle may pull it down causing impingement. Os acromiale is bilateral in 60 % of cases. Subacromial impingement is treated conservatively, with coracoacromial ligament release, resection of the distal clavicula, or with anterior acromioplasty (Neer 1972, 2005). End stage subacromial impingement is defined as complete SST tear with retraction, cranial migration of the humeral head with bony conflict against the acromion, eburnation of the acromion, glenohumeral joint non-congruity resulting in glenohumeral joint osteoarthritis, and secondary subcoracoidal impingement (section "External subcoracoid impingement").

External Subcoracoid Impingement

This type of impingement is related to compression of the subscapularis tendon and structures at the rotator interval between the coracoid process and the lesser tuberosity of the proximal humerus (in the coracohumeral interval). It may be due to congenitally elongated or angled coracoid process. Clinically anterior shoulder pain is present that is elucidated with *forward elevation*, *internal rotation*, *and horizontal adduction* of the humerus and is sometimes associated with a painful click. In sports primary external subcoracoid impingement is found related to slight distraction to the posterior glenohumeral shoulder capsule in the *end stage of endorotation* in racket swing or golf swing. The syndrome is easily overlooked, both clinically and with imaging. It is rarely isolated. The condition is treated with activity modification or coracoplasty. Normal coracohumeral interval distance is 8 mm in females and 11 mm in males. Stenosis related to subcoracoid impingement is defined as less than 6 mm. These measurements are not reliable; the diagnosis is made by clinical evaluation and anesthetic infiltration. Bone marrow cystic and reactive changes in the LT or coracoid tip with SSC tendinosis and (partial thickness) tears may be found (Fig. 17.5a, b long arrow). Subcoracoid impingement is most frequently found as end stage of subacromial impingement with cranial migration of the head of the humerus in complete SSP tear with retraction leading to decreased distance of the coracoid process and the humerus. This mechanism defines the biphasic evolution of subacromial impingement, in the first stage with clinical signs of subacromial impingement and in a second stage the clinical signs of subcoracoidal impingement.

17.3.3 Labrum, SLAP, and Biceps Lesions

Imaging plays an important role in the diagnosis of superior labrum anterior to posterior (SLAP) tears. Knowledge of glenolabral anatomy, related structures, and variants, proper imaging techniques, and a systematic approach to MRI interpretation are important in the diagnosis and treatment planning of the ten types of SLAP lesions. Arthroscopy offers definitive diagnosis (Modarresi et al. 2011a, b).

Table 17.8 SLAP lesions

SLAP I: Fraying of superior portion of the labrum, no frank tear, intact biceps tendon (10–21 %)
SLAP II: Fraying with stripping of the superior labrum and biceps tendon. Most frequent SLAP lesion related to repetitive microtrauma injury. Accounts for 41–55 % of lesions. Three types are distinguished based on the location.
SLAP II A anterosuperior
SLAP II B posterosuperior
SLAP II C central
SLAP III: Bucket handle tear of the superior labrum (3–15 %). The central portion of the tear is displaced into the joint. The biceps tendon is not involved.
SLAP IV: Bucket handle tear with extension into the biceps tendon (3–15 %) (Fig. 17.32).
SLAP V : Extension anteroinferior
SLAP VI: Flap tear
SLAP VII: Extension anterior in MGHL
SLAP VIII: Extension posterior (more extensive then IIB) (Fig. 17.33)
SLAP IX: Circumferential
SLAP X: Extension in RI

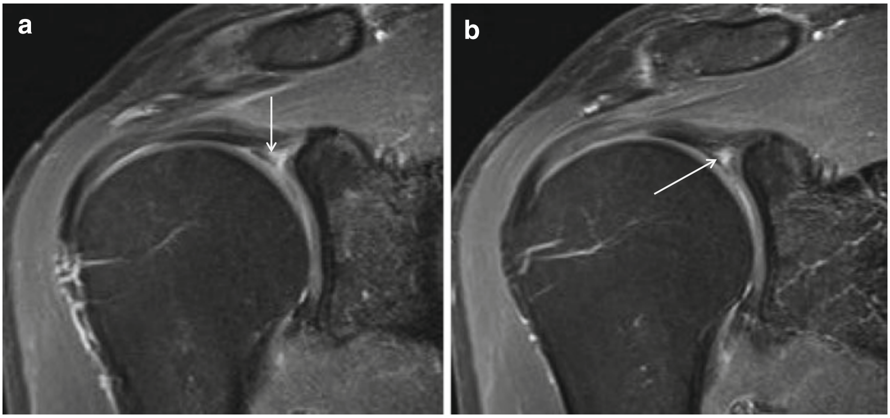


Fig. 17.32 SLAP IV. 3 T I-MRA T1 FS coronal slices (**a**, **b**) demonstrating gadolinium enhancement at the labrotendinous junction with lateral distention into the biceps (*arrows*)

17.3.3.1 SLAP Lesions

The arthroscopic prevalence of SLAP lesions in a population with shoulder pain ranges from 3.9 to 11.8 %. Surgeons use mostly the 4 original described types centered at the attachment of the LHB tendon (Snyder et al. 1990) (Table 17.8 and Figs. 17.23a, 17.32, and 17.33). Isolated LHB tears are rarely anterosuperiorly located. Tears are usually associated with SLAP lesions or tears that extend anteroinferior in the labrum. In current literature there is no sufficient support that MRI can accurately differentiate all SLAP lesions. Different mechanisms are related with SLAP lesions: SLAP I is related to degenerative labrum with aging; SLAP I and II are related to repetitive overhead motion: SLAP II, IV (Fig. 17.32a, b), and V are

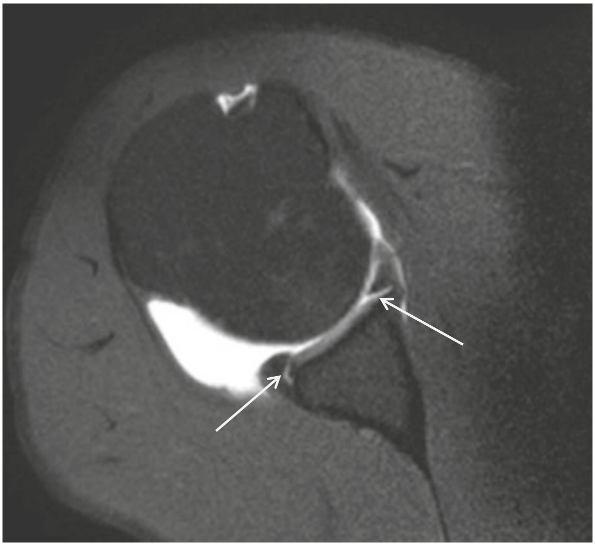


Fig. 17.33 SLAP VIII. Anterior and posterior labrocartilaginous disruption (*arrows*) demonstrated on axial 1 T D-MRA T1 FS Bigliani and Vanarthos acromion types

related to falls on outstretched hand; SLAP V and VII are related to glenohumeral instability. A practical approach to radiological diagnosis of SLAP lesions is to describe the location using clock face or quadrants, define if the biceps tendon is involved, and describe the anterior-posterior extension and the morphology of the lesion: fraying versus tearing. Displaced (bucket handle) or free fragments and associated lesions or extension in the MGHL or anteroinferior labrum (implies GH instability and different surgical treatment) should be mentioned.

17.3.3.2 Labral Cysts

Labral cysts typically arise through labral tears and may cause nerve compression. The suprascapular nerve may be compressed at the level of the suprascapular foramen below the transverse ligament with denervation of the supraspinatus and infraspinatus muscle. If the cyst is located at the spinoglenoid notch, the suprascapular nerve is compressed more distally with denervation only of the infraspinatus muscle (Fig. 17.23 thick arrow mid lower position, Figs. 17.34, 17.35, and 17.36). The axillary nerve may be compressed in inferior location of the labral cyst causing denervation of the teres minor and deltoid muscles.

On D-MRA the cyst often is not filled with contrast and remains with low SI on T1-WI FS. Muscular denervation edema or muscle enhancement with IV gadolinium administration may be present (I-MRA) on T1 FS (Fig. 17.34b) and increased muscle signal on PD and T2 (FS) images on D-MRA and I-MRA. I-MRA T1-WI FS may show contrast enhancement in the wall/surrounding tissue of the cyst. Denervation edema or contrast enhancement on T1-WI FS is found in early stages (within the first month) of denervation. In late stages fatty infiltration in the muscle is detected on MRI and ultrasound (Fig. 17.36).

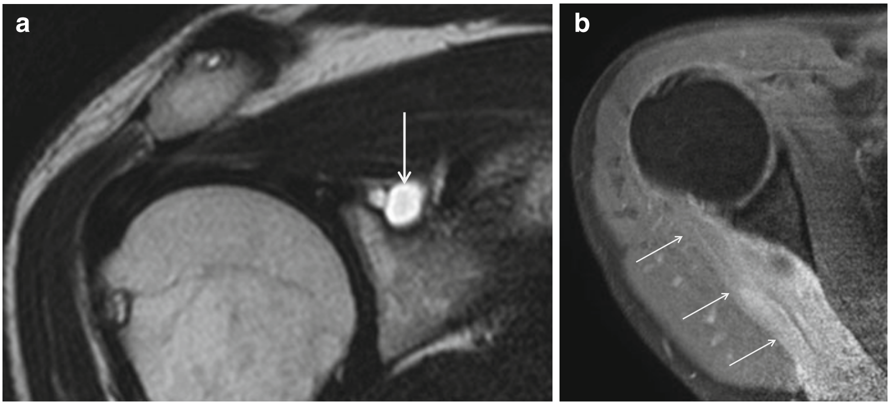


Fig. 17.34 Paralabral cyst with denervation of ISP muscle, 1 T D-MRA. (**a**) Coronal T2-WI demonstrating high SI cyst at spinoglenoid notch (*arrow*) with compression of the distal part of the suprascapular nerve. (**b**) Axial T1-WI FS demonstrating global enhancement (*arrows*) of ISP muscle related to early denervation (first 3 weeks)

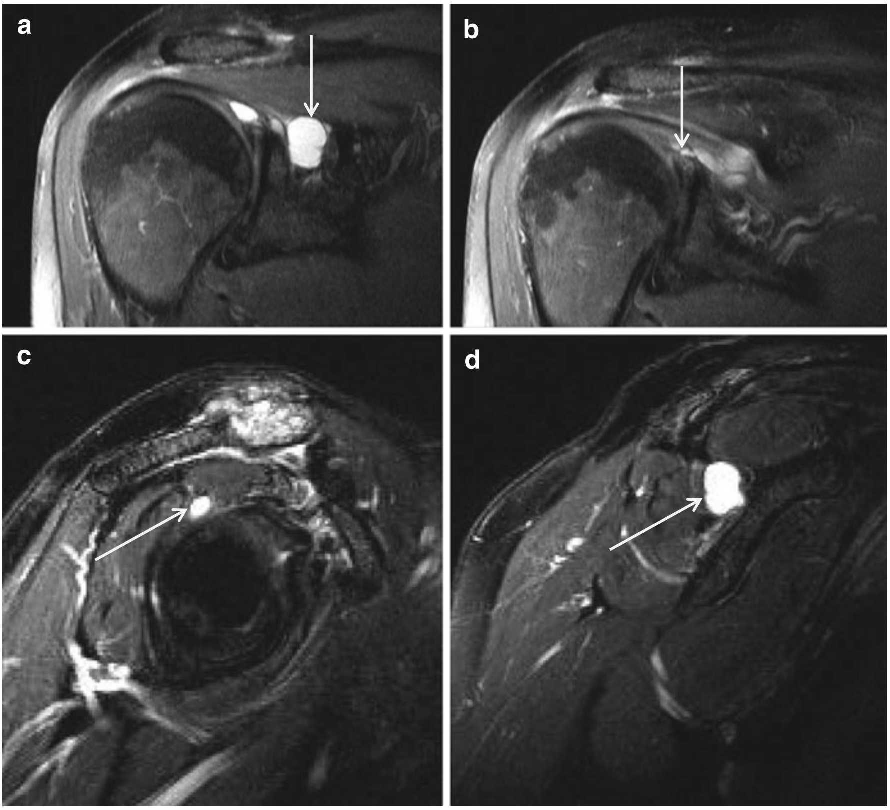


Fig. 17.35 Labral cyst at spinoglenoid notch. 1,5 T I-MRA (**a**) coronal intermediate TE FS and (**b**) coronal T1-WI FS, (**c**, **d**) sagittal intermediate TE FS in spinoglenoid notch (**d**) and more laterally at the cyst stalk (**c**). Specific location at spinoglenoid notch is best demonstrated on sagittal images (*arrows*). No denervation signs at infraspinatus muscle belly

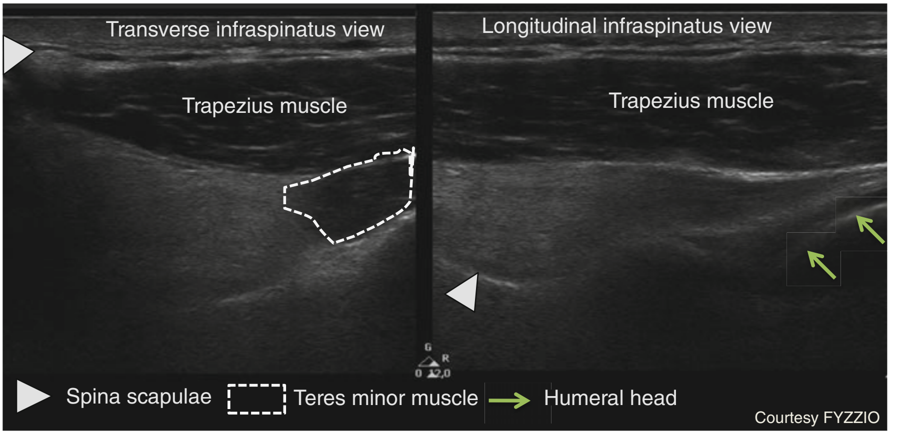


Fig. 17.36 US demonstration of fatty involution of ISP in a male professional volleyball player without paralabral cyst at the spinoglenoid notch (Courtesy of FYZZIO, the Netherlands). Marked global increased reflectivity grade II according to Strobel (Table 17.15) of the ISP muscle is obvious when compared with trapezius and teres minor muscle

Denervation of ISP muscle without labral cyst is a specific finding in elite volleyball players (Fig. 17.36).

17.3.3.3 Biceps CL Tendon Lesions

Tendinopathy and Tenovaginitis

In LHB tendinosis MR shows brightening in the tendon on T1 without high T2 SI; one should be careful to discriminate magic angle phenomenon (at 54.7° relative to B0 magnetic field of 1.5 T Sect. 17.3.4.3) specifically on the turn into the groove (Fig. 17.37). The tendon can be swollen in the intracapsular portion ("hourglass" tendon) producing a mass effect with incarceration (Fig. 17.37b). Major sign on US is focal thickening of the tendon (Fig. 17.38). The mechanism of tendinopathy of the biceps is subacromial impingement of the tendon in RC tears with subacromial osteophytes in the bicipital groove or subluxation or medial dislocation of the tendon. Bone marrow edema can be found at the level of the intertubercular groove. Increased fluid in the tendon sheath without associated increased glenohumeral joint fluid is found. Associated stenosing tenosynovitis and adhesions with lack of contrast passage to the synovial tendon sheath may be found (Fig. 17.26 thick arrow). Inflammatory arthropathy (RA) may cause tenosynovitis of the LHB tendon sheath.

LHB Tear

LHB tendon rupture is usually related to preexisting tendinosis. Musculotendinous rupture of the healthy tendon is related to severe trauma (weight lifters). Patients complain of an audible "pop" followed by Popeye sign with distal retraction of the muscle belly. Partial tears are documented on US or MRI with thinning, irregularity,

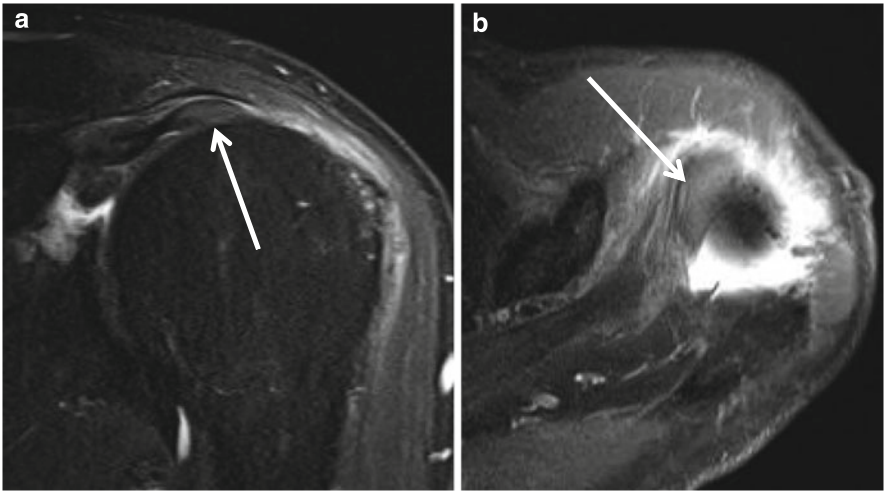


Fig. 17.37 Intraarticular LHB tendinopathy, I-MRA demonstration. 1 T I-MRA with (**a**) coronal intermediate TE FS and (**b**) axial T1 FS slices demonstrating increased SI and thickened (hourglass aspect) of the tendon (**b** *arrow*)

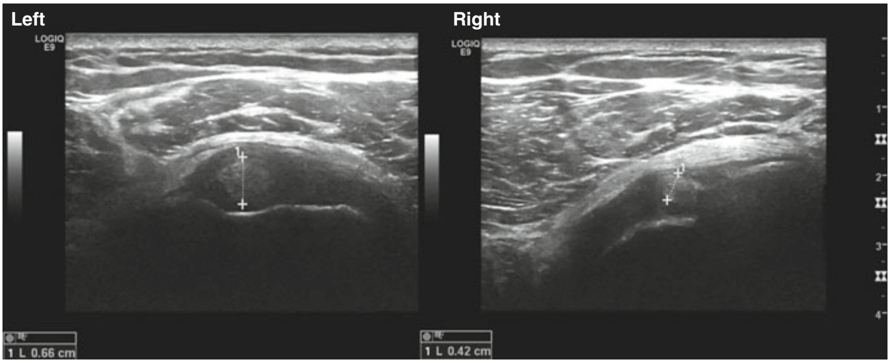


Fig. 17.38 LHB tendinopathy at intertubercular groove, US demonstration. Axial US images at the junction of RI and intertubercular groove, *left image* demonstrating thickened LHB (0.56 cm) compared to right LHB (*right image*) with thickness of LHB of 0.42 cm

fragmentation, and high SI of the tendon. A longitudinal fissure should be discriminated from a constitutional bifid tendon (Figs. 17.13a, b and 17.39a, b). Most tears are located proximal in the intertubercular groove. Neer discriminated three FTT types: type I, tear without retraction (Fig. 17.40); type II, tear with retraction; and type III, self-attaching tear without retraction. The radiologist should describe the location of rupture and retracted stumps. In case of distal retraction the tendon is absent in the intertubercular groove. Proximal from the intertubercular groove the stump can move in the RI which may cause glenoid and humeral head chondromalacia. The sensitivity for lesion detection of biceps CL lesion for CT arthrography

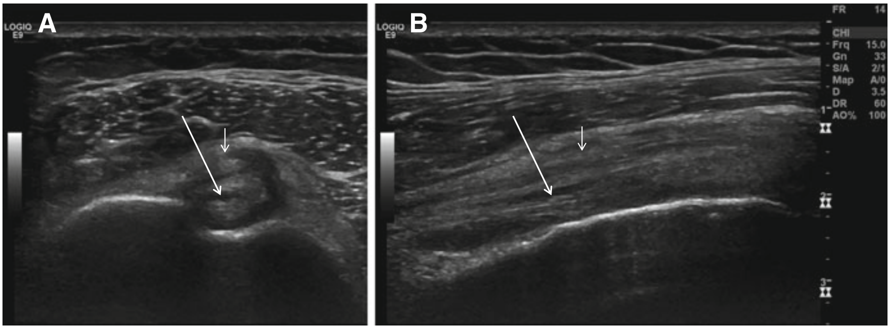


Fig. 17.39 Split long head of the biceps with LHB tendinopathy at the posterior part and longitudinal split at the intertubercular groove, US demonstration with probe position. Axial (**a**) and longitudinal (**b**) images demonstrating three structures at the intertubercular sulcus, split anterior LHB (*small arrow*) and thickened posterior LHB with the longitudinal split (*long arrow*)

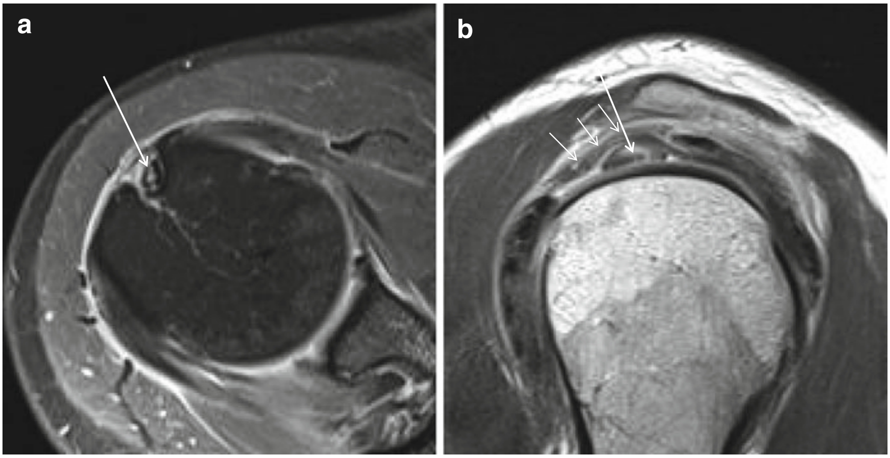


Fig. 17.40 Partial-thickness LHB tear (type I tear according to Neer), 3 T I-MRA demonstration. (**a**) Oblique axial T1-WI FS and (**b**) sagittal T1-WI demonstrating central gadolinium enhancement at the tendon at the RI (**b**) and at the intertubercular groove (**a**). Thickening of the midportion of the biceps pulley at CHL level (*short arrows*). Tear at the LHB (*long arrow a and b*)

was 31 % and the specificity 95 % which is comparable with the sensitivity for MRA arthrography that was 27 % and the specificity 94 %. There were no statistically significant differences between CT and MR. The interobserver agreement calculated with the kappa statistic was poor for CT and for MR. Both CT arthrography and MR arthrography perform poorly in the detection of biceps tendon pathology of the shoulder.

LHB Subluxation and Dislocation

The biceps pulley or "sling" is a capsuloligamentous complex that acts to stabilize the long head of the biceps tendon in the bicipital groove. The pulley complex is composed of the SGHL, the CHL, and the distal attachment of the SSC tendon and is located within the RI between the anterior edge of the SSP tendon and the superior edge of the SSC tendon (Fig. 17.41). Because of its superior depiction of the capsular components, D-MRA is the imaging modality of choice for demonstrating both the normal anatomy and associated lesions of the biceps pulley. Oblique sagittal images and axial images obtained with a high image matrix are valuable for identifying individual components of the pulley system (Figs. 17.41 and 17.42). Various pathologic processes occur in the biceps pulley as well as the RI. These processes can be traumatic, degenerative, congenital, or secondary to injuries to the surrounding structures. The term "hidden lesion" refers to an injury of the biceps pulley mechanism and is derived from the difficulty in making clinical and arthroscopic identification (Habermeyer et al. 2004b). Subluxation and luxation of the LHB tendon is frequently encountered. LHB dislocations are demonstrated on US and MRI, with the possibility of dynamic examination on US. In subluxation some contact with the intertubercular groove exists; in dislocation there is no contact with the groove. Three categories are described: tendon displacement (type I, II, and III Figs. 17.43, 17.44, and 17.45), the extra-articular dislocation (type IV Fig. 17.46), or intraarticular displacement (type V and VI Figs. 17.47 and 17.48).

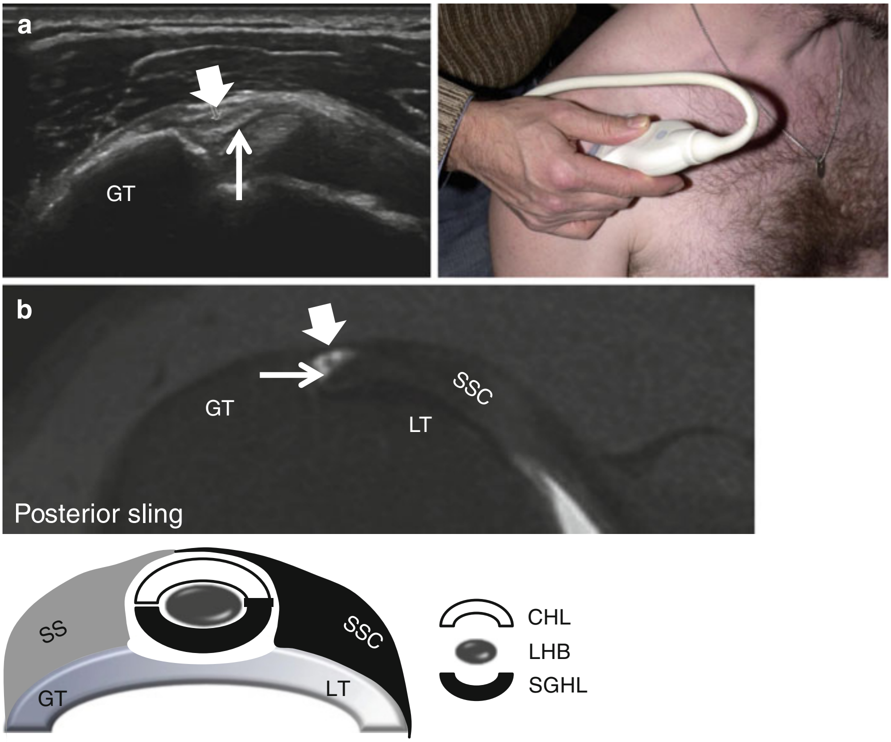


Fig. 17.41 Biceps pulley at the entrance of intertubercular groove. US with probe position, D-MRA demonstration. (**a**) Oblique axial US and (**b**) oblique axial MRA T1- WI FS demonstration of posterior sling of biceps pulley (*CHL*) (*arrows*) with schematic drawing. LHB is covered with TL (*thick arrows*)

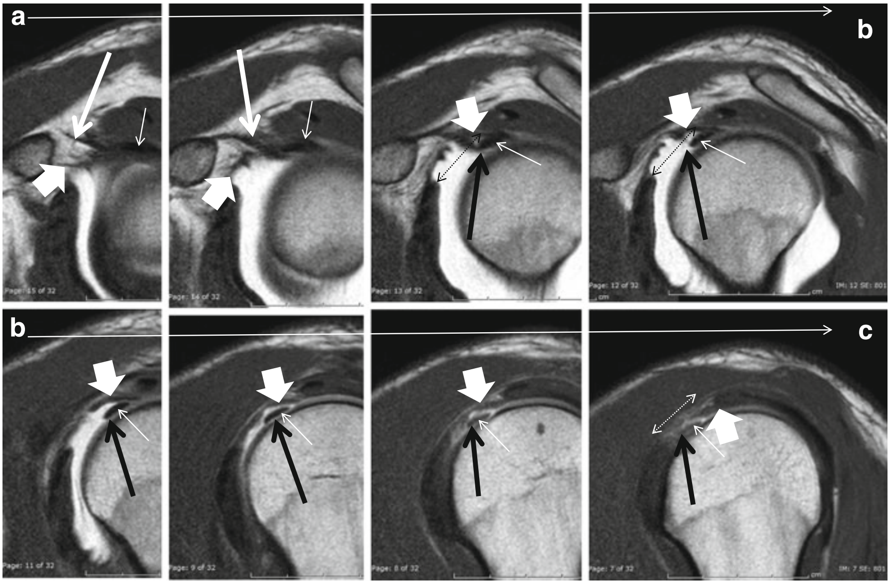


Fig. 17.42 (**a–c**) Biceps pulley demonstration on D-MRA. Oblique sagittal D-MRA T1-WI A. Medial slice near origin of LHB, CHL, and SGHL until C. Lateral near to entrance of intertubercular groove. LHB (*thin arrows*), CHL (*thick arrows*), and SGHL (*long arrows*). (**c**) Demonstration of connection of CHL with rotator cable (*thick arrow*). RI: *double-sided dotted arrows*

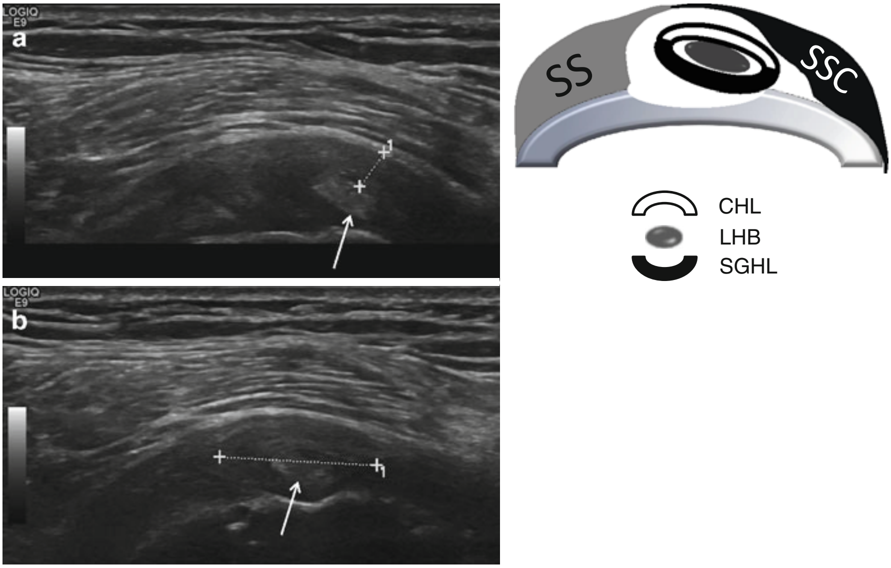


Fig. 17.43 LHB type I instability, US demonstration with schematic drawing. Partial intrasubstance tear of SSC with intact pulley and minimal shift of the biceps. Thickening of the LHB pulley at the interval area (**a** *cross marks*) with medial off center location of the biceps (**a** *thin arrows*) and widening of the interval up to 13 mm (**b** *cross marks*). Difficult differentiation from LHB type III instability

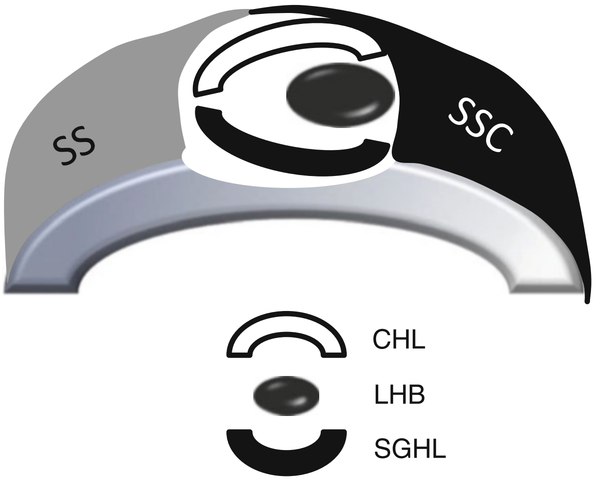


Fig. 17.44 LHB type II instability. Schematic drawing. Intact SSC attachment but medial tear of biceps pulley with medial subluxation of the biceps tendon

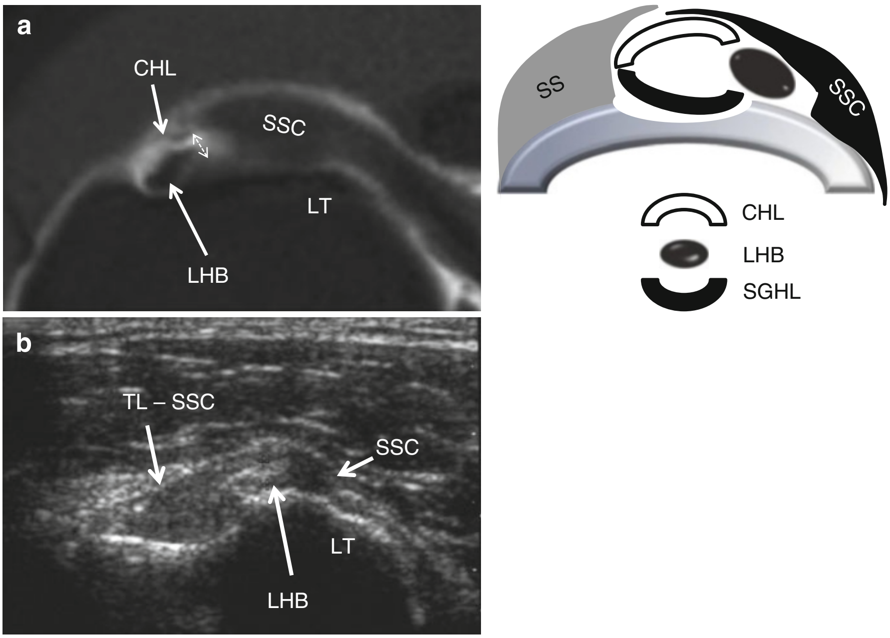


Fig. 17.45 LHB type III instability. Schematic drawing and US and D-MRA demonstration in different patients. Intrasubstance tear of SSC with medial pulley tear (*double-sided arrow*) and extra-articular medial subluxation of LHB. (**a**) axial CTA and (**b**) axial anterior US in different patients

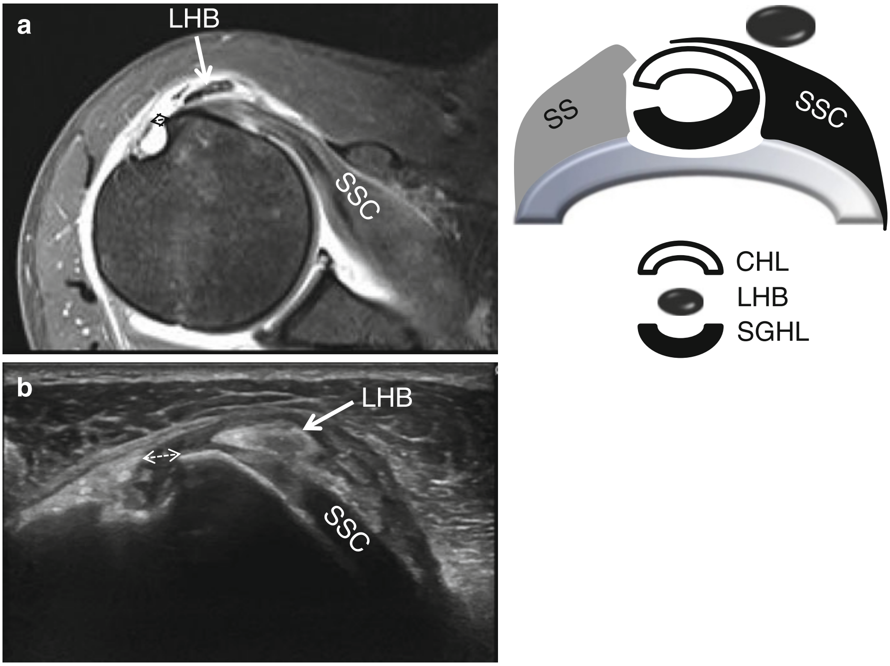


Fig. 17.46 LHB type IV instability. Schematic drawing and I-MRA and US demonstration in a 31-year-old female. Rupture of the pulley is located at the lateral limbs; associated tear of TL (*double-sided arrows*) with extra-articular migration of the biceps that is located anterior to the intact SSC

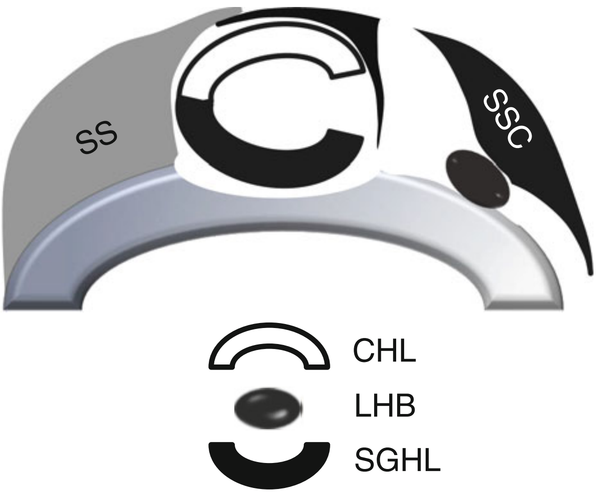
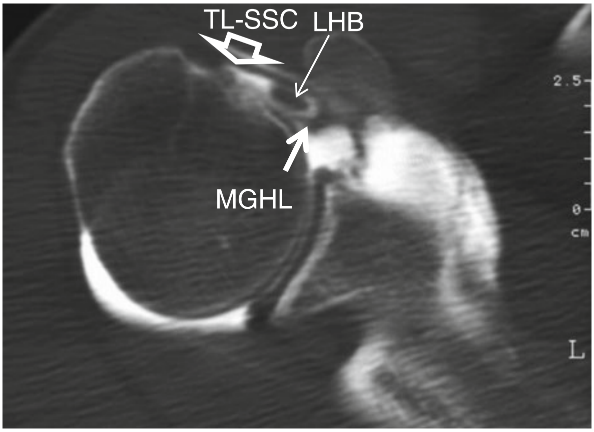


Fig. 17.47 LHB type V instability. Schematic drawing. Full-thickness tear of SSC with medial pulley tear and medial intraarticular dislocation of the biceps



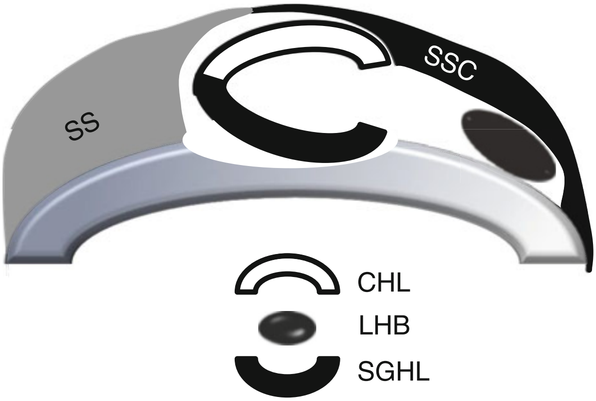


Fig. 17.48 LHB type VI instability. Schematic drawing with CTA demonstration. Detachment of the SSC with intact continuing fibers to TL and GT, medial biceps pulley tear with medial intraarticular dislocation of LHB

Table 17.9 Modified Habermeyer classification of biceps CL instability

Type I: Partial intrasubstance tear SSC with intact pulley can result in minimal medial shift of the biceps tendon
Type II: Intact SSC attachment but medial tear of the biceps pulley with medial subluxation biceps tendon
Type III: Intrasubstance tear of the SSC with medial pulley tear
IIIA: Biceps remains extra-articular
IIIB: Biceps intraarticular (bursal partial tear SSC)
Type IV: Tear of lateral limbs of biceps pulley with intact SSC and extra-articular dislocation of the biceps tendon
Type V: FFT of the SSC with medial (and lateral) biceps pulley tear and medial intraarticular dislocation of the biceps tendon
Type VI: Detachment of the SSC with intact continuing fibers of the SSC to the GT, medial biceps pulley tear, and medial intraarticular dislocation of the biceps tendon

Six types are defined (modified Habermeyer classification) (Habermeyer et al. 2004b) (Table 17.9 and Figs. 17.43, 17.44, 17.45, 17.46, 17.47, and 17.48). A partial intrasubstance tear of the SSC with intact pulley can result in minimal medial shift of the biceps tendon, type I Habermeyer biceps dislocation (Fig. 17.43).

17.3.4 Rotator Cuff

17.3.4.1 Ultrastructure of the Rotator Cuff

The rotator cuff tendons are histologically heterogeneous. They are assembled of up to four layers depending on the overall direction of collagen bundles, the fifth layer is the shoulder capsule. The major and superficial or bursal layer of the cuff has collagen bundles parallel to the overall direction of the tendon (layer II). Deep to this, layer III, has no prominent bundle direction, whereas layer IV the cable or transverse band has a bundle direction perpendicular to layer II. The cable is also known as ligamentum semicirculare humeri. The cable is located adjacent to the glenohumeral joint capsule (V) (Table 17.10) (Figs. 17.49a, b and 17.50a, b). The cable represents a thickening at the articular side of the tendon located approximately 1–1.5 cm medial to the enthesis (footplate) of the tendons which is the area of relative hypovascularity also known as critical area of the SSP and ISP. The rotator cable and crescent are located in the distal SSP and ISP tendon only (Fig. 17.50) (Burkhart et al. 1993). The cable starts anterior at the level of the intertubercular groove to end posteriorly at the level of the teres minor enthesis (Fig. 17.50a, b). It is regarded as a deep extension of the CHL by Clark and Harryman (Fig. 17.42c) (Clark and Harryman 1992). The crescent is the part of the tendon between enthesis and cable (Figs. 17.50a, b and 17.42c). Mean thickness of the crescent is 1.82 mm and of the cable 4.72 mm (Burkhart et al. 1993). The anatomical thickening of the cable is variable and may be detected on imaging in cable-dominant cuffs (Fig. 17.51). In cable-dominant cuffs the thick rotator cable acts as a suspension bridge preventing tears at the crescent to widen; it reduces the functional impact of cuff tears (PTT and FTT). Most of the cuff tears are allocated at the crescent; these are typically the tears related to subacromial impingement. The different layers of the cuff are not detected on MRI (Fig. 17.51a). High-resolution US may detect layer II, III, and IV (cable) (Figs. 17.51 and 17.52a). Cuff tears located at the cable itself are located at the critical area and result in more important retraction and functional cuff disability. Also cuff tears at the crescent in non-cable-dominant cuffs result in more retraction.

17.3.4.2 Tendinopathy

Focal thickening of a tendon is a major sign of tendinopathy (Fig. 17.52b). Tendinopathy is essentially a degenerative process (no prominent inflammation) related to impingement or overuse. Tendinitis is a misnomer as tendon inflammation is not prominent. Intrinsic tendon lesions related to overuse or acute traumatic tear are

Table 17.10 Rotator cuff, five layers from subbursal to articular

Layer I: coracohumeral ligament superficial fibers
Layer II: thick main cuff portion: parallel bundles
Layer III: thick cuff portion: smaller bundles with less uniform orientation
Layer IV: rotator cable or transverse band (perpendicular bundle) deep fibers of coracohumeral ligament at the SSP and ISP
Layer V: capsule, random fiber orientation

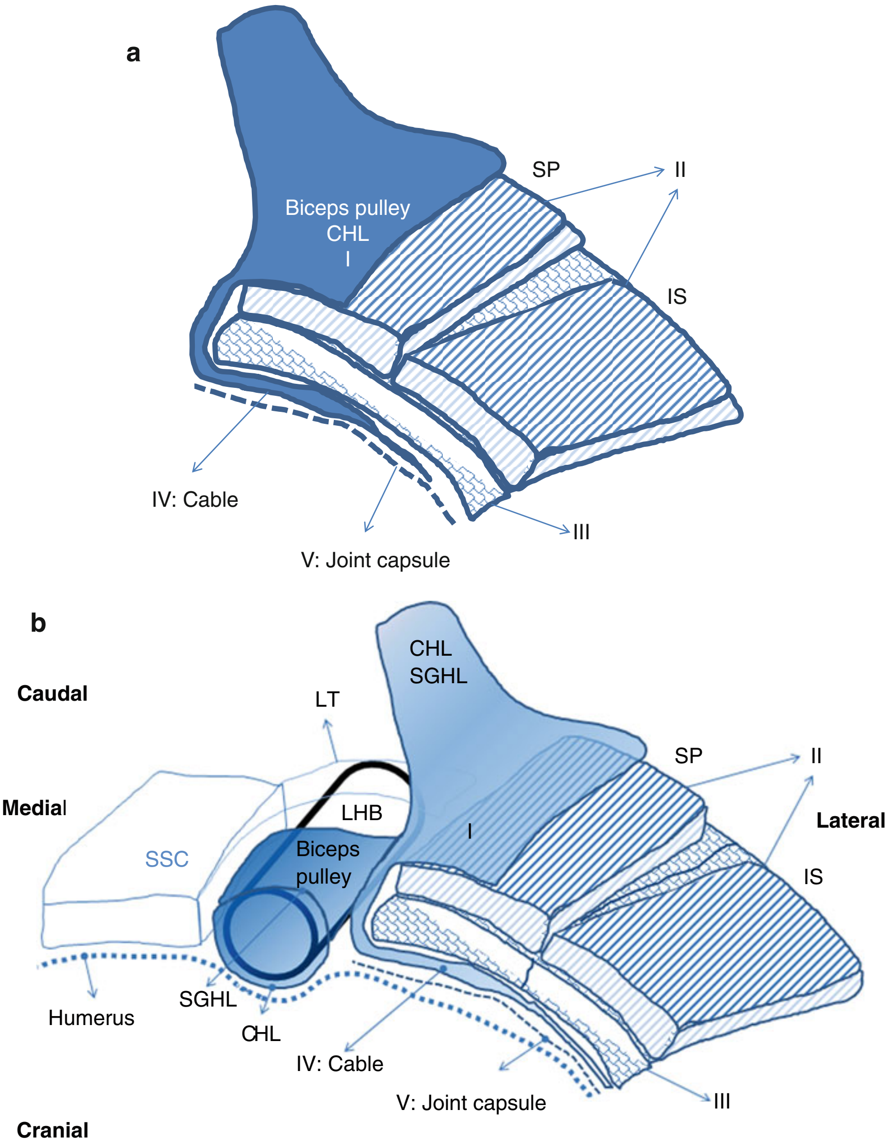


Fig. 17.49 Ultrastructure of rotator cuff. Schematic drawing

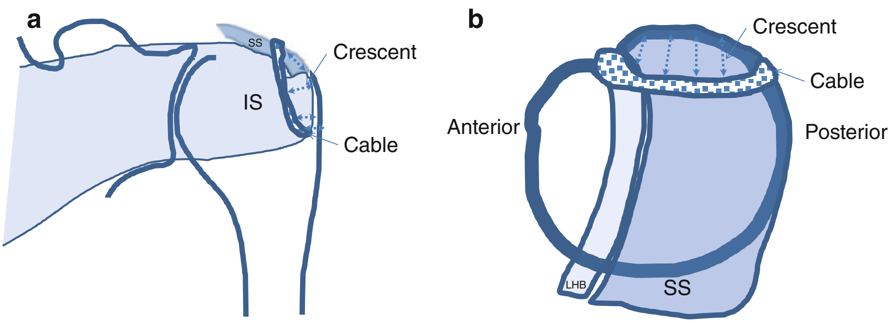


Fig. 17.50 (**a**, **b**) Rotator cable and crescent. Schematic drawing. (**a**) Posterior shoulder and (**b**) cranial view. Contours of bony landmarks of proximal humerus and scapula (*thick lines*). Contours of soft tissue landmarks of ISP and SSP (*thin lines*). Location of the cable (*dotted structure*) perpendicular to the direction of the tendons. Crescent is the distal part of the tendon, width 1 cm, located between cable and enthesis (*double-sided dotted arrows*)

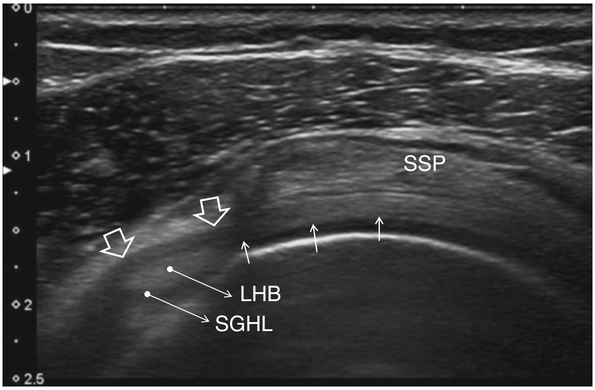


Fig. 17.51 Rotator cable, US demonstration. US SSP at RI with demonstration of cable (*arrows*) continuity with CHL (*thick arrows*), for comparison similar view on Fig. 17.42c

located at the “critical area,” mid-tendinous, with critical vascular supply. In subacromial impingement the insertional area or enthesis of the SSP and ISP at the GT is involved. Focal structural anomaly in tendinopathy is detected on MRI with increase SI or on US with decreased reflectivity. Structural hyporeflective anomalies on US should be detected on longitudinal and transverse imaging (Fig. 17.52c, d). The subacromial bursa may be thickened with or without fluid accumulation; inflammation is not prominent; this bursa thickening is most prominent at the area of impingement and

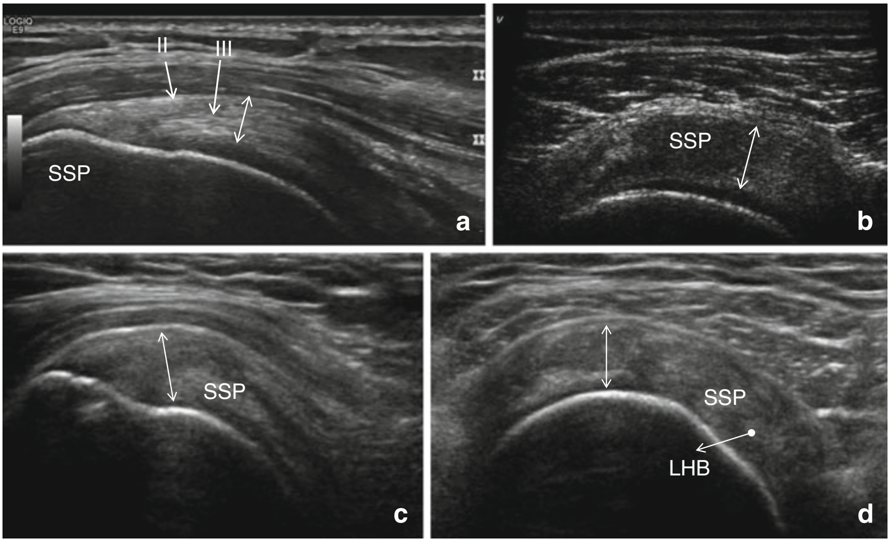
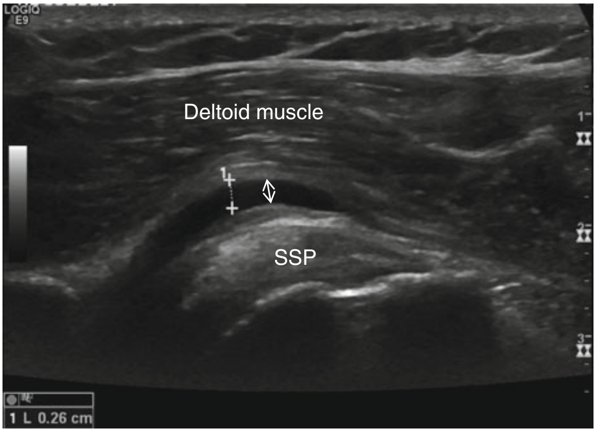


Fig. 17.52 Thickened SSP in tendinopathy demonstrated on US. (**a**) Longitudinal US view of normal SSP tendon with demonstration of layer II and III (*arrows*). (**b**) Longitudinal US view of focal thickening with hyposonant aspect related to tendinopathy of the SSP tendon. (**c**) Longitudinal and (**d**) axial US view in another patient

Fig. 17.53 Fluid at the SA-SD demonstrated on US. Asonant area of fluid (*double-sided arrow*) at the SA-SD bursa superficial to SSP and deep to deltoid muscle area



demonstrated on US and MRI on PD FS or T2 FS series but not on T1 FS series in D-MRA (Fig. 17.53). Gadolinium DTPA enhancement is demonstrated on I-MRA (Fig. 17.54). Tendon calcifications are caused by hydroxyapatite deposition (HADD) and may have low SI on all MRI pulse sequences (Fig. 17.54). Intratendinous calcifications are not discriminated from low SI collagen and can easily be missed on MRI. US and radiographs are more accurate to detect RC calcifications (Fig. 17.55). Clinically four stages of calcifying tendinopathy are described (Table 17.11). Most often calcifications are silent without clinical complaints (phase 1). In phase 2 when

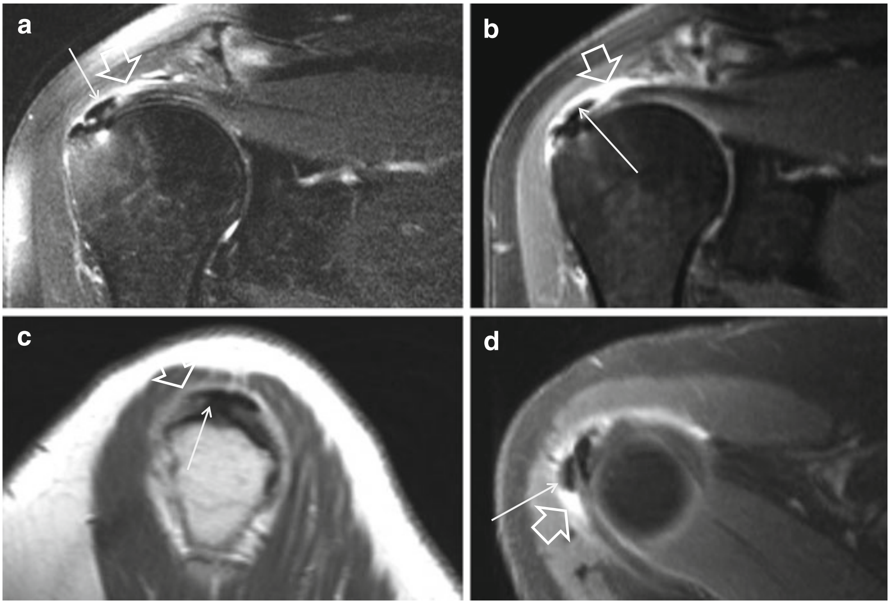


Fig. 17.54 Fluid at the SA-SD bursa and SSP calcifications demonstrated on I-MRA. (**a**) Coronal T1-WI FS, (**b**) coronal intermediate TE FS, (**c**) sagittal T1-WI, (**d**) axial T1-WI FS. Calcifications with low SI on all sequences (*thin arrows*), partial extrusion of the calcification to the SA-SD bursa (**d** *thin arrow*). Fluid (*thick arrows*) at the SA-SD bursa with enhancement on T1-WI (**a**–**c**) and high SI on fluid sensitive sequences (**b**)

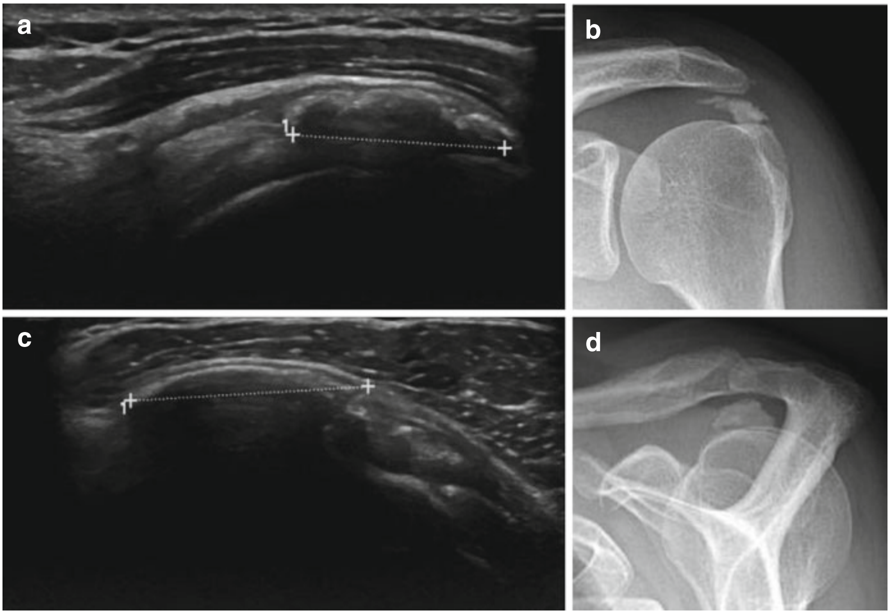


Fig. 17.55 Calcification at SSP demonstrated on US and radiograph. (**a**) Coronal view and (**c**) sagittal view on the SSP with hyperreflective calcification with acoustic shadowing and enlargement of the cuff. Demonstration of dense calcifications on 3/4th view (**b**) and scapular Y view (**d**)

Table 17.11 Phases of RC calcifications

1. Silent phase
2. Mechanical phase, elevation of bursal floor
3. Inflammatory phase: subbursal rupture
4. Inflammatory phase: intrabursal rupture

the calcification causes bulging on the bursal aspect of the tendon, pain with movement is related to tendon and SA-SD bursa impingement. For example, pain during glenohumeral elevation-abduction "painful arc" is found in SSP calcifications. Pain during glenohumeral endorotation movement is characteristic for SSC calcifications. Subbursal (phase 3) and bursal (phase 4) with extrusion of the calcifications is characterized by bursitis with acute inflammatory pain (Fig. 17.54).

17.3.4.3 RC Tears

Tendon tears are characterized by discontinuity of collagen bundles. Bundle discontinuity is directly demonstrated on US. Fluid in the tendon will be detected on MRI. In case of high SI in a tendon on fluid sensitive MRI sequences (T2, intermediate TE, and PD with and without FS) tendinosis has to be discriminated from artifacts (motion, vessels, metal, etc.), HADD with high SI (calcium milk phase), immediate postoperative status or after recent tendon platelet-rich plasma (PRP) injection or percutaneous needle tenotomy (PNT) procedure. High SI on PD and T1-WI in tendons can be caused by tendinopathy and should be discriminated from magic angle phenomenon, fibrosis, and granulation tissue in tear and is found in the ISP in internal rotation position (overriding the SSP), it is also a normal finding in children and adolescents. Increased SI related to magic angle phenomenon is specifically found in sequences with short TE (shorter than 37 ms on 1.5 T (T1 and PD)) in tissues with well-ordered collagen fibers in a single direction (tendon, ligament, cartilage) with an angle of about 50° with the permanent magnetic field B0 (54.7° in 1.5 T). Discrimination of magic angle phenomenon and tendinopathy is done by comparison of T2-WI (with long TE) in which the magic angle artifact disappears.

PTT

PTT and FTT are discriminated through a direct communication of the SA-SD bursal space with the glenohumeral joint in FTT (Fig. 17.62). In D-MRA an injection of the glenohumeral joint results in opacification of the SA-SD bursa in case of FTT. This D-MRA sign is void in I-MRA. PTT are twice as frequent compared to FTT. PTT can be located at the bursal side, at the articular side, or intrasubstantial in the tendon. Morphologic features of tears should be described: location in long axis and short axis with dimensions, characteristics (vertical, horizontal, oblique, thinning, irregularity, delamination, articular sided retraction, undersurface flap). Low-grade PTT have a depth of less than half of the tendon thickness (Fig. 17.56), medium-grade PTT are half of the tendon thickness, and high-grade PTT are more than half of the tendon thickness (Fig. 17.57). On arthroscopy PTT are staged differently (Table 17.12) (Millstein and Snyder 2003).

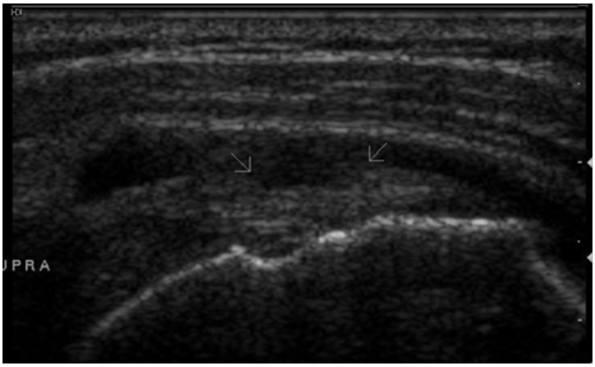


Fig. 17.56 Low-grade bursal sided PTT at SSP demonstrated on US. Longitudinal US of low-grade bursal sided PPT at SSP (*arrows*)

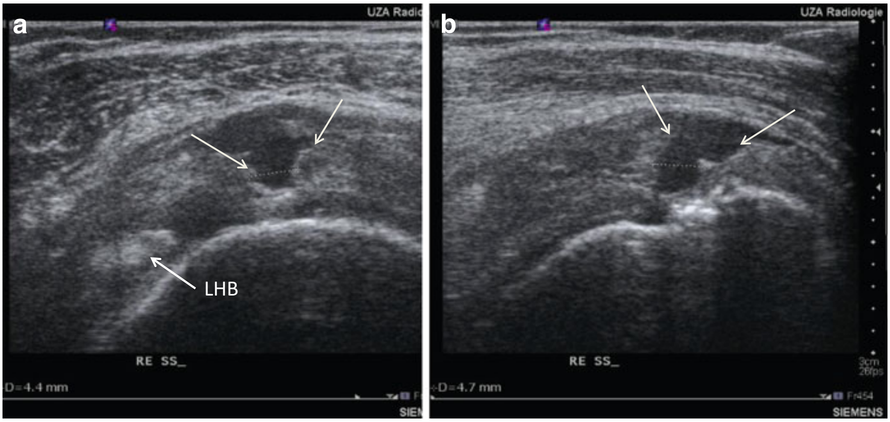


Fig. 17.57 High-grade bursal sided PTT at SSP crescent demonstrated on US. Transverse (**a**) and longitudinal (**b**) with discontinuity of tendon fibers (*arrows*) filled with asonant fluid

Table 17.12 Arthroscopic stages of RC PTT (Snyder)

Stage 0: Normal
Stage 1: Minimal superficial bursal or synovial irritation or mild capsular fraying in a small localized area less than 1 cm
Stage 2: Fraying and failure of some RC fibers + synovial bursal or capsular injury <2 cm
Stage 3: Fraying and fragmentation of tendon fibers involving whole tendon surface less than 3 cm
Stage 4: Severe tear with tendon fraying, fragmentation, and large flap involving more than one tendon

Articular sided PTT are the most common; they are associated with GH instability, microinstability, and internal impingement (Fig. 17.58).

Bursal sided tears are more related to extrinsic impingement. Bursal puddle sign is recognized (bursal sided fluid SI continuous with the SA-SD bursa) in bursal sided PTT (Figs. 17.56 and 17.57).

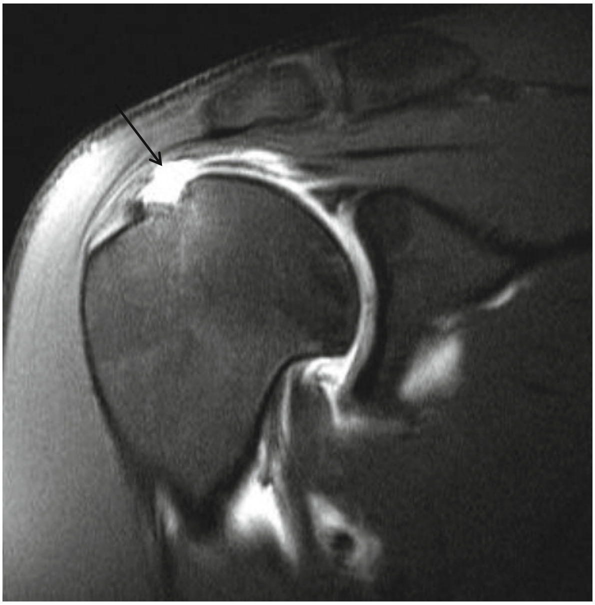


Fig. 17.58 Medium-grade articular sided PTT at critical area (cable) demonstrated on 1.5 T D-MRA. Coronal T1-WI FS demonstrating gadolinium infiltration at thinning of the SSP tendon in the area of the tendon

Intrasubstance PTT are typically delamination or loosening of the different tendon layers and may be missed on arthroscopy. MRI presents with low to intermediate SI on T1-WI and PD and with high SI on T2, PD FS, and T2* (PTT and degeneration present with similar signal) (Figs. 17.59 and 17.60). On D-MRA at the glenohumeral joint, articular sided PTT and FTT are demonstrated. Tears are understaged when there is granulation tissue in the tear. D-MRA will not demonstrate bursal sided PTT on T1-WI; they are only detected on the T2 or intermediate TE WI (Fig. 17.60a, b). I-MRA will demonstrate bursal sided PTT on T1-WI (Fig. 17.61).

A *rim rent* tear is an articular side PTT of the SSP at its attachment to the GT. These lesions start where the loads are greatest, i.e., the articular surface of the anterior SSP (Fig. 17.62). This lesion is more frequent in younger people and is associated with erosions and cystic changes. They can easily be missed on the coronal images. If the footprint is exposed over 7 mm lateral from the cartilage edge, this lesion is surgically repaired.

A rim rent lesion evolves into a *PASTA* (periarticular articular sided SSP tendon avulsion), i.e., a type of Snyder stage 2 or 4 articular surface delamination tear with significant fragmentation or flap. It is more common in younger people and overhead sports (Fig. 17.63). Reversed PASTA lesion is a selective delamination of the bursal surface of the SSP.

PTT and FTT can extend into the longitudinal tendon plane by delamination of the layered structure of the RC (Figs. 17.60, 17.61, 17.62, 17.63, and 17.64).

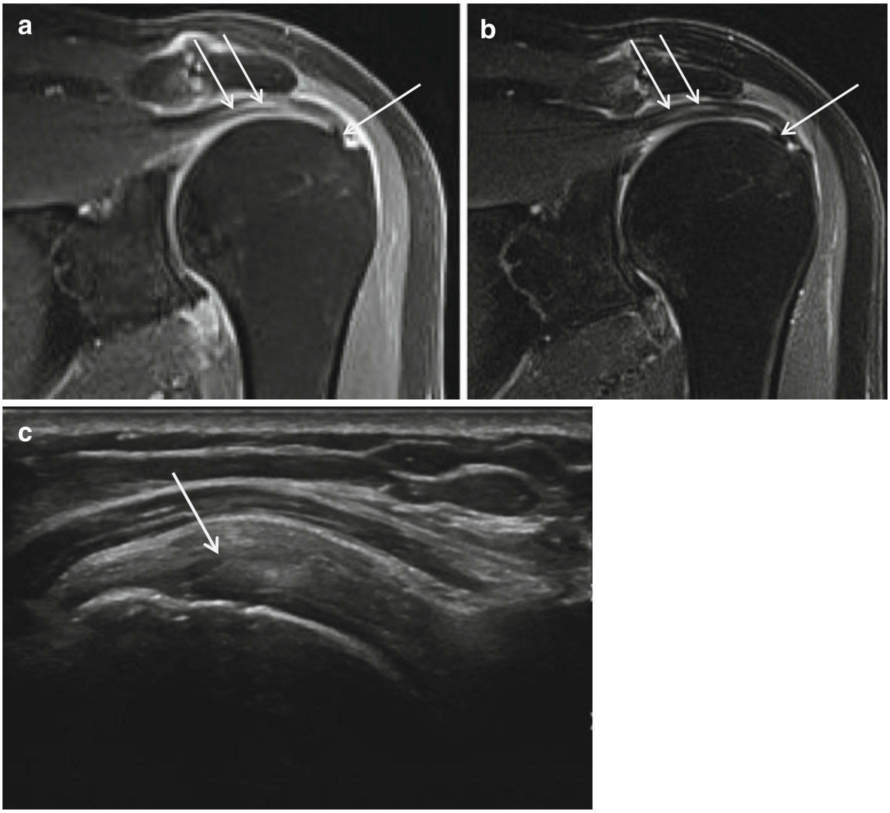


Fig. 17.59 PTT intrasubstantial delamination of SSP in 68-year-old women demonstrated on I-MRA and US. (**a**) Coronal T1-WI FS and (**b**) coronal intermediate TE FS longitudinal high-intensity area at SSP (*arrows*). (**c**) Longitudinal hyporeflective area between level II and III of the SSP

As a result of the low therapeutic consequence of non-detection of low-grade partial-thickness RC tears, US is regarded as the primary investigation tool. Major diagnostic advantage of US over MRI is the dynamic evaluation of impingement during elevation or endorotation. The LHB in its extra-articular and distal RI course is accurately demonstrated on US.

FTT and Complete Tears

PTT may evolve to *FTT* (Fig. 17.61). The mayor advantage of direct arthrography is the communication of the glenohumeral joint space through the RC with enhancement of the SA-SD bursa; this is pathognomonic for FTT (Fig. 17.65b, c). FTT are in early stages frequently located anterior in the SSP and propagate to the posterior aspect of the RC; 40 % extend into the ISP. Anteriorly they propagate to RI, LHB,

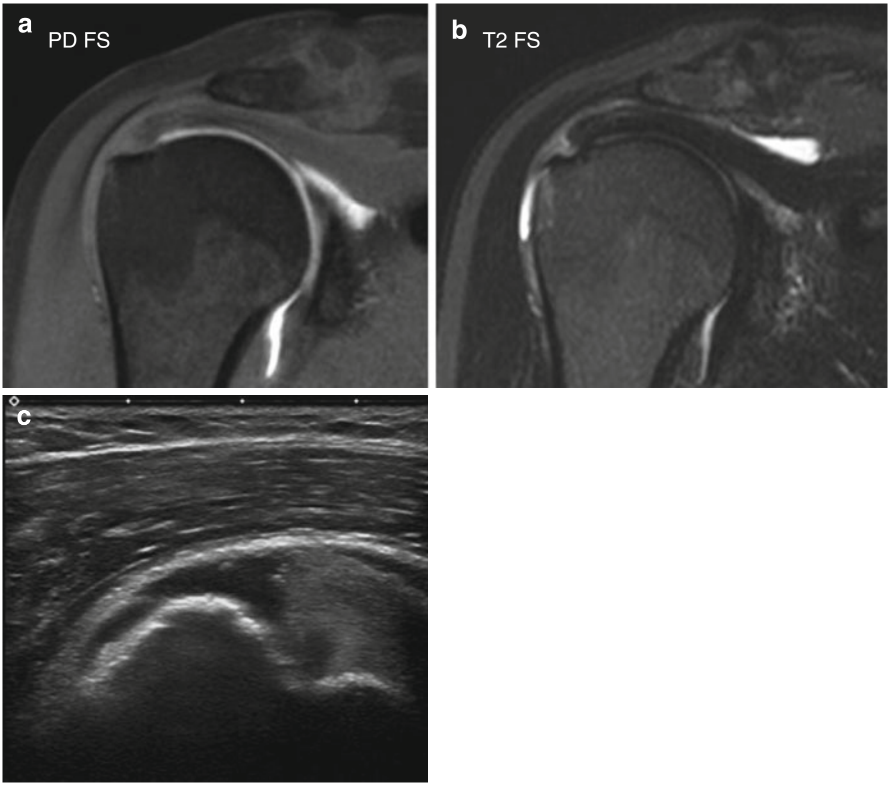


Fig. 17.60 SSP PTT bursal sided demonstrated on 1 T D-MRA and US. (**a**) Coronal T1-WI FS, no demonstration of the tear. (**b**) Coronal intermediary TE FS demonstrating puddle sign. (**c**) Longitudinal SSP view

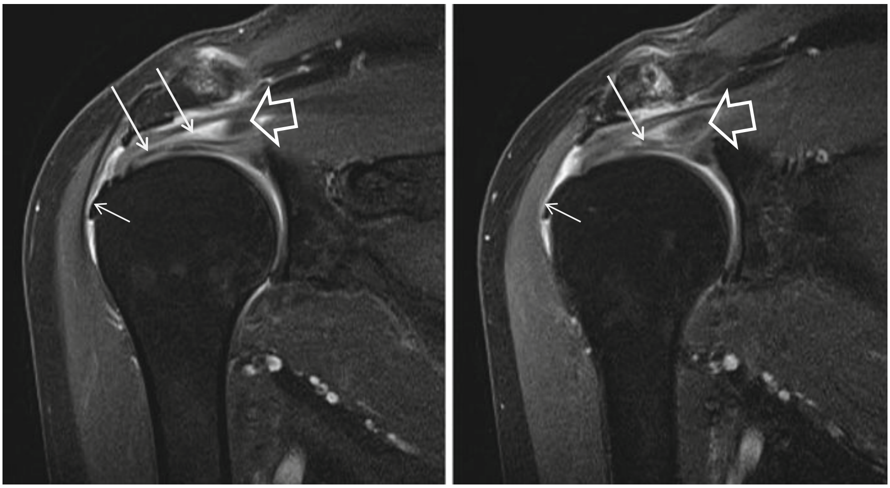


Fig. 17.61 PTT bursal sided with delamination of SSP in 61-year-old women demonstrated on I-MRA. Coronal T1-WI FS with delamination (*arrows*) containing HADD (*thick arrow*). Extrusion of HADD at bursal side (*small arrows*) with irregular bursal margin of the tendon at the enthesis and partial cover of the GT footplate

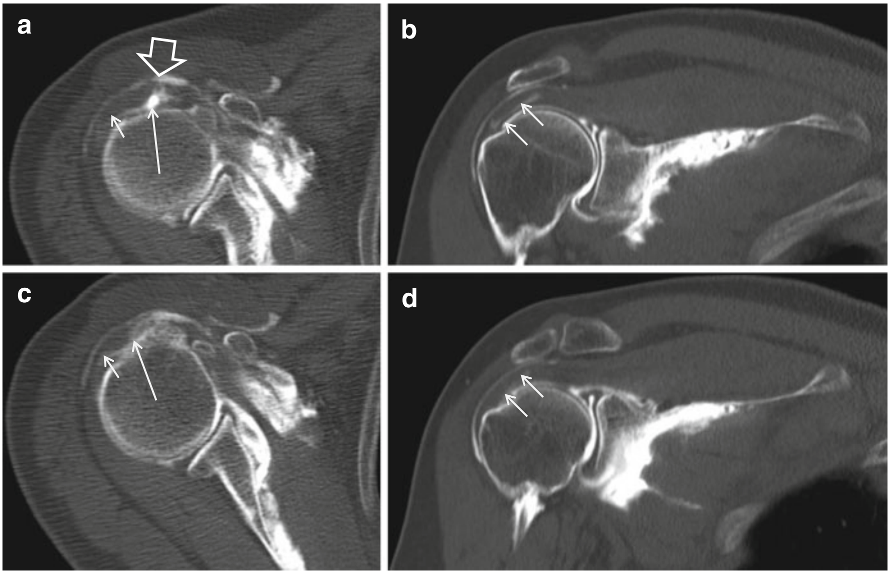


Fig. 17.62 Rim rent PTT at SSP demonstrated in a 66-year-old female on glenohumeral CTA. (**a**, **c**) Axial and (**b**, **d**) coronal slices with anterior articular sided SSP tear (*long arrows*) with delamination enhancement of the tendon medial-posterior (*small arrows*). Small full-thickness tear is located anterior (*thick arrow*) with enhancement of SA-SD bursa

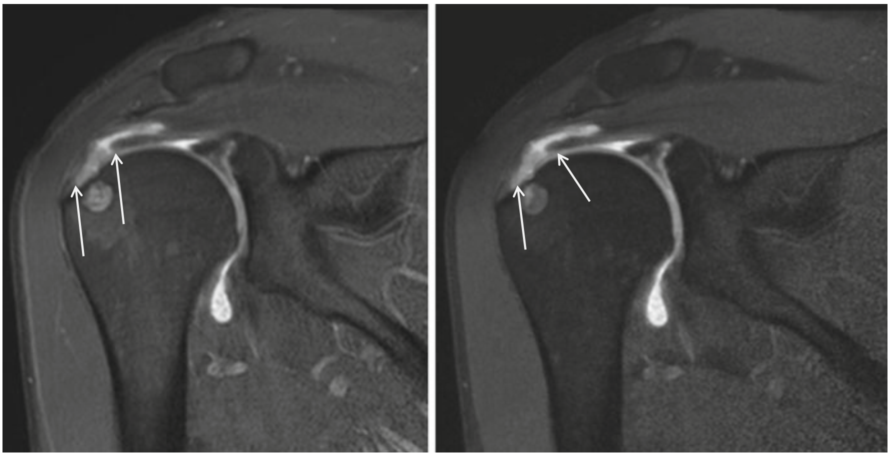


Fig. 17.63 PASTA PTT at SSP demonstrated on glenohumeral D-MRA. Gadolinium enhancement at SSP enthesis with broad retraction of the SSP from the medial part of the footplate (*arrows*) and enhancement of intratendinous delamination area. No enhancement of the bursa in articular sided PTT

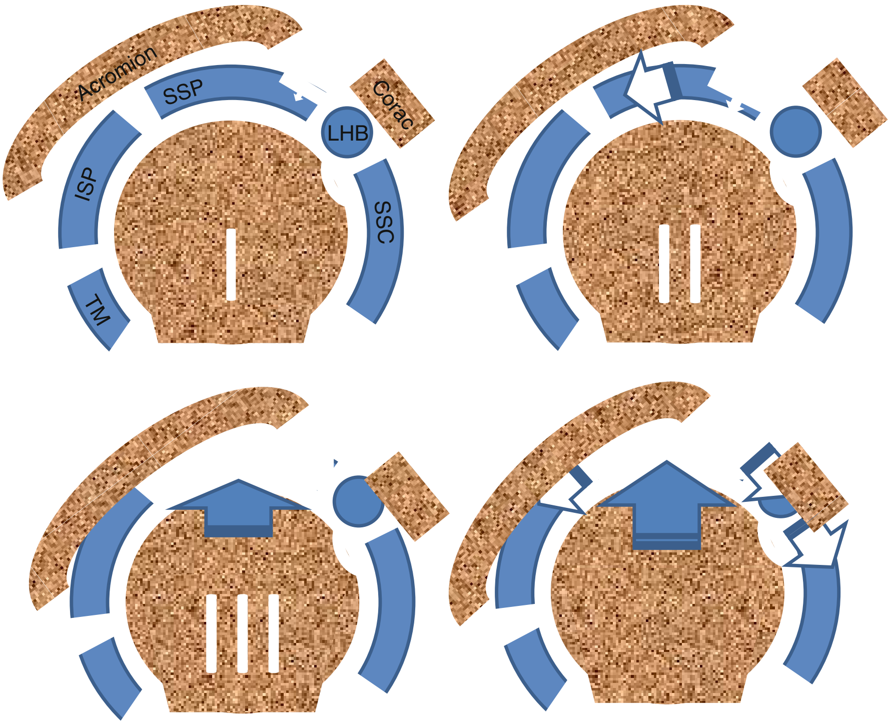


Fig. 17.64 Schematic drawings demonstrating the progression of subacromial impingement related PTT in FTT. In the first stage SSP PTT evolves into FTT (stage II) with complete tear and retraction of the tendon (III). In the last stage cranial migration of the humerus causes impingement of ISP posteriorly and LHB and SSC anteriorly (subcoracoidal external impingement) with tendinopathy and tears as a result. This is clinically known as the biphasic evolution starting with subacromial impingement complaints and subsequently subcoracoidal impingement complaints

and SSC. The size of the lesion should be reported in two dimensions, longitudinal and transverse (Figs. 17.66 and 17.67).

A FTT with extension into the whole tendon is a massive or *complete* tendon tear; in these, the tendon may retract with lipomatous involution of the dependent muscle as a result. Arthroscopic stages of FTT are listed in Table 17.13. Tendon retraction should be reported and is staged on MRI or CT according to Goutallier or Patte (Lippe et al. 2012) (Table 17.14).

Tears dominantly located at the *cable* show less retraction and are easier to repair compared to lesions located at the crescent of the RC where retraction is more medial and repair more difficult (Fig. 17.68b; for comparison Fig. 17.50). Articular sided PTT with extension into the cable are more symptomatic compared to bursal sided PTT (Fig. 17.69a) (Burkhart 1992; Burkhart et al. 1993; Halder et al. 2002; Su et al. 2009).

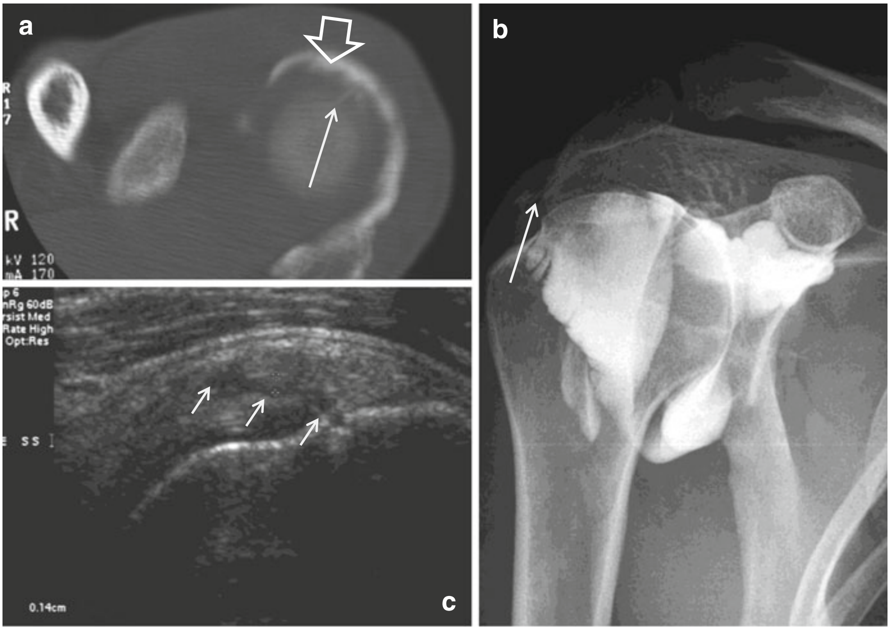


Fig. 17.65 (**a–c**) US and arthrography and CTA demonstration of small FTT at footplate of SSP tendon in a middle-aged woman. Small erosion at the GT footplate often is a landmark for tendon disease; small FTT tear (*arrows*) is demonstrated on US (**c**), arthrography (**b**), and CTA (**a**) with demonstration of contrast enhancement at the SA-SD bursa (*thick arrow*)

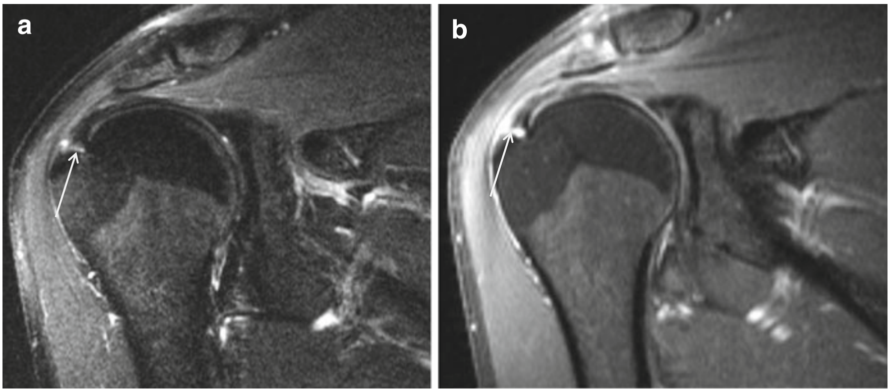


Fig. 17.66 I-MRA demonstration of small FTT at footplate of SSP tendon. (**a**) Coronal intermediary TE FS and (**b**) coronal T1-WI FS imaging plane

Although interobserver reliability is low, rotator cuff *muscle atrophy* has to be graded according to Goutallier and/or Warner (Table 17.15). In Goutallier's system muscle fatty infiltration is graded on sagittal CT images (Goutallier et al. 1994, 1999). Strobel defined accuracy of US in grading of SSP and ISP fatty

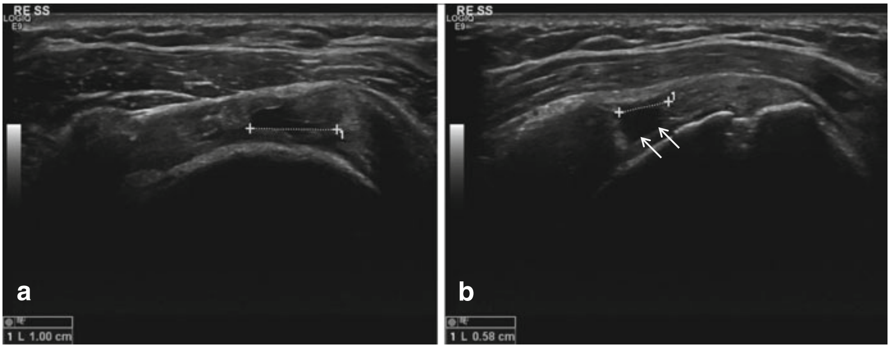


Fig. 17.67 (**a**, **b**) FTT at critical area of SSP in a 65-year-old female patient. Fiber discontinuity filled with assonant fluid about 1.5 cm proximal to the enthesis of the SSP tendon is demonstrated in sagittal (**a**) and coronal plane (**b**). Coronal plane demonstrates hyperreflective cartilage sign related to fluid-cartilage interface (*arrows*) at the area of tendon retraction stage 2 according to Patte, Table (17.13)

Table 17.13 Arthroscopic stages of FTT

Stage 0: PTT (articular or bursal) without communication
Stage 1: Small FTT (puncture)
Stage 2: Moderate (<2 cm) tear involving one tendon without retraction
Stage 3: Large (3–4 cm) tear involving an entire tendon with minimal retraction
Massive (complete): Tear involving two or more tendons, usually associated with retraction and scarring of the tendon ends

Table 17.14 Staging of the tendon retraction according to Patte is done on paracoronal images

Stage 1: Adjacent to tendon insertion
Stage 2: Superior to humeral head
Stage 3: Glenoid margin

atrophy (Strobel et al. 2005) and calculated a moderate accuracy of US of 75–85 % for SSP and ISP, respectively (Fig. 17.36). Assessed US parameters were visibility of muscle contour, visibility of pennate pattern, visibility of the central tendon, and muscle echogenicity (Table 17.16). In Warner's classification muscle volume is related to a tangent line on sagittal images at the level of the coracoid process (MRI or US) connecting the cranial cortical margin of the spina with the cranial cortical lining of the coracoid process for the supraspinatus and of the posterior cortical margin of the spina with the posterior-inferior margin of the scapula for the infraspinatus muscle (Fig. 17.70a) (Warner et al. 2001; Tingart et al. 2003; Lippe et al. 2012).

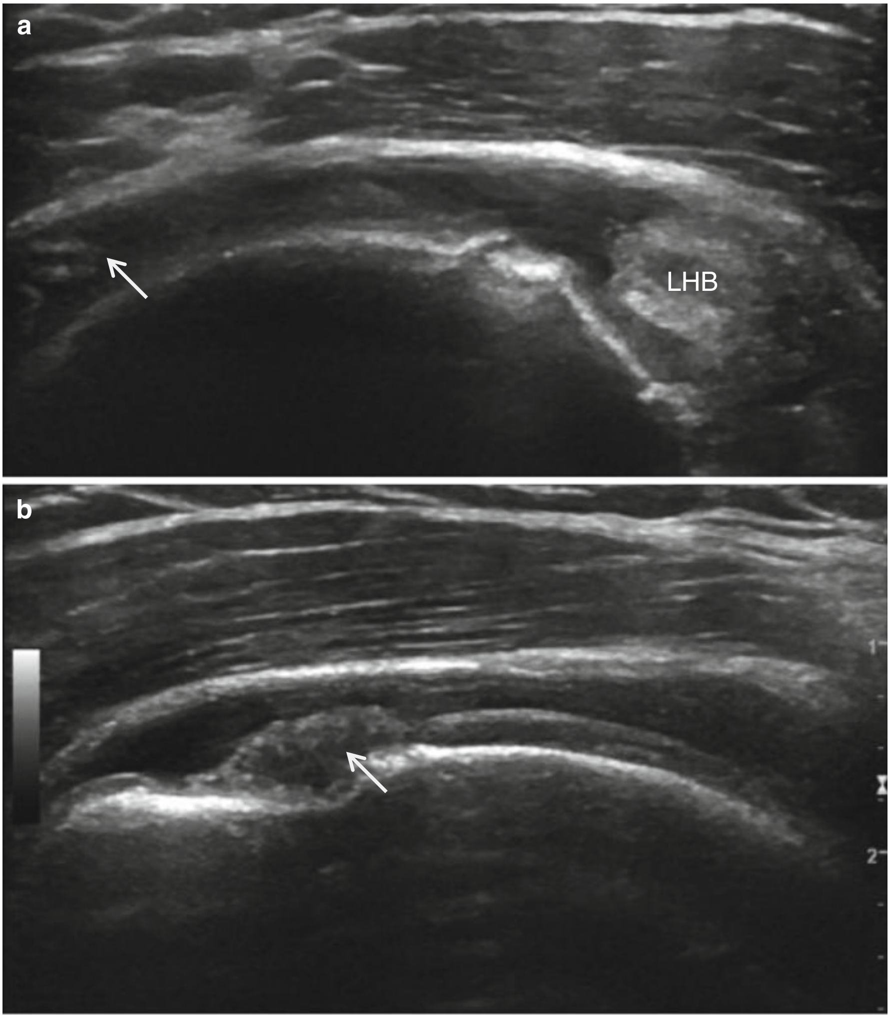


Fig. 17.68 (**a**, **b**) Schematic drawings illustrating suspension action of rotator cable. (**a**) Tear located at crescent results in minor tendon retraction related to transverse fortification. (**b**) Tear with disruption of the cable results in marked tendon retraction

17.3.5 Postoperative Shoulder

Postoperative MRI of the shoulder is subject to artifacts that hamper interpretation of the images (Table 17.17). Metal artifact reduction sequences (MARS) are used to enhance MR image quality but have the drawback that gradient imaging and FS is avoided. MARS protocol includes SE or TSE sequences with view angle tilting,

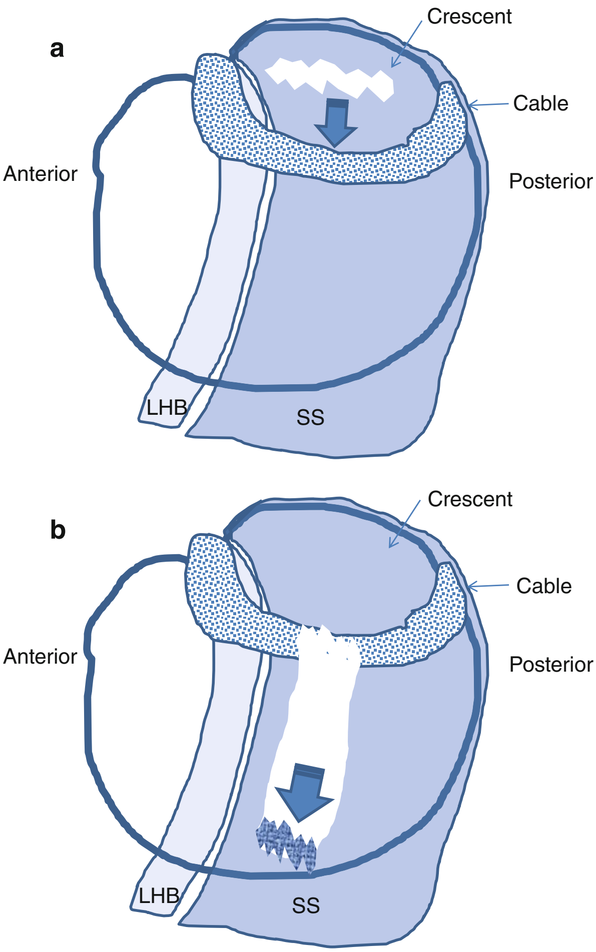


Fig. 17.69 (**a**, **b**) Complete SSP tear demonstrated on US. Sagittal (**a**) imaging plane with fluid at subdeltoid area anterior up to LHB and posterior up to ISP (*arrow*). Coronal (**b**) imaging plane demonstrates small tendon stump (*arrow*) at medial part of GT footplate. The retracted SSP tendon is not visible; it is retracted beyond the right margin of the image until the glenoid margin (stage 3 according Patte, Table 17.13)

Table 17.15 Staging fatty atrophy according to Goutallier

Stage 0 – Normal muscle
Stage 1 – Some fatty streaks
Stage 2 – Less than 50 % fatty muscle atrophy
Stage 3 – 50 % fatty muscle atrophy
Stage 4 – Greater than 50 % fatty muscle atrophy

increased TSE factor (max 4TE), increased slice selection gradient strength with reduced slice thickness, and reduced ratio of FOV and pixel number in phase encoding direction and STIR instead of FS (Table 17.18) (Petersilge et al. 1996; Olsen et al. 2000; Chang et al. 2001; Lee et al. 2001). Moreover anatomic evaluation of

Table 17.16 Staging fatty atrophy on US according to Strobel

A Scoring of muscle structure	
	0: clearly visible muscle contours, fibers, and central tendon
	1: partially visible structures
	2: structures no longer visible
B Scoring of echogenicity in comparison to trapezius or deltoid muscle	
	0: iso- or hypoechoic
	1: slightly more echoic
	2: markedly more echoic

Substantial fatty atrophy is diagnosed if combined score A + score B is 2 or more

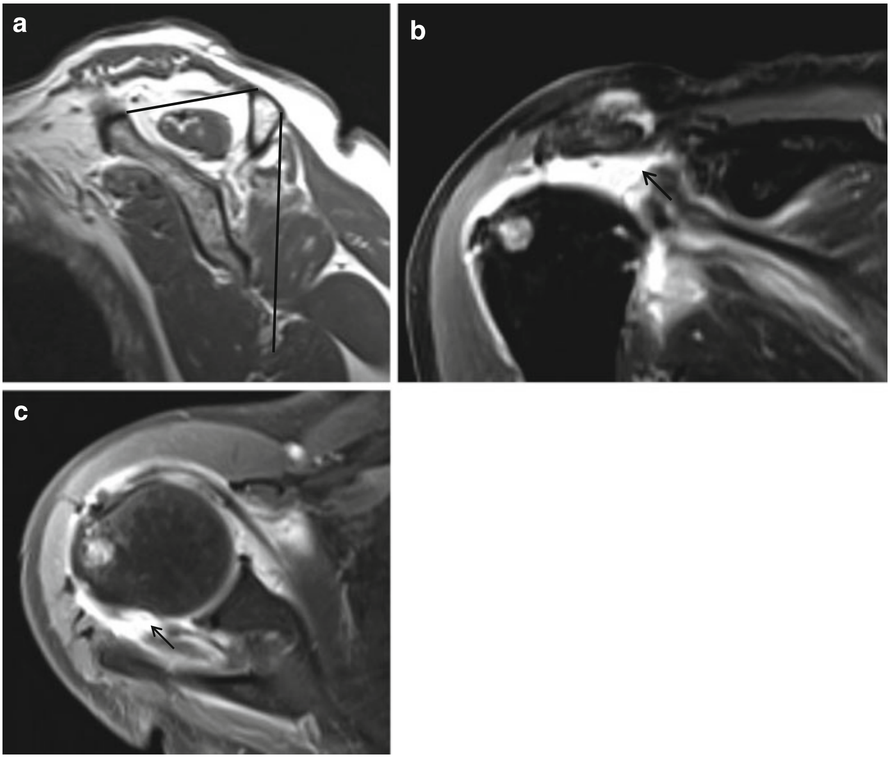


Fig. 17.70 (**a**–**c**) Complete SSP and ISP tendon tear with stage 3 retraction demonstrated on I-MRA. (**a**) Sagittal T1-WI demonstrating increased fat at the SSP and reduced muscle volume according to Warner below the cranial tangent lining of the scapula. Cranial half of ISP muscle also reveals increased SI related to fatty involution but without major muscle volume decrease (posterior tangent lining of the scapula). (**b**) Coronal intermediary TE FS image with retraction of the SSP tendon (*arrow*) stage 3 according to Patte, Table 17.13c. Axial T1-WI FS demonstrating retraction of the ISP tendon (*arrow*) stage 2 according to Patte

Table 17.17 MRI artifacts related to surgery and implants

Surgery/implant	Artifact on MRI	Recommendation
Bioabsorbable implant (radiolucent)	None to mild	No change of protocol
Osteotomy (distal clavicula resection)	None to mild	No change of protocol
Metal anchors (cuff, labral repair)	Mild to moderate	Change of protocol may be required
Rod/plate	Moderate to severe	Change protocol or modality
Screw	Moderate to severe	Change protocol or modality
Burring (acromioplasty)	Severe	Change protocol or modality
Shrapnel/bullet	Severe	Change protocol or modality
Prosthesis	Severe	Change protocol or modality

Table 17.18 MARS protocol

Protocol change	Drawback	Usefulness
Increase bandwidth	Decreases SNR	High
Avoid GE		High
Use STIR instead of T2 FS	Gadolinium may be suppressed	High
Lower TE		High
Avoid FS		Moderate
Use lower field strength	Reduced S/N	Low
Use larger matrix		Low
Use TSE instead of SE		Low
Swap phase/frequency		Low

tendon and labrum repair is prone to erroneous conclusions on CTA, US, and MRI. US and CTA are good alternatives to MRI for the evaluation of the postoperative cuff. CTA is a good alternative for the evaluation of labrum repair.

17.3.5.1 RC Repair

Articular PTT that do not involve more than two-thirds of the tendon thickness respond well to debridement of the necrotic torn tissue, with or without anterior acromioplasty. Full-thickness tears can require open surgery. Arthroscopy-assisted (mini-open) rotator cuff repairs or purely arthroscopic repairs are possible in some tears. Open repair offers the best exposure of the lesion for the surgeon, but this procedure prolongs recovery time. Mini-open repair technique includes a vertical spit in the deltoid muscle with arthoscopic acromioplasty and RC repair. Pure arthroscopic repair offers the fastest rehabilitation but is surgically challenging for large tears (double-row suture is difficult).

In PTT surgical debridement of granulation tissue is performed. In FTT or massive tears tendon to tendon repair is performed with single- or double-row sutures (Fig. 17.71). Tendon to bone repair is done with use of bioresorbable anchors (radiolucent) or with metal anchors.

Complications of cuff repair (retear 6.2 %, nerve injury 1.1 %, infection 1.1 %, deltoid dehiscence 0.5 %, frozen shoulder 0.5 %) may be indications for imaging. Deltoid dehiscence or detachment of the deltoid muscle from the acromion with

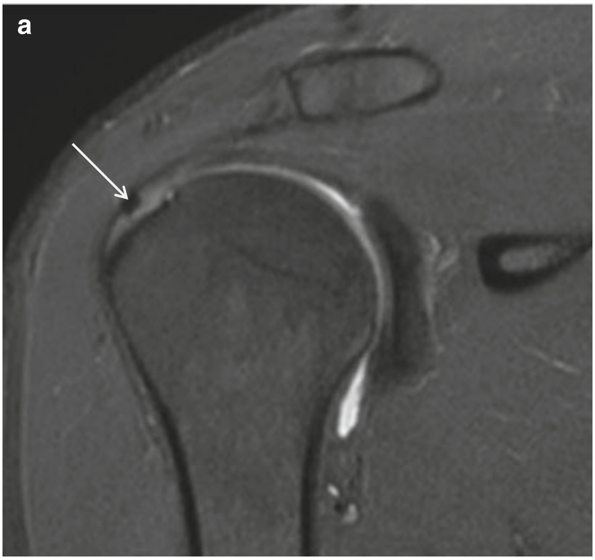
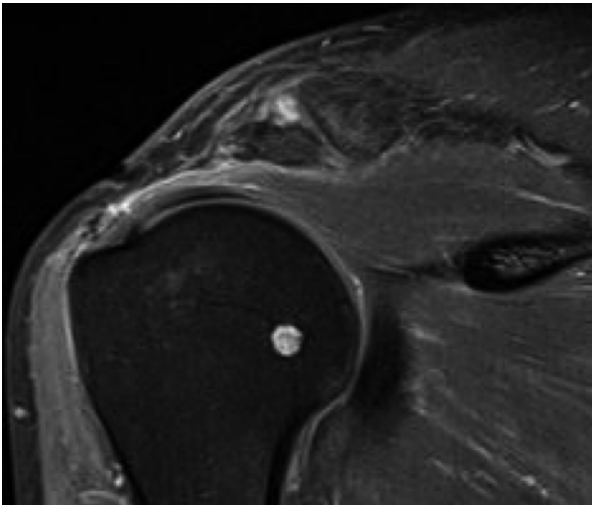


Fig. 17.71 End to end SSP tendon repair demonstrated on 1 T D-MRA. Increased SI on coronal PD WI FS with small low SI blooming artifact at area of suture (*arrow*)

Fig. 17.72 Deltoid dehiscence after end to end cuff repair on 1 T D-MRA. Coronal intermediate T FS image demonstrating normal cuff but absent deltoid muscle



pain and weakness on arm abduction is early postoperatively detected and has to be discriminated from retear (Fig. 17.72). MRI of tendon repair shows intermediate to low SI in the tendon related to granulation tissue and fibrosis, respectively (Figs. 17.71 and 17.72); with disturbed fibrillation on US, the morphology of the tendon is regular or irregular on MRI or US depending on the procedure and the tissue quality of the tendon related to preexistent tendinosis. Only 10 % of repaired tendons have a normal appearance on MRI. Mild superior subluxation of the humeral head may be related to capsular tightening, scarring, cuff atrophy, or bursectomy. Fluid in the subacromial-subdeltoid space is a nonspecific postoperative finding. “Geyser sign” on postoperative MR images is a common finding secondary to injury of the acromial undersurface during surgery. Bioabsorbable sutures and anchors are increasingly used. They produce a signal void with small artifact, may be C shaped, and dissolve over time (Figs. 17.71 and 17.72). Release of the components in the joint is not necessarily abnormal. Fluid or contrast under the tendon repair area with displaced anchor may be a sign of too early resorption. Small full-thickness defects with communication of the glenohumeral joint and the SA-SD bursa are normal. Pathologic communications are larger than 1 cm and have retracted tendon with progression in follow-up examinations, anchor displacement, muscle atrophy, large amounts of fluid in the SA-SD bursa, and GH OA. MRA may produce misleading results through enhancing granulation and scar tissue at tendon anastomosis. Ultrasound may be used to evaluate the integrity of a repaired rotator cuff tendon and constitutes a comparable alternative to MRI when evaluating the integrity of a rotator cuff repair. Clinical investigators should compare their postoperative ultrasound results with their postoperative MRI results for a certain time period to establish the accuracy of ultrasound before relying solely on ultrasound imaging to evaluate the integrity of their rotator cuff repairs (Codsi et al. 2014).

17.3.5.2 Acromioplasty

Arthroscopic subacromial decompression is the method of choice for treatment of chronic extrinsic impingement. This procedure includes resection of the coracoacromial ligament (recently this ligament is preserved or reattached), anterior and posterior acromion resection, resection of acromioclavicular joint osteophytes, and, if necessary, distal clavicular resection. Evaluation of acromioplasty is done on sagittal images, except for the resection of the distal clavicula that is better evaluated on the axial imaging plane and results in widening of the acromioclavicular distance by 1–2 cm. Postoperatively the undersurface of the acromion resembles Bigliani type I.

17.3.5.3 Surgery for Instability

Bankart repair includes anteroinferior labral capsular repair. The anterior-inferior capsule may be shifted through inferior capsular shift procedure or with arthroscopic thermal shrinkage. The Latarjet procedure includes anterior glenoid bone augmentation by the coracoid process including the short head of the biceps and coracobrachial muscle origin and is performed in case of failed capsular reconstruction. The short head of the biceps acts as a stabilizator in abduction and exorotation. Capsular thickening is a common finding after surgical repairs of instability and labral tears. In nonanatomic reconstructions labral and capsular lesions are not directly repaired, and abnormalities due to these lesions are still visible on postoperative post repair MRI.

17.4 Accuracy of MRI Compared to US

The diagnostic performance of C-MRI, D-MRA, and US may be similar for detection of any rotator cuff tears (Table 17.19) (Rutten et al. 2010). However, C-MRI, MRA, and US may have poor sensitivity for detecting (low-grade) partial-thickness tears, and the sensitivity of US may be much lower than that of MRI (Lenza et al. 2013).

D-MRA and I-MRA show comparable sensitivities and specificities for rotator cuff and glenoid labrum pathology (Vahlensieck et al. 1998; Fallahi et al. 2013). We also found a high accuracy of I-MRA for FTT of the RC but lower accuracy (76–77 %) for PTT with lowest accuracy for low-grade tears at the bursal side. The major cause of error is the discrimination of tendinopathy and low-grade partial-thickness tear (Van Dyck et al. 2009). Obvious diagnostic advantages of I-MRA in comparison with direct arthrography are the detection of pathology through tissue enhancement: for example, the thickened and enhancing capsule in retractile capsulitis, thickening and enhancement of the SA-SB wall in subacromial bursitis, and enhancement of the wall of arthrosynovial ganglia.

MRA (direct and indirect) is the most accurate and sensitive available imaging method for the detection of labral tears (glenoid labrum, Bankart, and SLAP lesions). I-MRA is more and more regarded as a standard practice in patients with shoulder instability due to suspected labral pathology where further investigative imaging is indicated (Fallahi et al. 2013).

Recently comparable accuracy for anteroinferior labroligamentous lesions and SSP PTT was calculated comparing single D-MRA in ABER position and D-MRA by trained radiologists reducing the added value of ABER position (Schreinemachers et al. 2009).

MRA in the ADIR position provides high accuracy for the diagnosis of ALPSA lesions and complements routine MRA when used to diagnose labroligamentous lesions in patients with recurrent shoulder dislocations (Song et al. 2006).

Cartilage MRI offers only moderate accuracy. Best results are achieved with T2 mapping and D-GEMRIC techniques. These techniques are not routinely used in daily clinical practice.

Table 17.19 US and MRI (C-MRI and D-MRA on 1.5 T) for the diagnosis of PTT and FTT RC tears

	US		MRI	
	PTT (%)	FTT (%)	PTT (%)	FTT (%)
Sensitivity	89	95	67	100
Specificity	80	93	86	91
ACC	81	94	94	94
PPV	40	88	43	85
NPV	98	98	94	100

Rutten et al. (2010)

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Nuclear Medicine Imaging of Shoulder Injuries

18

S.A. Eshuis

Contents

Abstract

As participation in sports is increasing during the last decades, the amount of sports injuries, including those of the shoulder, has grown as well. The shoulder consists of several articulations, which makes it difficult to localise the lesion in the painful shoulder. Nuclear imaging techniques, possibly combined with CT, may be useful in the diagnostic process. Most often bone scintigraphy is used, which shows higher uptake at places with increased bone metabolism. Bone scintigraphy can be used for the diagnosis of several shoulder injuries: rotator cuff pathology, adhesive capsulitis, tendinopathy/enthesopathy, (stress) fractures, muscle injuries and osteoarthritis. Using single-photon emission computerised tomography (SPECT),

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three-dimensional images of the shoulder can be obtained. SPECT can be combined with a CT, thereby combining early functional changes with anatomic information. Positron emission tomography with ^{18}F-labelled fluorodeoxyglucose (^{18}F-FDG-PET), visualising glucose metabolism, can also be used, as increased uptake of ^{18}F-FDG in joints is associated with inflammatory and degenerative disorders. Other, more rarely used, techniques are arthroscintigraphy and immunoglobulin scintigraphy.

Abbreviations

ASES	American Shoulder and Elbow Surgeons
CT	Computed tomography
FDG	Fluorodeoxyglucose
HIG	Human immunoglobulin
MDP	Methylene diphosphonate
PET	Positron emission tomography
SPECT	Single-photon emission computed tomography

18.1 Introduction

During the last decades, participation in sports has increased enormously. People tend to have more interest in general in a healthy body composition, and because of an increase in leisure time, more time can be spent sporting. Not only easy assessable sports activities like running are being practised but also more sports at risk, like skiing and scuba diving. This results in an increase of sports injuries, including shoulder injuries. Especially overhead sports (e.g. volleyball, baseball, racquet sports, softball) and weightlifting (including weight training for football) put the shoulder at risk for injuries (Cassas and Cassettari-Wayhs 2006; Sinha et al. 1999). Van der Wall et al. studied 12 amateur weightlifters, for whom weightlifting was used as an adjunctive form of training for other sporting activities, like running, football or tennis (Van der Wall et al. 1999). The majority of their injuries was localised in the upper limbs, mainly around the shoulder. Most of the injuries appeared when free weights were used instead of fixed-weight machines.

Although the shoulder can be regarded as a mobile joint, it is still very stable. This stability is due to the rotator cuff, which is a musculotendinous structure around the capsule of the shoulder joint. The shoulder joint consists of several functional articulations; consequently, it can be difficult to localise the site of the painful shoulder lesion. Imaging techniques may be useful in the diagnostic process.

18.2 Nuclear Imaging Techniques

Several nuclear imaging techniques can be used to assess shoulder injuries. Bone scintigraphy is most often used, optionally combined with SPECT(-CT). But also other techniques can be used for evaluation of the shoulder, although less common.

18.2.1 Bone Scintigraphy

Bone scintigraphy shows higher uptake at places with increased bone metabolism and is able to detect functional changes that may precede anatomic abnormalities. More than 30 years ago, scintigraphy using ^{99m}Tc pertechnetate was applied for understanding the painful shoulder (Wright et al. 1975), and the application of diphosphonates (MDP or HDP) has subsequently been recognised (Binder et al. 1984).

Diphosphonate is selectively bound to hydroxyapatite in metabolically active bone, reflecting osteoblastic activity. After intravenous injection of the radiopharmacon, a gamma camera detects the radioactive decay and planar images are produced (Leffers and Collins 2009). The scans can be performed in three phases: the blood flow phase, the blood pool phase and the delayed phase. Bone scintigraphy is a very sensitive diagnostic tool. While plain radiographs of, for example, stress fractures may initially be normal without any structural abnormalities in the acute phase, bone scintigraphy may already be able to detect the altered bone metabolism and thus be helpful in diagnosing occult musculoskeletal injuries, like stress fractures (Nagle and Freitas 1987).

One should be aware of the normal pattern of uptake to be able to recognise and understand abnormal uptake of the tracer. When interpreting focal increased uptake in the shoulder area, focus should be drawn to the handedness of the patient. In approximately 30 % of the right-handed patients and 37.5 % of the left-handed patients, increased uptake in the corresponding shoulder can be shown, without any pathology involved (Sebes et al. 1976). On a normal bone scan of the shoulder, three areas of focal increased uptake of radiotracer can be identified, because of the position of these structures nearby the camera (Ackerman and Shirazi 2002): distal clavicula, including the acromioclavicular joint, glenoid fossa and the humeral head. For better imaging and interpreting the focal uptake around the shoulder joint complex, oblique anterior and posterior prone imaging may be helpful. When no SPECT-CT option is available, an oblique anterior view (in which the detector is 20° tilted medially over the patient) may reduce the effect of coracoid and anterior glenoid superimposition. A clear view of the posterior glenohumeral joint space can best be obtained by positioning the detector parallel to the scapular blade (30–45°), while the patient is lying prone and the arm is hanging vertically (Clunie et al. 1997). In spite of these positions yield scintigraphic abnormalities in the painful shoulder in 79 % of the patients, compared to 33 % of radiographs, few specific diagnoses are possible due to the lack of a reference standard for the various patterns of uptake of the tracer (Van der Wall et al. 2001). Clunie and colleagues have evaluated whether specific patterns of uptake of diphosphonates could be detected in 24 patients with shoulder complaints using ^{99m}Tc-methylene diphosphonate (MDP) (Clunie et al. 1997). Bone scintigraphy was abnormal in 19 of these 24 patients (79 %), while radiographs showed abnormalities in 8 of 24 patients (33 %). They were able to identify distinct patterns of ^{99m}Tc-MDP uptake for adhesive capsulitis and lesions in the subacromial region. No increased uptake of the tracer was noticed in the asymptomatic shoulders in 21 of 24 patients (86 %). Complete agreement between observers was noticed in 85 %, while partial agreement was achieved in over 99 % of scores.

18.2.1.1 SPECT-CT

Using single-photon emission computerised tomography (SPECT), it is possible to obtain three-dimensional images of the shoulder. SPECT bone scintigraphy is a more accurate scanning method than planar imaging because of the ability to separate overlying and underlying structures. SPECT can be combined with a low-dose or even with a diagnostic CT. Thus early functional changes can be combined with anatomic information. Schillaci and colleagues have shown that SPECT-CT has several advantages compared to SPECT alone (Schillaci et al. 2004). The hybrid camera was able to provide correct location of SPECT findings and to exclude disease in sites of physiological uptake of tracer. These advantages resulted in a significant improvement of 41 % in diagnostic accuracy compared to scintigraphy alone (Schillaci et al. 2004). By measuring the uptake of the tracer on the SPECT images, the uptake can be quantified, which can be used for developing diagnostic patterns of uptake (Park et al. 2009). Hirschmann and colleagues showed that SPECT-CT scanning of the shoulder can also be a helpful diagnostic tool for shoulder surgeons in their process of decision-making and further treatment for complex shoulder problems (Hirschmann et al. 2011).

18.2.2 ^{18}F-FDG-PET-CT

PET-CT with ^{18}F-FDG is often being used for staging, restaging and therapy monitoring in oncology patients. This imaging technique can also be applied in the diagnostic process of inflammatory processes. ^{18}F-FDG-PET visualises the metabolism of glucose. Diffuse uptake of ^{18}F-FDG in several joints is associated with inflammatory and degenerative disorders (Wandler et al. 2005). Increased uptake of ^{18}F-FDG is associated to enhanced tissue metabolism and is not specific to inflammatory processes. When assessing the uptake of ^{18}F-FDG in the shoulder area, one should be aware of the fact that physical activity can cause increased muscle ^{18}F-FDG uptake (Omi et al. 2010), even more than 48 h after cessation of strenuous muscle activity (Gradinscak et al. 2003). Uptake of ^{18}F-FDG in the acromioclavicular joint is frequently asymmetrically increased, which is probably due to the presence of degenerative alterations or active inflammation (Sopov et al. 2009). Sopov et al. have described the spectrum of focal benign uptake of ^{18}F-FDG at PET-CT of the shoulder and found that mainly the acromioclavicular joint, subacromial space, greater tubercle of the humeral head (tendinopathies of the muscles attached at this site), inferior glenohumeral compartment and the proximal diaphysis of the humerus (tendinopathy) can show focal increased uptake of ^{18}F-FDG (Sopov et al. 2009). If shoulder injuries are successfully (surgical) treated, no increased uptake of ^{18}F-FDG will be seen when the postsurgical period with increased uptake (approximately 3 months) has passed (Moon et al. 2010).

18.2.3 Arthroscintigraphy

Arthroscintigraphy is a method which is usually used in the diagnostic process of loosening of (hip) prostheses. Contrast arthrography in combination with arthroscintigraphy shows better results for the detection of loosening of hip protheses than contrast arthrography alone (Abdel-Dayem et al. 1981; Rosenthall et al. 1985). Due to the lower viscosity of the saline solution of the radiocolloid compared to the contrast agent, the colloid can easier permeate into the space caused by loosening of the prosthesis, resulting in an increased sensitivity. Arthroscintigraphy hardly causes any complications like allergic reactions or chemical synovitis. Besides, scintigraphy is not difficult to interpret and possible sites of leakage can be visualised early after injection. These advantages of arthroscintigraphy make it a possible attractive diagnostic tool for the evaluation of rotator cuff ruptures. Therefore, the efficiency of arthroscintigraphy, in combination with bone scintigraphy, has been studied in patients with suspected rotator cuff ruptures (Gratz et al. 1998).

18.2.4 Immunoglobulin Scintigraphy

Two of the most common causes of shoulder injuries, subacromial impingement and adhesive capsulitis, have been related to tissue inflammation (Fukuda et al. 1994; Uitvlugt et al. 1993). In rotator cuff damage, associated with subacromial impingement, granulation tissue and vascular proliferation has been described. In patients with adhesive capsulitis, synovial inflammation can be identified, although at variable sites. Labelled human immunoglobulin (^{99m}Tc-HIG), injected intravenously, accumulates at sites of infection and inflammation due to increased vascular permeability. It is widely used for the detection of various infectious and inflammatory diseases. The use of ^{99m}Tc-HIG has also been evaluated in patients with inflammatory shoulder injuries (Clunie et al. 1998; Senocak et al. 2002), like adhesive capsulitis and subacromial impingement. Demonstration of persisting inflammation is one of the parameters for staging adhesive capsulitis and thereby determining the appropriate treatment; imaging by means of immunoglobulin scintigraphy may thus play a role in the decision-making of the most appropriate therapy (Hannafin and Chiaia 2000).

18.3 Shoulder Injuries

18.3.1 Impingement Syndrome/Rotator Cuff Pathology

18.3.1.1 Bone Scintigraphy

In a study, performed by Clunie et al., 13 patients with subacromial lesions were enrolled, in which 10 (77 %) had an abnormal bone scan, while only 3 out of 13 patients (23 %) had abnormal radiographs. In 90 % of the abnormal bone scans, increased uptake was observed in the anteromedial humeral head, while no abnormalities were seen on the posterior images. This is in contrast to the patients with capsulitis, in which also increased uptake was not only seen in the anteromedial head of the humerus but also on the posterior humeral head and posterior glenoid. This pattern of increased uptake in the coracoid, acromion and medial head on the anterior images, without abnormalities on the posterior images, can possibly be explained by the presence of (mild) inflammatory tissue adjacent to the periosteum of the three bony structures: medial humeral head, acromion and coracoid (Clunie et al. 1997).

The combination of bone scintigraphy with quantitative SPECT has been described to be used to diagnose impingement syndrome, with or without rotator cuff tear. In patients with impingement syndrome without tear and with partial-thickness rotator cuff tear, the uptake of the tracer tended to be increased in acromion, distal clavicle and greater and lesser tuberosity of the proximal humerus; however, this increase in uptake was only significant in the greater and lesser tuberosities. In patients with full-thickness rotator cuff tear, uptake was also increased in the above-mentioned four areas but only significant in the greater tuberosities. The authors concluded that the greater tuberosity could be the most appropriate region for diagnosing impingement syndrome. Quantified uptake measures of the tracer using SPECT were significantly correlated to improvement of functional scores, proposed by the American Shoulder and Elbow Surgeons (ASES) after surgery (Park et al. 2009). However, no significant correlation was found between quantified uptake measures using SPECT and preoperative pain scores nor postoperative functional shoulder scores.

18.3.1.2 ^{18}F-FDG-PET

Sopov and co-workers described focal increased uptake of ^{18}F-FDG in the shoulder area in case of impingement syndrome or rotator cuff pathology (Sopov et al. 2009).

18.3.1.3 Arthroscintigraphy

Suspected rotator cuff tears can also be examined by means of the combination of arthroscintigraphy and bone scintigraphy. Increased uptake of ^{99m}Tc-MDP on the bone scans was regarded as probably due to degenerative or inflammatory disease of the shoulder. The bone scintigraphy was further used for the interpretation of the radionuclide arthrography. Normally, the radionuclide arthrogram shows homogenous uptake in the shoulder with an ellipsoidal-shaped joint capsule. In case of an incomplete rupture, the arthroscintigraphy shows a fingertip-shaped dip only in the subacromial and subdeltoid recesses, without diffusion of the radionuclide into the recesses. Most often this was seen on the central and/or lateral region of the capsule of the joint. When the subacromial and subdeltoid recesses were filled, shown on the lateral region, it was considered to be a complete rupture of the rotator cuff (Gratz et al. 1998).

18.3.1.4 Human Immunoglobulin Scintigraphy

Clunie and colleagues performed human immunoglobulin scintigraphy in 12 patients with subacromial impingement. No difference in uptake of the tracer could be found between symptomatic and asymptomatic shoulders, and all images were considered negative, irrespective of duration of symptoms or time since the last injection with glucocorticoids (Clunie et al. 1998). These negative results may be due to an insufficient degree of changes in vascular proliferation, perfusion and permeability.

18.3.2 Frozen Shoulder or Adhesive Capsulitis

The inferior shoulder capsule, which mainly consists of the inferior glenohumeral ligament, comprises anterior and posterior bands and an axillary pouch. Inflammation of this pouch or involvement of the inferior glenohumeral ligament may lead to limited and painful range of motion of the shoulder (passive as well as active): frozen shoulder or adhesive capsulitis. The aetiology of this injury is still unknown.

18.3.2.1 Bone Scintigraphy

Clunie et al. performed bone scintigraphy and radiographs in 7 patients with capsulitis. Bone scintigraphy showed abnormalities in 5 out of these 7 patients (71 %), while in only 1 of these 7 patients (14 %) radiographs were abnormal. Four of five of the abnormal scans showed increased uptake in the anteromedial humeral head. All of the five positive scans showed abnormalities on the posterior images in the posterior glenoid and posterior humeral head regions (Clunie et al. 1997). This is more or less in agreement with other studies, which showed that bone scintigraphy in patients with frozen shoulder or adhesive capsulitis can show abnormal uptake, limited to the humeral head and glenoid, mainly located posteriorly (Ackerman and Shirazi 2002; Clunie et al. 1997).

18.3.2.2 ^{18}F-FDG-PET

In case of adhesive capsulitis, increased uptake of ^{18}F-FDG can be noticed in the area of the inferior glenohumeral compartment (Sopov et al. 2009).

18.3.2.3 Arthroscintigraphy

Frozen shoulder can also be examined by arthroscintigraphy, in combination with bone scintigraphy. Shrinkage and deformation of the shoulder joint capsule can be seen when a patient had adhesive capsulitis (Gratz et al. 1998).

18.3.2.4 Human Immunoglobulin Scintigraphy

As adhesive capsulitis is associated with synovial inflammation, human immunoglobulin scintigraphy has also been performed. In four patients with adhesive capsulitis, human immunoglobulin scanning did not show any differences in uptake of ^{99m}Tc-HIG between symptomatic and asymptomatic shoulders (Clunie et al. 1998). This may be due to the fact that all patients were already treated. Another study, however, in which both human immunoglobulin scintigraphy and three-phase bone scintigraphy were performed in 21 patients with adhesive capsulitis, showed a significant correlation between the uptake of ^{99m}Tc-HIG and functional scores and pain scores (Senocak et al. 2002). All patients with increased uptake of ^{99m}Tc-HIG in their affected shoulder also had increased osteoblastic activity on bone scintigraphy. No correlation was found between clinical scores and the findings on the bone scintigraphy. The major limitation of this study, however, is the lack of arthroscopic and histological findings as a gold standard for inflammatory processes.

18.3.3 Tendinopathy/Enthesopathy

Enthesopathies refer to disorders or inflammation of ligaments and tendons at the attachment to the bone. These can be detected on bone scintigraphy (Leffers and Collins 2009), showing focal increased uptake of the tracer at the site of the tendon attachment to the bone (see Fig. 18.1).

Increased uptake of ^{18}F-FDG can also be noticed in enthesopathies, e.g. adjacent to the greater tubercle of the head of the humerus in case of enthesopathies of the tendons of the rotator cuff (supraspinatus, infraspinatus and teres minor) (Sopov et al. 2009). The tendon of the pectoralis major and the deltoideus muscles are attached to the proximal diaphysis of the humerus. Tendinopathy of any of these two muscles can also result in focal increased ^{18}F-FDG uptake (Sopov et al. 2009).

18.3.4 Stress Fractures or Microfractures

Stress fractures can be the result of repeated or prolonged muscular action on bone that is not accommodated to this stress. Stress fractures in the upper limbs, including the shoulder, are far less common than stress fractures in the lower limbs. However, upper limb stress fractures have been described, mainly occurring in upper limb-dominated sports, like swimming, tennis or throwing sports. Especially throwing sports seem to be involved in stress fractures of the proximal upper extremities. When a stress fracture of the upper limb is suspected, imaging should be done to confirm the diagnosis. Plain radiography often fails to detect a stress fracture in the early stages and sometimes not until several weeks have passed (Nagle and Freitas 1987). Bone scintigraphy can be performed for confirmation of the diagnosis. Stress fractures induce increased uptake of radiotracer in the blood flow and blood pool phases and a fusiform-shaped increased uptake of the tracer in the delayed phase.

Sinha et al. evaluated 44 cases of upper extremity stress fractures (Sinha et al. 1999). They divided the patients into four categories based on the predominant type of movement of the upper extremities: weightlifters (weightlifting/powerlifting), weight bearers (gymnastics, diving), throwers (softball/baseball pitcher, javelin, soccer goalie) and swingers (golf, tennis). In this study, all patients who underwent bone scintigraphy had a positive bone scan with increased uptake of radiotracer at the site

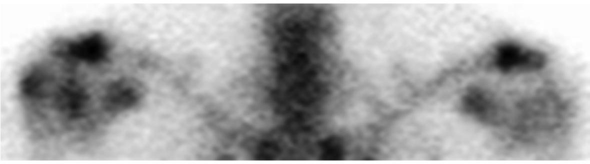

Fig. 18.1 Bone scintigraphy of a patient with enthesopathy of the right supraspinatus and the right subscapularis muscle. Focal increased uptake is seen at the insertion sites of the supraspinatus and the subscapularis muscle at the head of the humerus

of the injury on the delayed images. They found that throwers almost all had their stress fractures in the area of the shoulder girdle. Weightlifters had injuries throughout the upper extremity. Weight bearers did not have any stress fractures in the area of the shoulder girdle, but all stress fractures occurred distal to the elbow in this group. All of the stress fractures in the lower ribs occurred in swingers (Sinha et al. 1999).

18.3.4.1 Clavicle

Stress fractures of the clavicle are rare in athletes and are mainly described as a late complication after radical neck dissection. A few cases of stress fractures of the clavicle, in which bone scintigraphy has been performed, have been described in a javelin thrower (Jones 2006), a springboard diver (Waninger 1997), a professional baseball player (Wu and Chen 1998) and a human tower stuntman (Roset-Llobet and Salo-Orfila 1998). Radionuclide bone scan supported the diagnosis of a stress fracture of the clavicle and showed distinct increased uptake. Radiographs showed periosteal reaction in the majority of these cases. In the professional baseball player, radiography did not show any abnormalities. The stress fracture in the javelin thrower was thought to be caused by repeated stress from contractions of the clavicular parts of the pectoralis and deltoid muscles. The position of extended fingers and wrists, pronated forearms and overlapping hands, when entering the water, may have transmitted impact stress from the hands to the clavicle thereby resulting in the stress fracture in the springboard diver. In the sport of building human towers, a traditional Catalan sport, the feet are put on both sides of the neck (Roset-Llobet and Salo-Orfila 1998). The heels are being placed on the trapezius muscles, while the tarsal bones are put on the clavicles. The weight pushes down the clavicles, while the muscles and ligaments are pulled upon. Approximately 1–3 times the body weight may be the critical force for collapsing the clavicles. In human towers, the force may be over four times the body weight, and this is sustained for more than 5 min, several times a day (Harrington et al. 1993). It is obvious that these pressures can be stressful enough to result in stress fractures. The stress fracture in the baseball player can probably be explained by the high demands on the throwing shoulders (Wu and Chen 1998).

18.3.4.2 Osteolysis of the Clavicle

Clavicular osteolysis is a well-known complication (Cahill 1982, 1992) of weightlifting but can also occur in overhand athletes, like tennis (Cahill 1982) (Schwarzkopf et al. 2008). It can be a disabling injury if it is not recognised in an early phase and no early intervention takes place. It is a stress failure syndrome of the distal clavicle. Early in the course of symptoms, bone scintigraphy shows intense uptake in the distal end of the clavicle (Schwarzkopf et al. 2008). In a study with 12 amateur weightlifters, two of them had osteolysis of the clavicle, with a positive bone scintigraphy, possibly caused by intense acceleration in weight training (Van der Wall et al. 1999). Matthews et al. described a case report of a female body builder with osteolysis of the distal clavicle. Bone scintigraphy was performed and showed asymmetric increased uptake in the affected acromioclavicular joint (Matthews et al. 1993)

18.3.4.3 Scapula

Stress fractures of the scapula are also rare in athletes and have been described occasionally. Veluvolu et al. described a case of a jogger using weights in his hands for about eight weeks. Bone scintigraphy showed a linear band of increased uptake in the superomedial portion of the scapula, which was later confirmed by radiographs. Possibly the stress fracture was caused by overuse of the supraspinatus muscle when stabilising the humeral head during jogging with weights (Veluvolu et al. 1988). A scapular stress fracture has also been described in an offensive lineman who developed a painful shoulder during a game of American football (Ward et al. 1994). As part of an intensive training programme, he was lifting weights and he had already noticed pain before the game. Radiography showed an incomplete transverse radiolucent line in sclerotic bone at the underside of the acromion near its origin from the scapular spine. Bone scintigraphy showed increased uptake in this region. This stress fracture can possibly be explained by the intense weightlifting programme (Ward et al. 1994). A third case of stress fractures of the scapula has been described in a young female gymnast, after activities with excessive shoulder stress. Bone scintigraphy showed focal increased uptake in the scapula (Nagle and Freitas 1987). A fracture of the coracoid process has been described in a professional trap shooter. Plain radiograph showed a fracture through the base of the coracoid process; no bone scintigraphy was performed in this patient (Boyer 1975).

Khoury et al. described the case of a breakdancer who suffered from bilateral shoulder pain. Plain radiography of the shoulders was normal. However, bone scintigraphy showed symmetric and bilateral V-shaped uptake of the tracer at the borders of both scapulae. Possibly "bottom rock moves", in which the dancer's weight is supported by the neck and shoulders, have caused repetitive mechanical stress involving both scapulae, resulting in microfractures (Khoury et al. 2009).

18.3.5 Muscle Injuries

Bone scanning can be used in the diagnosis of muscle injuries. Bone scintigraphy will be positive when cellular necrosis is present. Although the exact mechanism of the uptake of tracer into necrotic muscular tissue is unknown, it can possibly be explained by binding of the radiopharmacon to intracellular calcium deposits or denatured proteins (Nagle and Freitas 1987). No increased uptake of tracer will be seen in muscle cramps after exercise, as they are not associated to disruption of the muscle fibres.

Bone scintigraphy performed 24–48 h after running a marathon has demonstrated increased uptake in the affected muscles; the intensity of uptake is correlated with the perception of muscle tenderness. The uptake decreased over time and disappeared within a week (Matin et al. 1983). Increased uptake of the bone tracer in muscles (including shoulder muscles), damaged by exertion, has also been observed in a weightlifter (Valk 1984).

Muscle strain is a common sports injury. Usually muscle tears occur at the junction of the tendon and the muscle when the muscle is stretched beyond a critical tenseness. When a sufficient amount of necrosis occurs, those muscle tears can be detected on bone scintigraphy (Nagle and Freitas 1987). Murray has published a case of a weightlifter with muscle necrosis and ischemia with involvement of the teres minor muscle (Murray 1998).

Contusion of muscular tissue can happen when a muscle and its surrounding tissue have been struck forcefully. This may result in incomplete disruption of muscular fibres and often also in a haematoma. When the muscle contusion is correlated with the formation of a haematoma, uptake of radiotracer can be increased. This increased uptake peaks 3–4 days after the injury and then decreases as a result of removal of the necrosis.

Myositis ossificans may occur in injured muscular tissue, especially when this is accompanied by the formation of a haematoma. The uptake of bone tracer can be intense and may precede the occurrence of radiographically visible abnormalities by weeks or months (Nagle and Freitas 1987).

18.3.6 Osteoarthritis of the Acromioclavicular Joint

Primary osteoarthritis is the most common type of noninflammatory joint disease. Ageing is the most important risk factor for osteoarthritis. Degeneration of the AC joint progresses more rapidly after repetitive stress or a trauma. Bone scintigraphy shows increased periarticular uptake (Elgazzar 2004). The degree of uptake is proportional to the severity of the disease (McCrae et al. 1992) as is shown in Fig. 18.2.

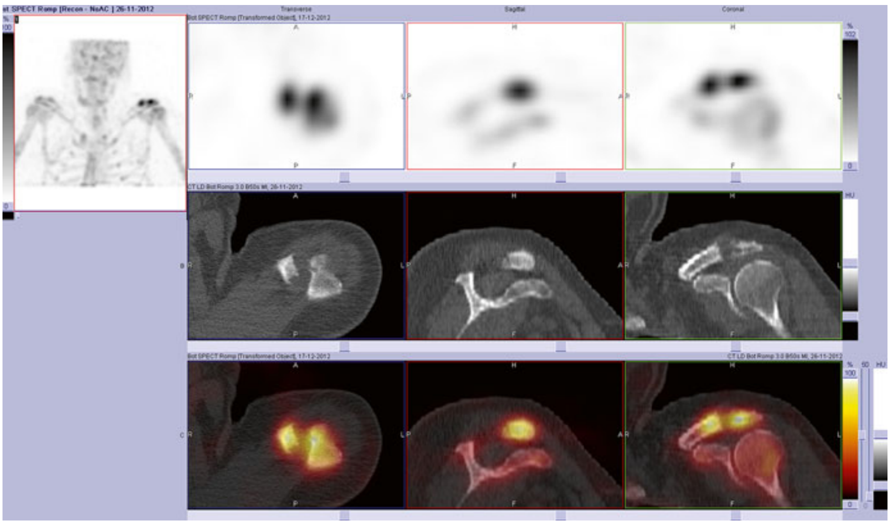

Fig. 18.2 Bone scintigraphy of osteoarthritis of the acromioclavicular joint. Because of a painful left shoulder, bone scintigraphy is performed for further analysis. SPECT-CT images of the shoulders show periarticular increased uptake around the left acromioclavicular joint

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Part VI

The Musculoskeletal System Topographically: Elbow and Forearm

Injuries of Elbow and Forearm

19

E.J.M. van Heeswijk, A. Beumer, and D. Eygendaal

Contents

Abstract

The elbow facilitates the highly skilled functions of the forearm, wrist, and hand that are needed for sports. Sporting activities involving throwing, catching, hammering, pushing, pulling, and hitting with a racket produce significant stresses around the elbow joint that can result in acute and chronic injuries.

Sports injuries to the elbow may involve the muscles, ligaments, tendons, capsule, bones, articular surfaces, and nerves and subsequently impair elbow function. Elbow injuries, particularly chronic overuse injuries, occur most commonly in athletes that participate in throwing or overhead activities and

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frequently are the result of valgus stress. Fractures usually result from a fall on the outstretched hand but can also occur due to a direct impact to the elbow. Fractures can range from simple fissures to severe open fracture dislocations. Seemingly harmless fractures with associated ligamentous injuries can result in an unstable elbow and long-term posttraumatic arthritis.

19.1 Introduction Including Epidemiology

This chapter focuses on functional anatomy, etiology, injury mechanism, and clinical description of specific sports-related injuries related to the elbow with the exception of treatment. The clinical descriptions are divided in anterior, posterior, medial, and lateral elbow soft tissue injuries and fractures.

Exact numbers of sports injuries of the elbow are unknown. Table 19.1 shows a small list with the prevalence and incidence of some conditions.

19.2 Functional Anatomy

The elbow plays an important role in the flexion-extension of the arm and supination-pronation of the forearm. It consists of three bones: the distal part of the humerus and the proximal parts of the ulna and the radius. These three bones articulate in the elbow in three separate joints: the radiohumeral joint, the ulnohumeral joint, and the proximal radioulnar joint.

The three elbow joints are surrounded by a joint capsule. It covers the tip of the olecranon, the coronoid process, and radial fossa but not the humeral epicondyles. The capsule is most lax at 80° of flexion and holds a capacity of 23 ml in this

Table 19.1 Prevalence and incidence of some clinical conditions

Clinical condition	Incidence per year	References	Prevalence	References
Distal biceps tendon pathology	1.2 per 100,000	Safran and Graham (2002)	–	
Triceps tendon ruptures	<1 %	Anzel et al. (1959)	>70 cases reported in the literature	Harris et al. (2004)
Elbow dislocation	6 per 100,000	Eygendaal (2009)	–	
Medial epicondylitis	1 per 1000	Hamilton (1986), Wolf et al. (2010)	Of all musculoskeletal disorders, 0.4 %	O'Dwyer and Howie (1995), Shiri et al. (2006), (2007)
Lateral epicondylitis	4–7 per 1,000	Kivi (1983), Verhaar (1992)	1–3 % in the general population	Verhaar (1992), Allander (1974)
Radial head fractures	–		5 % of all fractures	Mason (1954)

position (van Glabbeek and Clockaerts 2009). Patients with acute elbow injury and inflammation find this position therefore most comfortable.

Elbow stability results from the interplay of the articular surfaces, ligaments, and muscles. The radial head has an important role in maintaining elbow stability. The three primary static stabilizers of the elbow are the ulnohumeral articulation and the medial and lateral collateral ligaments. Secondary constrains include the radial head, capsule, and the common flexor and extensor origins. The muscles around the elbow, especially the anconeus, triceps, and biceps, function as dynamic stabilizers. If the coronoid process or medial collateral ligament is injured, the radial head becomes a critical stabilizer (O'Driscoll et al. 2001). The radiohumeral joint is the primary restraint to proximal migration of the radius. The interosseous membrane, a fibrous membrane between radius and ulna, and the triangular fibrocartilage complex (TFCC) at the distal radioulnar joint also contribute to longitudinal stability of the forearm (Hotchkiss et al. 1989).

Normal range of motion (ROM) is from full extension of 0–145° of flexion. Pronation and supination show large normal variations but usually are 80° of pronation and 85° of supination. Interindividual variation is wide (Soucie et al. 2011). Full ROM is not necessary for normal activities of daily living. Morrey et al. showed that for most activities in daily life, flexion-extension of 130 to −30° and a pro-supination arc of 100° would be sufficient (Morrey et al. 1981).

19.3 Etiology and Injury Mechanism

The elbow facilitates the highly skilled functions of the forearm, wrist, and hand that are needed for athletic endeavors. Athletic activities involving throwing, catching, hammering, pushing, pulling, and hitting with a racket, stick, or club produce significant stresses around the elbow joint that can result in acute or chronic injuries. Injuries to the elbow may involve the muscles, ligaments, tendons, capsule, bones, articular surfaces, and nerves or a combination of these structures and subsequently impair elbow function. Elbow injuries, particularly chronic overuse injuries, occur most commonly in athletes that participate in throwing or overhead activities and frequently are the result of valgus stress (Safran 2009).

Injuries to the elbow may be the result of acute trauma, such as a fall on an outstretched hand or a direct injury to the elbow itself. This may result in fractures with or without dislocation of the elbow joint. The majority of injuries to the elbow in the athlete are chronic overuse injuries. These injuries are the result of repetitive intrinsic or extrinsic overload, or both, resulting in micro-rupture of soft tissue such as ligament or tendon. Intrinsic overload is the force from muscular contraction which can lead to tendinitis or muscular injury. Extrinsic overload is a tensile overload caused by excessive joint torque forces stressing the soft tissue which results in stretching and eventual disruption. Extrinsic overload may also be due to compression of the soft tissues causing abrasion or impingement of the tissue. These micro-ruptures of the soft tissue may result in compromise of the soft tissue if followed by an imperfect healing process. In children, the growth plates are most susceptible to stress injuries. This is important, because a forceful acute injury in a patient with open growth plates as well as microtrauma may result in an apophyseal avulsion.

During overhead athletic activities, tremendous valgus forces are generated across the medial side of the elbow joint, resulting in tensile forces on the medial site, compression forces on the lateral site and shear forces in the posterior compartment. This combination of symptoms is often referred to as "valgus extension overload" (Ahmad and ElAttrache 2004).

19.4 Sports Injuries

19.4.1 Anterior Elbow Soft Tissue Injuries

19.4.1.1 Distal Biceps Tendon Pathology

At its origin, the biceps consists of two heads, a short head originating from the coracoid process of the scapula and a long head originating from the superior lip of the glenoid. The short head inserts distally to the radial tuberosity and is believed to be a more powerful flexor of the elbow, whereas the tendon of the long head inserting on the tuberosity further from the axis of rotation of the forearm is believed to be a stronger supinator. The bicipital aponeurosis consists of three layers and completely encircles the ulnar forearm flexor muscles. This aponeurosis may be important in stabilizing the tendons distally. A bursa is a potential cavity lined by a synovial membrane, which lies between two adjacent structures, aiming to provide friction-free motion. The bicipitoradial (or cubital) bursa either fully or partially envelops the distal biceps tendon. The bursa can exist as a distinct structure or can communicate with the elbow joint or other bursae around the elbow. The distal biceps tendon can be inflamed or (partially) ruptured.

Distal biceps tendon ruptures make up 3–12 % of all biceps injuries (D'Alessandro et al. 1993). The dominant arm is affected 86 % of the time (Safran and Graham 2002). The average age of patients is 50 years old (range 18–72) (Ramsey 1999). Risk factors include male gender, smoking, anabolic steroid use, and bodybuilding (Visuri and Lindholm 1994). The proposed etiology includes the presence of a bony prominence or irregularity of the radial tuberosity, radial bursitis, a watershed area of poor arterial supply, and mechanical impingement of the tendon (Hughes and Morrey 2000). The tendon will most commonly tear at its insertion. Tears within the length of the tendon and at the musculotendinous junction are rare (Schamblin and Safran 2007). The proximal portion of the tendon is more likely to retract into the brachium if the bicipital aponeurosis is also torn.

The patient usually recounts having sustained a sudden, unexpected, sharp extension load to an elbow flexed at 90°, followed by sudden antecubital pain. The patient may complain of weakness and aching in supination and flexion of the elbow with physically demanding activities (Ramsey 1999). Immediately after the injury, antecubital ecchymosis may be visible on examination; the patient may feel tenderness over the radial tuberosity or have a palpable gap in their tendon. There is usually weakness of supination. With partial ruptures, there may be tenderness over the radial tuberosity with no palpable gap in the tendon but crepitus or grinding on rotation of the forearm (Dellaero and Mallon 2006). Complete rupture is suggested by a positive hook test. The patient flexes the elbow to 90° and actively supinates the forearm. The examiner then hooks their finger under the biceps tendon from the lateral side. With a complete rupture, the examiner is unable to hook their finger under the cordlike biceps tendon (O'Driscoll et al. 2007).

19.4.2 Posterior Elbow Soft Tissue Injuries

19.4.2.1 Olecranon Bursitis

Olecranon bursitis is the most common form of superficial bursitis. The olecranon bursa lies superficial to bone and provides frictionless motion of the skin over the bony prominence of the olecranon. Given its superficial location on the extensor aspect of the elbow, it is vulnerable to repetitive trauma and penetrating injury.

Septic olecranon bursitis is caused by direct inoculation through the overlying skin or by seeding from surrounding tissues or a distant site (Ho et al. 1978). It can also be a presentation of septic arthritis of the elbow in cases where there is communication between the bursa and the elbow joint, e.g., rheumatoid arthritis. It has been reported to account for approximately 20 % to one third of cases of acute bursitis (Stell 1996). Immune compromise plays an important role in septic olecranon bursitis with approximately half of the patients having coexisting conditions such as alcohol abuse, steroid use, diabetes mellitus, renal impairment malignancy, or others which can impair the patient's immune function (Behar and Chertow 1998). Septic bursitis can be difficult to differentiate clinically from a sterile inflamed bursa. The diagnosis is confirmed by aspiration and positive fluid culture. The most common organism is staphylococcus aureus (80–90 %) with beta hemolytic streptococcus being the next most common (Zimmermann et al. 1995).

More common is sterile inflammatory bursitis. Overuse or repetitive stress can result in recurrent inflammation of the olecranon bursae and has been named "student's elbow" or "miner's elbow." Rheumatoid disease, gout, chondrocalcinosis, hydroxyapatite crystal deposition, and pigmented villonodular synovitis have all been associated with olecranon bursitis (Mathews et al. 1981). The condition has also been seen in uremic patients, especially those undergoing dialysis (Irby et al. 1975). It has been reported to occur in athletes due to repetitive trauma after falls on artificial turf.

19.4.2.2 Triceps Tendinopathy

Triceps tendon ruptures are among the rarest of tendon injuries with an incidence of <1 % (Anzel et al. 1959). The male to female ratio is 3:2, with a mean age of 33 years and range of 7 to over 80 years (Viegas 1990). The mechanism of injury is typically that of an extending elbow that is suddenly decelerated. The triceps muscle pulls the distal attachment off of the olecranon of the ulna. The tear is most commonly at the insertion of the tendon. Tears of the musculotendinous junction or the muscle belly are very rare. It is not uncommon for the patient to suffer associated injures such as a fracture of radial head or wrist (Levy et al. 1982).

The patient will usually recount a fall onto an outstretched hand, possibly with an extending elbow forced into flexion. Pain is typical over the olecranon at the site of the insertion of the triceps, and tenderness is usually elicited on palpation. There may be a palpable defect in the tendon. There is usually weakness of elbow extension against resistance. The anconeus muscle can sometimes overcome this weakness with the aid of gravity; therefore, extension should be assessed by asking the patient to extend the elbow against gravity with the affected arm held over the head (Bain et al. 2009).

Another triceps tendinopathy is the “snapping tendonitis.” A snapping elbow is a sensation that can be caused by a portion of the triceps mechanism. It may be confused with subluxation of the ulnar nerve over the medial epicondyle of the humerus on flexion and extension of the elbow (Spinner and Goldner 1998). Snapping tendonitis is caused either by abnormal medial triceps insertion, an aberrant triceps tendon, or cubitus varus. Both snapping tendonitis and subluxation of the ulnar nerve typically present with concurrent irritation of the ulnar nerve (Rolfsen 1970).

19.4.2.3 Posteromedial Impingement

Posteromedial impingement can be seen as an isolated condition or as part of the valgus extension overload. It is the result of repetitive microtrauma in the elbow (Kooima et al. 2004). Increased forces are transmitted to the posteromedial aspect of the olecranon and olecranon fossa articulation. This is often a result of attenuated medial soft tissues, namely, the anterior bundle of the medial collateral ligament (MCL) (Ahmad and ElAttrache 2004). In addition to pain, patients may report locking or limited elbow extension from an olecranon osteophyte.

The physical exam can be highly suggestive of valgus extension overload. Pain will be reproduced with the valgus extension overload test, where the slightly flexed elbow is forced into extension while applying a valgus load.

Given the role of MCL deficiency in the progression of valgus extension overload, the elbow must be assessed for valgus instability from 30° to 70° of flexion, as the MCL plays the most prominent role in stability in 70° of flexion (Eygendaal and Safran 2006). It is always critical to compare the stability to that of the uninjured limb, and it has been shown that neutral forearm rotation is the best position in which to uncover valgus laxity. A number of specialized tests have been described to test the integrity of the MCL. The moving valgus stress test is deemed positive when pain is reproduced in the 80–120° range. Another common test is the modified milking maneuver, which should be performed at 70° of elbow flexion (see Fig. 19.1) (Safran et al. 2005).

While the term posterior impingement has often been used to describe posteromedial impingement, true posterior impingement also exists as a discrete entity. It can stem from repetitive hyperextension microtrauma or emerge as the result of singular acute trauma. Due to its mechanism, it is seen most typically in football linemen, gymnasts, rodeo riders, weight lifters, fastpitch softball pitchers, and those competing in shot put (Moskal 2001). Patients typically complain of posterior pain, locking from loose bodies, or extension loss.

Fig. 19.1 Milking maneuver of the elbow

In true posterior impingement, instability should not be present. Instead, a block to terminal extension and pain with forced extension are often found. Imaging will often reveal direct posterior osteophytes. If posteromedial or posterolateral osteophytes are found instead, it should alert the physician to the possibility of coexisting valgus or varus laxity, respectively.

Posterolateral elbow impingement represents a heterogeneous group of bony and soft tissue impingement pathologies sharing the common absence of medial-sided instability.

19.4.3 Medial Elbow Soft Tissue Injuries

19.4.3.1 Medial Epicondylitis

Medial epicondylitis or golfer's elbow is much rarer than its lateral counterpart. Of all epicondylitis diagnoses, only 10–20 % involves the medial side (Shiri et al. 2006). Medial epicondylitis occurs mostly in the fourth and fifth decades and affects men and women equally (O'Dwyer and Howie 1995). Medial epicondylitis is caused by forceful or repetitive activity (e.g., wrist flexion, forearm pronation) of the upper extremity (mostly occupational or sports related) and is also associated with smoking and obesity (Shiri et al. 2007). Commonly, the dominant arm is affected.

Repetitive overuse may lead to microtearing of the musculotendinous origin at the medial humeral epicondyle, mostly of the pronator teres, flexor carpi radialis, and palmaris longus muscles. Subsequent degeneration and failure of tendon healing (disruption of the normal collagen architecture with ingrowth of fibroblastic and granulation tissue) have been reported (Ollivierre et al. 1995). The pathology is degenerative rather than inflammatory; therefore, the term "tendinosis" is more appropriate (Nirschl and Ashman 2004).

A "burning" pain along the medial epicondyle, aggravated by repetitive wrist activity characterizes medial epicondylitis. The pain may radiate into the forearm. The onset of symptoms is usually insidious but may be acute – following an acute event. Range of motion is often unaltered but may be affected later on. Although articular signs are normal, grip strength may be decreased. In up to 10 % of all cases, involvement of the ulnar nerve is seen with numbness of the fourth and fifth fingers especially at night. Motor dysfunction of the ulnar nerve is rarely encountered. Just proximal to the medial epicondyle, the intermuscular septum inserts on the medial epicondyle; inflammation of this structure can mimic medial epicondylitis. In general, muscle function is less impaired in medial epicondylitis than in lateral epicondylitis (Pienimaki et al. 2002).

Medial epicondylitis may be diagnosed from the patient's history and clinical examination. Palpation may reveal point tenderness directly on the medial epicondyle or slightly (up to 5 mm) distally and anterior to it. Resisted wrist flexion or pronation aggravates pain along the medial elbow. Grip strength is commonly diminished in the affected extremity.

However, the examiner should evaluate the cervical spine and shoulder as well in order to exclude radicular or referred arm pain.

19.4.3.2 Medial Collateral Ligament Injuries

In the normal elbow joint, stability is maintained by the combination of joint congruity, capsule-ligamentous integrity, and balanced intact musculature. The olecranon and olecranon fossa articulation provides primary stability at less than 20° of elbow flexion or flexion greater than 120°. In-between stability is provided by soft tissue constraints, mainly the MCL (Morrey et al. 1991).

The MCL consists of an anterior part or anterior medial collateral ligament (AMCL), a posterior part or posterior medial collateral ligament (PMCL), and a transverse band (see Fig. 19.2). This transverse band is also known as Coopers' ligament and originates and inserts on the ulna and does not provide stability. Its function is unknown.

The three most common causes of MCL injury are elbow dislocation, chronic attenuation in athletes, or acute valgus injury. The incidence of elbow dislocation in the general population is estimated to be 6/100,000. More than 95 % of all dislocations occur in a posterolateral direction. Posttraumatic chronic ligamentous instability used to be divided into medial or valgus instability and posterolateral rotatory instability (PLRI).

A new entity, the varus posteromedial injury (PMRI) mechanism, was more recently recognized and is increasingly understood. In PMRI, a fall onto the extended arm leads to a varus force with a posteromedial rotation. The varus force creates a lateral collateral ligament injury and a fracture of the anteromedial facet of the coronoid process, with resultant varus subluxation of the elbow that in some cases is apparent only on stress views of the elbow. If the injury force continues, the medial collateral ligament fails, and the elbow can dislocate completely. Complete dislocation and medial collateral ligament injury usually occur in association with a small anteromedial facet coronoid fracture, and larger fractures are associated with

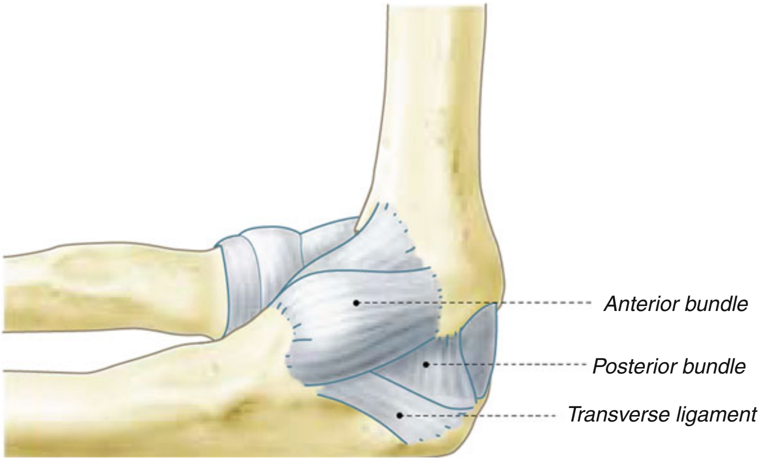

Fig. 19.2 Anatomy of the medial collateral ligament complex

subluxation or disruption injuries rather than dislocation injuries. The radial head is not usually injured.

History taking is of utmost importance in the work-up of MCL insufficiency. At physical examination, comparison with the uninvolved elbow should always be performed to differentiate between physiologic laxity and pathologic instability. The degree of instability is often underestimated. Occasionally, the presenting symptoms of valgus extension overload (as posteromedial elbow pain, ulnar nerve symptoms, and chondromalacia at the lateral side) overshadow the symptoms of MCL insufficiency. Physical examination should also assess the degree of extension loss. The joint must be tested for valgus instability in 30° and 90° of flexion. Comparison with the uninvolved elbow should always be performed to differentiate between physiologic laxity and pathologic instability. The degree of instability is often underestimated.

Medial-sided pain of the elbow is not always a tendinosis of the flexor tendons or medial epicondylitis. Medial epicondylitis can be confused with and may coexist with MCL injury.

19.4.4 Lateral Elbow Soft Tissue Injuries

19.4.4.1 Lateral Epicondylitis

Lateral epicondylitis or tennis elbow is a common disorder in primary care. The name tennis elbow is derived from the description of “lawn tennis arm.” However, tennis contributes in only 5–10 % of all cases (Gruchow and Pelletier 1979). It is rather related to manually intensive work, requiring forceful and repetitive rotation of the forearm, wrist extension, or flexion (e.g., in mechanics, butchers, construction workers). Usually, the condition occurs with a peak between 35 and 54 years of age, and the dominant arm is involved (Hamilton 1986). Men and women are equally affected, according to most studies (Allander 1974).

Repetitive rotation causes degenerative inflammation of the wrist extensors that insert on the lateral epicondyle, most commonly the extensor carpi radialis brevis (ECRB). The pathology is degenerative rather than inflammatory; therefore, the term "tendinosis" is more appropriate (Nirschl and Ashman 2004).

The correct diagnosis of tennis elbow starts with a thorough history, revealing an activity or occupationally related "burning" pain located over the lateral epicondyle of the elbow or over the origin of the ECRB. The pain may radiate proximally or distally and is aggravated by lifting, gripping, or repetitive wrist activity. The onset of symptoms may be acute – secondary to an acute event –, or more gradual as a result of repetitive microtrauma. Although articular and neurological signs are normal, grip strength may be decreased. Eventually, even simple daily activities – such as shaking hands or turning a doorknob – may be painful. In severe cases, pain may also occur during the night or at rest.

Tennis elbow may be diagnosed from the patient's history and clinical examination. Palpation may reveal point tenderness directly on the lateral epicondyle or slightly (up to 5 mm) distal and anterior to it. Resisted wrist extension or passive stretching (flexion of the wrist) with the elbow extended can reproduce the pain. Extension of the middle finger against resistance may be painful, as this movement strains the ECRB, which inserts at the base of the third metacarpal. Grip strength is commonly diminished in the affected extremity (Pluim and Groot 2009).

Moreover, the examiner should evaluate the cervical spine (C6-7) and shoulder in order to exclude radicular or referred arm pain or compression of the posterior nerve in the radial tunnel.

Differential diagnosis includes intra-articular pathology, such as pathologic synovial folds or plicae, osteochondral damage of the capitellum, or posterolateral impingement.

19.4.4.2 Lateral Collateral Ligament Injuries

The lateral collateral ligament complex (LCLC) is the primary capsuloligamentous stabilizer of the elbow joint for varus and external rotation (Deutch et al. 2003). The LCLC consists of different bands which have been inconsistently described. Generally, it is agreed that the complex consists of the radial collateral ligament (RCL), the annular ligament (AL), and the lateral ulnar collateral ligament (LUCL) (see Fig. 19.3).

The functional anatomy of the ligament complex was shown to be the superior part, constituting the conjoined LUCL and RCL, and the inferior band, inserting on the ulna, since only complete division of one of these structures induced clinically significant joint laxity. The ligament complex is covered by the anconeus muscle, the supinator tendon, and the musculotendinous insertion of the extensor carpi ulnaris and the extensor digitorum (Cohen and Hastings 1997).

The insufficiency of the LCLC can be chronic or acute. It is usually caused by elbow distortion, elbow dislocation, or iatrogenic induced by surgery to the lateral side of the elbow joint. The diagnosis of chronic elbow joint instability can be

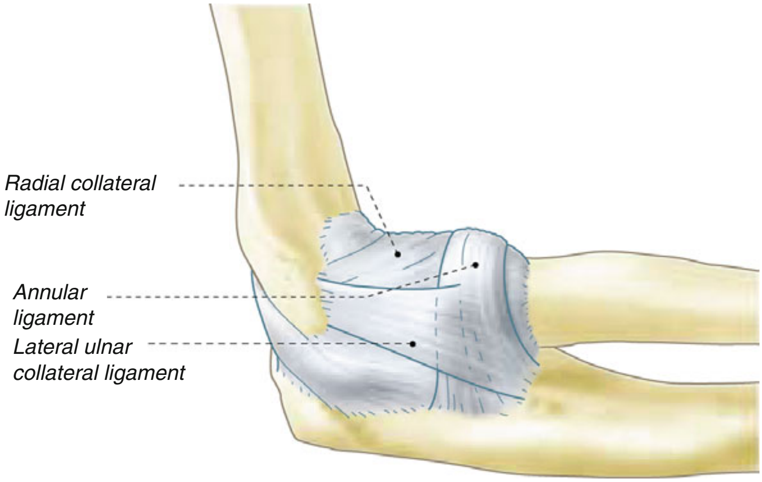

Fig. 19.3 Anatomy of the lateral collateral ligament complex. The accessory collateral ligament was defined as the most inferior fibers in the AL extending down and inserting with the fibers of the LUCL

difficult since the symptoms and the clinical presentation can be subtle. A few patients present with recurrent dislocations, but the majority present with subtle symptoms such as lateral-sided elbow pain or radial head subluxations.

During the clinical examination, usually with normal range of motion, the patient describes lateral elbow pain during forced external rotation in the semiflexed elbow joint positions, or during the pivot shift maneuver (maximal supination, valgus force, and slowly flexed from full extension). This pain is seen as apprehension at 30–50° of joint flexion. Alternatively, the "push-up" test can be used in which the patient is asked to push up his/her body weight in an armchair (Regan and Lapner, 2006). When the patient has PLRI, he or she will not be able to perform this test with extension of the elbow, due to subluxation of the radiocapitellar joint.

As in MCL insufficiency, history taking is of utmost importance in the work-up of LCLC insufficiency. The joint must be tested for external rotatory and varus laxity during semiflexed elbow positions and preferentially at a 90° joint flexion. Furthermore, a pivot shift stress test and a push-up test should be performed (O'Driscoll et al. 1991). Finally, it is important to rule out other causes for the elbow problem; therefore, valgus stability should be examined as well as performing tests for epicondylitis.

19.4.5 Osteochondritis Dissecans

Osteochondritis dissecans (OCD) is a process in which a segment of articular cartilage separates from the subchondral bone. The most common site in the elbow is the anterolateral aspect of the capitellum. This condition is thought to result from the combination of repeated valgus stress at the elbow and a tenuous blood supply to the capitellum (Singer and Roy 1984).

There is no evidence that osteochondritis dissecans of the elbow is linked to race or sex. Eighty-five percent of OCD cases involve males, but this may simply be a reflection of increased male participation in sports requiring overhand throwing activities, since a majority of these cases are sports related. Osteochondritis dissecans is also common among female gymnasts and athletes involved in racket sports and weightlifting. This condition usually presents in the second decade of life with average patient age ranging from 11 to 23 years. OCD is most frequently unilateral in the dominant arm, but 20 % of cases are bilateral, particularly in sports involving repetitive stress on both arms.

There is no proven etiology of OCD, only some convincing theories based on observation. A widely believed cause is injury due to repetitive stress on the affected bone. Continuous unrecognized injury over time may produce microscopic fatigue fractures that irritate the nearby cartilage. A concurrent reduction in blood supply to the area results in necrosis and may cause parts of the bone or cartilage in the area to loosen and separate. Further stresses across this joint can lead to fragmentation and loose bodies once the mechanical support of the articular cartilage is compromised (Omer 1981).

The typical patient is an adolescent overhead athlete 11 and 15 years of age who has been active for 3–5 years (Takahara et al. 1998). The clinical symptoms are different from Panner's disease (osteochondrosis), a self-limiting process that occurs in children who are younger, usually between the ages of 4 and 8. The most common complaint in an individual with OCD is pain, which is usually insidious and progressive and is associated with activity and relieved by rest. Tenderness can be palpated over the radiocapitellar joint, causing a dull pain that is poorly localized. Range of motion is commonly limited, especially extension. It is not uncommon to see flexion contractures of 5–23° (Bradley and Petrie 2001). Active pronation and supination of the forearm in full extension may reproduce symptoms due to compression at the radiocapitellar joint (Baumgarten et al. 1998). Catching or locking of the elbow is a late symptom indicative of articular cartilage fragmentation and loose body formation.

19.4.6 Fractures

The elbow is prone to injury. Fractures usually result from a fall on the outstretched hand or due to a direct impact to the elbow. Fractures can range from simple fissures to severe open fracture dislocations. Seemingly harmless fractures can result in an unstable elbow and long-term posttraumatic arthritis, when associated ligamentous injuries are not recognized.

19.4.6.1 Radial Head Fractures

Radial head fractures are the most common of all elbow fractures. They occur in 33 % of elbow fractures and in up to 5 % of all fractures (Mason 1954). The average

age at the time of fracture is 45 years. The radial head usually fractures from a fall on the outstretched hand with the elbow flexed between 0° and 80° in various degrees of flexion (Amis and Miller 1995).

Mason described three types of fractures, depending on the displacement and number of fragments – type 1: non-displaced, type 2: displacement >2 mm, and type 3: comminuted fractures, with multiple displaced fragments. Type 1 fractures are most common, followed by type 2 and type 3 (van Riet and Morrey 2008). The most recent augmentation of Mason's classification was based on findings in over 300 radial head fractures. It uses the Mason classification to describe the morphology of the fracture, but a suffix is added to clearly identify any associated lesions that may have an impact on elbow functioning and stability.

Inspection of the palm of the hand may reveal small wounds or indentations. The elbow and forearm of the patient are usually held in an antalgic position with the forearm somewhat pronated and the elbow slightly flexed. A swelling is noted on the posterolateral side of the elbow, where a hematoma may be visible. This represents a hemarthrosis and is a typical finding in elbow fractures. A visible hematoma on the medial side of the elbow may indicate damage or rupture of the medial collateral ligament.

Range of motion will be painful and limited by pain or mechanical block. Gross instability may be present in more severe types of radial head fractures. Palpation will reveal tenderness over the lateral side of the elbow and radial head. If the examiner carefully places a thumb or finger over the radial head and rotates the forearm, incongruency or crepitations may be palpable. Other joints of the upper extremity should be investigated carefully for associated injuries.

19.4.6.2 Olecranon Fractures

A fracture of the olecranon process is another common injury of the elbow. It is usually caused by a fall on the outstretched hand with the elbow slightly flexed. The force of the triceps essentially avulses the olecranon from the proximal ulna. The olecranon can also fracture due to a direct impact onto the elbow, and open fractures can occur in up to 30 % of the cases (Hak and Golladay 2000).

The majority of fractures will be intra-articular, but an extra-articular fracture could be a rare sign of a triceps tendon avulsion. Fractures are classified into three types, according to displacement and stability, in the Mayo classification. In type 1, there is displacement less than 2 mm, in type 2, fragments are displaced more than 2 mm in a stable elbow, and in type 3, fractures in the elbow joint is unstable.

History and clinical examination are similar to the history of radial head fractures. Swelling and hematoma are found at the posterior side of the elbow and in the olecranon bursa. A step or a gap between the fracture fragments can often be palpated in the subcutaneous border of the proximal ulna. Extension strength is decreased.

19.4.6.3 Coronoid Fractures

The coronoid process fractures due to a fall on the outstretched hand with the elbow flexed from 0° to 35°. Coronoid fractures often occur during elbow dislocations and can lead to chronic instability. The anterior band of the medial collateral band attaches to the base of the coronoid and can be involved in the injury.

Coronoid fractures are classified according to the Regan and Morrey classification (Regan and Morrey 1989). Fractures are classified into three types: type 1 – tip of the process, type 2 – fragment involving up to 50 % of the process, and type 3 – fragment involving more than 50 % of the process. A more complex classification has also recently been presented (O'Driscoll et al. 2003). The most important contribution of this system is the addition of an anteromedial fracture fragment that includes the insertion of the MCL and renders the elbow unstable. This fracture has previously often been diagnosed as a type 1 fracture but may have serious implications if not correctly diagnosed and treated. A coronoid fracture should always be suspected if there is a history of dislocation of the elbow ("bony Bankart" lesion of the elbow).

19.4.6.4 Distal Humerus Fractures

Fractures of the distal humerus can result from high-energy trauma such as a motor vehicle accident or from simple falls in osteoporotic patients. Treatment of these two types of patients may depend on the age, preexisting comorbidities, and associated lesions.

Several classification systems are used to classify distal humerus fractures. It is important to recognize the difference between intra- and extra-articular fractures. The most commonly used classification is that of the Arbeitsgemeinschaft für osteosynthesefragen (AO). Distal humerus fractures are classified into type A, nonarticular; type B, partial articular; and type C, complete articular. All types are subclassified depending on the anatomy of the fracture and can include epicondyle fractures, one or two column fractures with or without metaphyseal extension.

The distal humerus fracture is often displaced and comminuted in high-energy fractures, and an obvious deformity can be noted. Special attention should be given to the skin as open fractures can occur. In low-energy fractures, associated lesions occur less often. Obvious deformity is often present with a large hematoma. The patient is unable to move the elbow, and loose fragments can sometimes be palpated.

19.4.7 Pediatric Fractures

The pediatric elbow presents diagnostic challenges and treatment difficulties. Treating physicians must be familiar with the characteristic appearance and locations of the physes, as well as the timing of physeal closure. This varies according to patient maturity and, in some instances, from side to side on the same individual (see Fig. 19.4). With physeal injuries and unossified growth centers, fractures may not be readily apparent on injury films. Clinical examination must aid in the interpretation of any imaging.

Neurovascular status must be carefully documented when evaluating every elbow injury. This can be particularly difficult in the young child, but it is essential

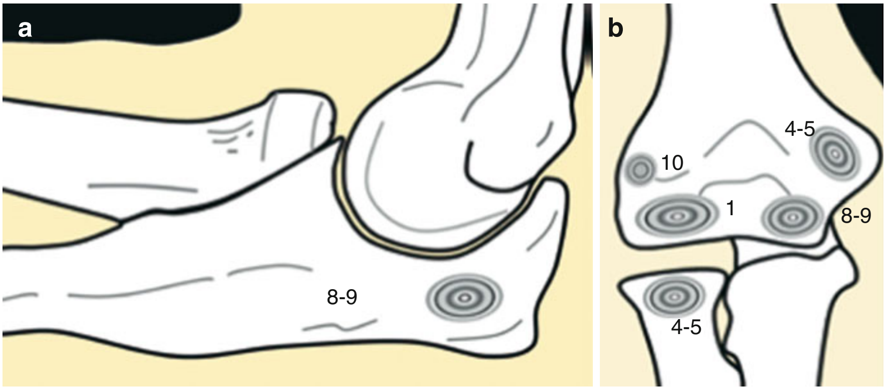

Fig. 19.4 (**a**, **b**) Order of physeal closure around the elbow in age. The order of physeal closure can be remembered using the abbreviation *CRITOE* Capitellum, Radial head, Internal (medial) epicondyle, Trochlea, Olecranon, External (lateral) epicondyle

to obtain a full preoperative sensory and motor exam, including finger abduction and thumb interphalangeal joint flexion to ensure function of the most commonly injured ulnar and anterior interosseous nerve (AIN). Compartment syndrome is an uncommon but devastating complication. The vascularity of the limb including perfusion and pulses must be carefully assessed.

19.4.7.1 Supracondylar Humerus Fractures

Supracondylar humerus fractures are the most common pediatric elbow fractures and the second most common pediatric fracture requiring hospital admission (Landin and Danielsson 1986). The injury typically occurs with a fall onto an outstretched arm in children between 5 and 10 years of age. The spectrum of injury can range from an elbow effusion with negative radiographs and decreased arm motion, to 100 % fracture displacement and a pulseless limb. A careful evaluation should be undertaken to verify neurovascular status prior to any treatment.

Extension injuries comprise the majority of supracondylar fractures. Flexion-type injuries occur in only 3 % of patients but have a higher associated rate of ulnar nerve compromise and more frequently require open reduction (31 % versus 10 %) (Mahan et al. 2007).

Nerve injuries are seen in up to 20 % of type 3 supracondylar fractures (Louahem et al. 2006). Median nerve injuries (AIN) are associated with posterolateral displacement and radial nerve injury with posteromedial displacement. An ulnar nerve injury can be associated with extension-type (posterolateral and posteromedial) fractures but is more commonly seen in flexion-type injuries (19 % versus 3 %). Complete disruption of the nerve is rare, and typically, neurologic deficits are due to neuropraxia and improve within one year of the injury. True vascular injuries have been reported in 2–8 % of type 3 supracondylar fractures. In many instances, a cool or pulseless limb on presentation is reperfused after simple closed reduction of the fracture or even flexing of the elbow. Persistently pale and cool hand following reduction is of greater concern than the absence of a radial pulse, since even if the artery is damaged, the extensive collateral circulation around the elbow usually allows for sufficient circulation to the arm to maintain perfusion.

19.4.7.2 Lateral Condyle Fracture

Lateral condyle fractures are the third most common pediatric elbow fracture (Landin and Danielsson 1986). This is a physeal fracture pattern with a high rate of associated complications, which may be avoided by early recognition and treatment. The Milch classification has historically been used, but Jakob et al. provide a more useful description of fracture types (see Fig. 19.5a–c).

19.4.7.3 Medial Epicondyle Fracture

These fractures tend to occur in older children and represent extra-articular apophyseal avulsion injuries. Rarely a medial epicondyle fracture results from chronic overuse, as in little leaguers elbows, but it is more commonly seen as an acute injury. The medial epicondyle is the origin of the medial collateral ligament complex and the flexor-pronator group. Displaced medial epicondyle fractures can be associated with elbow dislocation and are easily missed in young patients, with a very small medial ossification center. It is important to note that in the skeletally immature patient, elbow dislocations very rarely occur without associated fracture. Bone and fibrous unions have been shown to produce similar functional results (Josefsson and Danielsson 1986).

19.4.7.4 Proximal Radius Fractures

Children with open physes are more likely to sustain physeal injuries and radial neck injuries rather than the intra-articular radial head fractures seen in adults. Non-displaced radial neck fractures are common and may not be apparent on radiographs until evidence of fracture healing. No joint effusion may be present due to the extra-articular location of the fracture. Diagnosis is made by clinical evaluation. In both displaced and non-displaced fractures, patients have isolated tenderness over the radial neck and pain greater with supination-pronation than flexion-extension.

The mechanism for radial neck fractures is typically a valgus load to the radial head from a fall onto an outstretched arm. It is essential to exclude associated injuries. A posterior elbow dislocation may result in an anteriorly displaced or may cause a posteriorly displaced radial head fracture.

19.4.7.5 Monteggia Fracture Dislocation

Monteggia fracture dislocations are usually a fracture of the proximal ulna with a dislocation of the radial head. Isolated radial head dislocation without fracture is rare, even in the skeletally immature patients. Monteggia variants are more common, either associated with plastic deformation or a complete fracture of the ulna and dislocation of the radial head. Before diagnosing a traumatic radial head dislocation, it is important to exclude congenital radial head dislocation, which is characterized by a hypoplastic capitellum and a dome-shaped radial head.

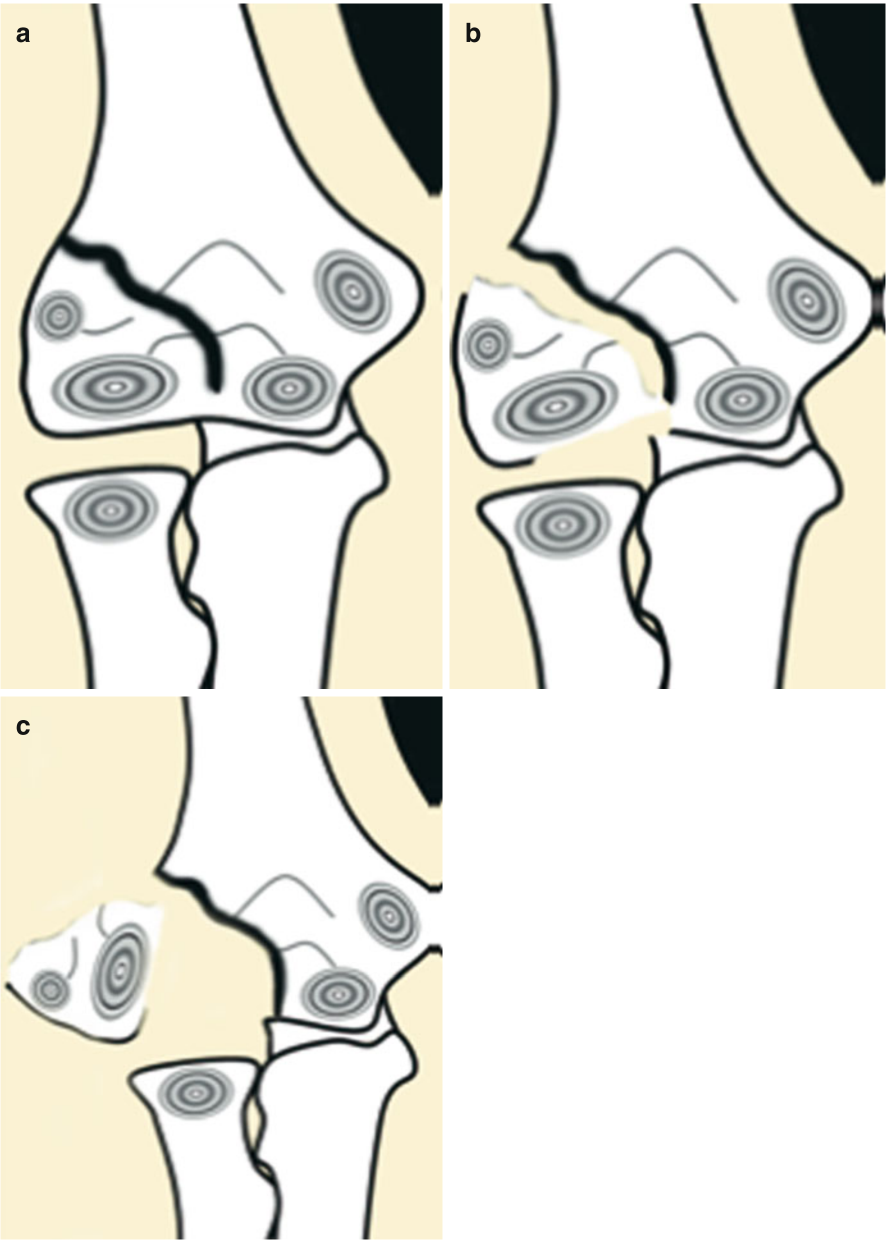

Fig. 19.5 Jakob classification of lateral condyle fractures. Type 1 fractures can be managed non-operatively. (**a**) Type 2 fractures may be percutaneously pinned if a satisfactory reduction can be maintained. (**b**) Type 3 fractures require open reduction and internal fixation to maintain joint congruity (**c**)

19.4.7.6 Galleazzi Fracture Dislocation

This is a rare fracture pattern in children involving fracture of the radius and associated dislocation of the distal ulna. Fractures can typically be treated with closed reduction and immobilization in supination.

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Radiologic Imaging of Elbow and Forearm Injuries

20

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Contents

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Abstract

The elbow joint has a complex "trochoginglymoid "architecture which allows for the wide range of motion, including hinged (elbow flexion and extension) and rotational (forearm supination and pronation) motion.

Stability is dependent on the congruity of this articulation with major support of the medial and lateral ligament complex but with only a minor contribution of the muscles.

Acute varus, valgus, anterior, and posterolateral overload may result in a variety of fractures and lead to recurrent instability and overuse injury.

Although lower limb injuries are the most common and comprise 74 % of all sports injuries (Alonso et al. 2012), upper limb injuries are an important cause of reduced performance and loss of playing time for athletes. Upper limb injuries are most common in throwing sports but frequently occur in weight-lifting sports as well.

Imaging of acute injuries in most cases involves conventional radiographs to visualise osseous anatomy and pathology but offers only limited soft tissue evaluation.

US provides high-resolution images of the muscle, tendons, and ligaments, including dynamic assessment of the joint movement and (sub)luxation of the tendons and nerves. Hypervascularisation and angiogenesis are easily assessed with Doppler ultrasound. The ultrasound examination is typically focused on the area of tenderness and discomfort.

MRI and MR arthrography are the best imaging techniques in complex pathology with involvement of bone, joint, and soft tissues.

The 2D and 3D multiplanar reconstruction capacity of CT depicts the complex osseous anatomy and pathology in fracture dislocation and fracture healing and in soft tissue calcification and ossification.

Good knowledge of the (functional) anatomy and its variants is mandatory.

Abbreviations

AIN(S)	Anterior interosseous nerve (syndrome)
CECS	Chronic exertional compartment syndrome
CT	Computerised tomography

DTPA	Diethylenetriaminepentaacetate
ECRL	Extensor carpi radialis longus muscle
ESWT	Extracorporeal shock wave therapy
FABS	Flexion, abduction and supination position of the elbow
FS	Fat suppression
LCL	Lateral collateral ligament
LCLC	Lateral collateral ligament complex
LUCL	Lateral ulnar collateral ligament
MCL	Medial collateral ligament
MR(I)	Magnetic resonance (imaging)
PIN	Posterior interosseous nerve (distal motor branch of the radial nerve)
PLRI	Posterolateral rotator instability
PNT	Percutaneous needle tenotomy
PPV	Positive predictive value
SI	Signal intensity
SNR	Signal to noise ratio
STIR	Short tau inversion recovery
US	Ultrasound
VEO	Valgus extension overload

20.1 Introduction

The elbow joint has a complex trochoginglymoid architecture which allows for the wide range of motion, including hinged (elbow flexion and extension) and rotational (forearm supination and pronation) motion.

Stability is dependent on the congruity of this articulation and is supported by the medial and lateral ligament complex with a minor contribution from the muscles as well.

Acute varus, valgus, anterior, and posterolateral overload may result in a variety of fractures and lead to recurrent instability and overuse injury.

Although lower limb injuries are the most common and comprise 74 % of all sports injuries (Alonso et al. 2012), upper limb injuries are an important cause of reduced performance and loss of playing time for athletes. Upper limb injuries are most common in throwing sports but frequently occur in weight-lifting sports as well.

Imaging of acute injuries in most cases involves conventional radiographs to visualise osseous anatomy and pathology but offers only limited soft tissue evaluation.

Ultrasound (US) provides high-resolution images of the muscle, tendons, and ligaments, including dynamic assessment of the joint movement and (sub)luxation of tendons and nerves. Hypervascularisation and angiogenesis are easily assessed with Doppler ultrasound. The US examination is typically focused on the area of tenderness and discomfort.

MRI and MR arthrography are the best imaging techniques in complex pathology with involvement of bone, joint, and soft tissues.

The 2D and 3D multiplanar reconstruction capacity of CT depicts the complex osseous anatomy and pathology in fracture dislocation and fracture healing and in soft tissue calcification and ossification.

Good knowledge of the (functional) anatomy and its variants is mandatory.

20.2 Lateral and Medial Epicondylalgia

Lateral tendinopathy (formerly called epicondylitis), or tennis elbow, is characterised by pain and tenderness at the lateral epicondyle of the humerus which is aggravated by resisted dorsiflexion of the wrist and/or wrist supination against resistance (Cyriax 1936). Medial tendinopathy, or golfers elbow, is characterised by pain at the anterior aspect of the medial epicondyle which is enhanced by resisted forearm pronation. Medial tendinopathy occurs 7–20 times less frequent than lateral tendinopathy and is more resistant to therapy (Chung et al. 2004). Both are self-limiting conditions. Lateral tendinopathy is actually seen more often in non-athletes as a result of repetitive work-related activities. It is developed in sports activities such as tennis and throwing sports. Medial tendinopathy is developed in activities that require repetitive valgus stress, such as golf, squash, bowling, weight-lifting, and similar activities. Medial tendinopathy occurs predominantly in athletes. Repetitive trauma or overuse of the radial extensor muscles leads to degeneration and microscopic and in advanced cases macroscopic tears of the common extensor tendon, formed by the extensor carpi radialis brevis and the extensor digitorum. Overuse of the ulnar flexor muscles leads to extensor carpi ulnaris as well as pronator teres, flexor carpi radialis, palmaris longus, flexor carpi ulnaris, flexor digitorum superficialis, and flexor digitorum profundus lesions. Treatment includes conservative methods such as rest, physical therapy, anti-inflammatory drugs, steroid injections, imaging-guided percutaneous needle tenotomy (PNT) with or without steroids, imaging-guided ESWT (extracorporeal shock wave therapy), or imaging-guided autologous blood injection. In the most refractory cases, surgical release is performed.

20.2.1 Radiologic Imaging of Medial and Lateral Epicondylalgia

Although the diagnosis is clinically evident, in refractory and complicated cases, radiologic imaging plays a role to exclude other possible causes of lateral elbow pain and to stage the tendinopathy.

Radiographs can show an erosive cortical lining of the epicondyle and calcifications in the region of the tendons. US findings include morphological abnormalities such as disproportional convex or concave external contour of the tendons compared with the opposite side and cortical bone irregularities with cortical erosions (Figs. 20.1 and 20.2). Changes in echogenicity with focal or diffuse reduced echogenicity, deep and superficial located calcifications, and partial or complete tears can be seen as well (Fig. 20.2).

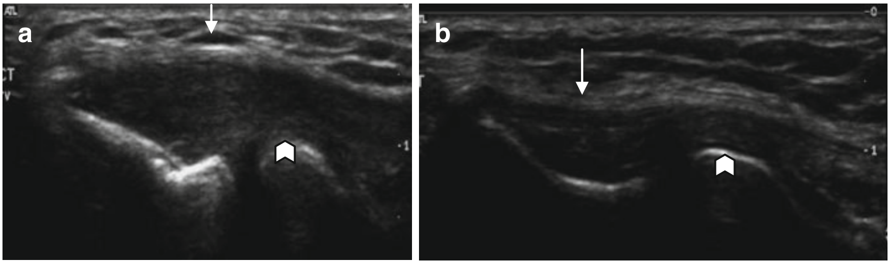

Fig. 20.1 Chronic lateral epicondylitis. (**a**) Longitudinal 12-5 MHz US scan demonstrates a convex, swollen external margin of the extensor tendons (*arrow*). (**b**) Longitudinal 12-5 MHz US shows a concave, atrophic external margin of the extensor tendons (*arrow*); *arrowhead*, radial head

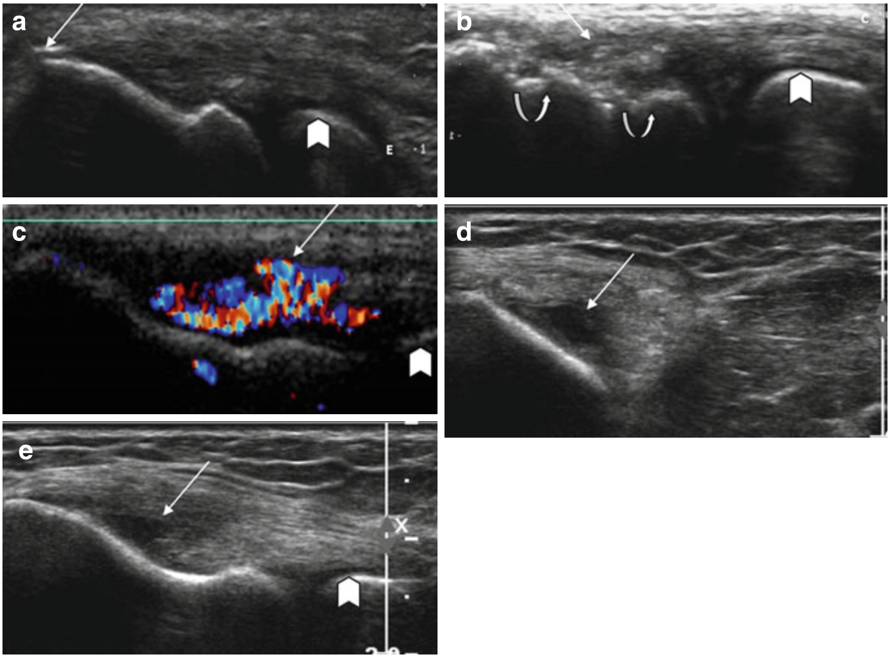

Fig. 20.2 Chronic lateral epicondylitis. (**a**) Longitudinal and (**b**) axial 12-7 MHz US of the common extensor origin, enthesophyte (**a**, *arrow*) and internal tendon calcification (**b**, *arrow*) and erosive cortex (*curved arrow*). (**c**) Longitudinal 12-7 MHz colour Doppler US, hypervascular extensor tendons. (**d**) Axial and (**e**) longitudinal 12-7 MHz US of the extensor carpi radialis brevis tendon tear (*arrow*); *arrowheads*, radial head

Hypoechogenicity with loss of the fibrillary pattern related to tendinosis is often found in the region of the extensor carpi radialis brevis. To discriminate this finding with anisotropy artefacts, it has to be shown in two orthogonal directions. This tendon indeed has an oblique course from depth to surface and thus is prone to anisotropy artefact, which is the well-known pitfall in US tendon assessment. A tear typically appears as an anechoic fluid-filled gap between the cortex and tendon origin (Conell et al. 2001; Jacobson and van Holsbeeck 1998). Contrary to deep calcifications, superficial linear calcifications continue with the bone at the origin of the ECR have a low specificity as it has been reported that only 39 % of all enthesophytes are symptomatic (Struijs et al. 2005).

Convex external contour, erosive cortex of the epicondyle, internal calcifications, a tear, and hypervascularity all have a specificity of 100 %, PPV 100 %, and a conclusive positive likelihood ratio (Obradov and Anderson 2012). Unfortunately, the sensitivity for these parameters is low; the respective values for the affected elbows are 33, 18, 33, and 14 %. Thus individually these findings are not sufficient as a stand-alone diagnostic criterion. Hypervascularisation has the highest sensitivity (57–95 %) in the group of individual findings, with 88–100 % specificity and with a confidence interval of approximately ±10 %(Torp-Pedersen et al. 2002; Noh et al. 2010; Obradov and Anderson 2012). Tendon hypervascularity is a relatively specific US sign for a painful tendon (Breidahl et al. 1996; Torp-Pedersen et al. 2002) (Fig. 20.2). However, the combination of grayscale and (power) colour Doppler changes is diagnostically superior to identify chronic tendinopathy.

Recently different authors concluded that the lack of both hypervascularity and grayscale changes on ultrasound examination substantially increases the probability that the condition is not present and should prompt the clinician to consider other causes for lateral elbow pain (Toit et al. 2008; Obradov and Anderson 2012). In the absence of US findings in tendinopathy in acute cases with duration of symptoms less than 6 months, it is wise to exclude other possible causes for the pain in the same region.

MRI demonstrates thickening of the tendon with increased signal intensity within the tendon on T1 and fluid-sensitive T2 sequences correlating with mucoid degeneration and neovascularisation presented with or without reactive epicondylar bone marrow oedema. Discrimination between degeneration and angiogenesis is not possible on MR imaging. In the case of partial or complete tears, signal intensity is similar to that of fluid, and a separation of the tendinous attachment from the condyle can be seen. Injury of the lateral collateral ligament complex can be associated with a tear of the extensor tendons and may result in therapy-resistant lateral tendinopathy. As the medial collateral ligament (MCL) is the primary stabiliser of the medial elbow joint, concomitant injury of the MCL and flexor tendons can occur as well. Calcifications in the tendon origin are presented as loss of the signal intensity on all sequences. Signs of the associated elbow injuries, ulnar neuritis, or secondary osteoarthritis may also be observed.

20.3 Triceps Tendinopathy

The triceps muscle consists of the long, medial, and lateral head. It originates at the scapula and humerus and is attached to the olecranon and the antebrachial fascia. Triceps tendinopathy is the result of intrinsic muscle overload in combination with

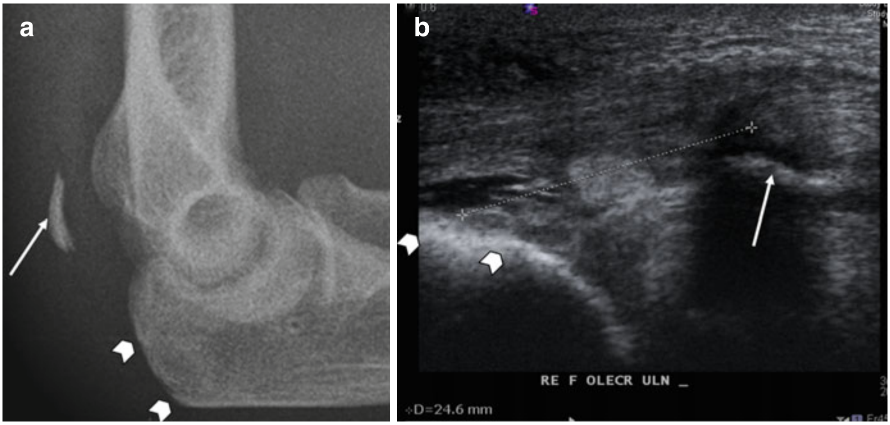

Fig. 20.3 A 25-year-old male, with shelf avulsion of triceps tendon insertion at the right elbow. (**a**) Lateral radiograph and (**b**) ultrasound examination of the right elbow with shelf-like bone fragment (*arrow*) with 2.5 mm diastasis from the olecranon; margins of avulsion site are marked with *arrowheads*

fast extension of the triceps as seen in baseball pitchers and javelin throwers. Pain during resisted elbow extension or complete flexion is typical for this injury.

Distal triceps tendon rupture is the least common of all tendon ruptures and can be associated with small shell-like bone avulsion (Viegas 1990) (Fig. 20.3). The injury is caused by either a direct blow or by forceful contraction of the triceps during active extension and is seen in weight-lifting and other strength sports. Olecranon bursitis, tendinopathy, and steroid injection can lead to the triceps rupturing (Van Riet et al. 2003).

20.3.1 Radiologic Imaging of Triceps Tendinopathy

Triceps tendinopathy is an uncommon finding, which in chronic cases can demonstrate calcifications in radiographs (Fig. 20.4).US shows a thickened often hypoechoic tendon at the place of the concordant pain. The calcifications are hyperreflective with acoustic shadowing if the calcification is solid. MRI shows abnormal morphology with increased thickness and increased signal intensity on all sequences.

The clinical diagnosis of an acute distal triceps tendon rupture can be difficult due to pain that limits the physical examination. Plain radiographs show if present a specific shell-like avulsion of the olecranon. MRI and US have a role in the early diagnosis and differentiation between partial and complete tears. US shows the retracted triceps tendon surrounded by fluid and can visualise atypical ruptures of the musculotendinous junction or tear of the muscle bellies (Kaempffe and Lerner 1996). The sagittal plane MRI with both flexed and extended elbow has been shown to most effectively distinguish between partial and complete

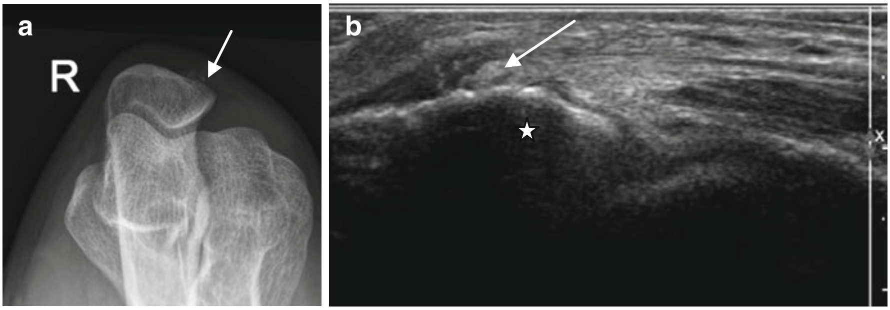

Fig. 20.4 Triceps tendinopathy. (**a**) Radiograph, axial view of the elbow demonstrates calcification (*arrow*) in the triceps tendon. (**b**) Longitudinal 12-5 MHz US of the olecranon with triceps tendon calcification (*arrow*); olecranon (*asterisk*)

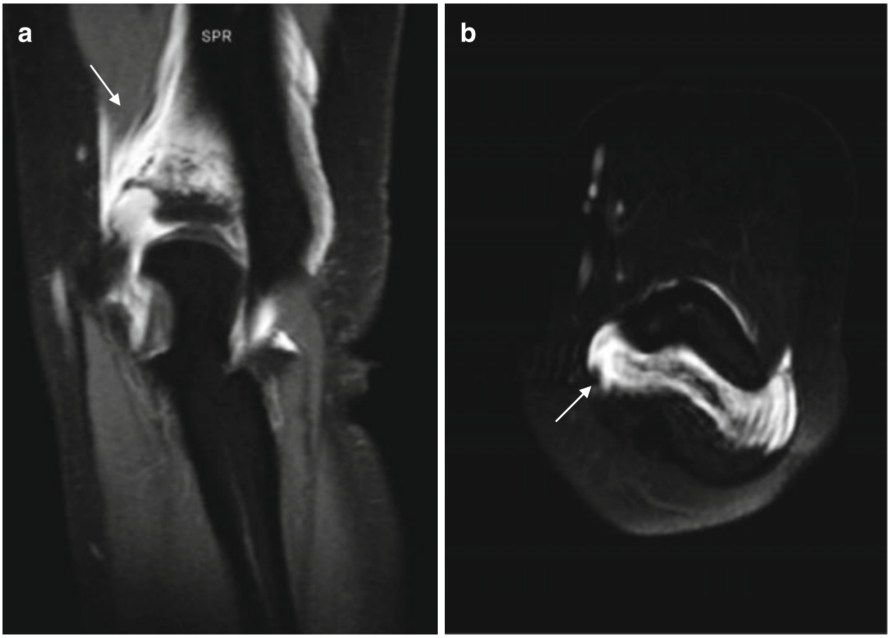

Fig. 20.5 Partial tear of the triceps tendon. (**a**) Coronal and (**b**) axial fat-suppressed T1-weighted MR arthrogram demonstrates intrasubstance focal areas (*arrow*) of the contrast corresponding to fluid-filled defects

tears (Murphy 1992). This is important as complete tears require surgery to avoid contraction; partial tears are treated conservatively. Specific MRI findings also include soft tissue oedema, reactive hyperaemia of the olecranon, bone trabecular fractures, intramuscular haemorrhages, and bursal fluid (Blease et al. 1997) (Fig. 20.5).

20.4 Olecranon Bursitis

Olecranon bursitis, also known as student's elbow or miner's elbow, is the most common superficial bursitis in the human body (Morrey 2000). The primary cause is acute or repetitive trauma from football, ice hockey, or wrestling injuries, and secondly it is associated with systemic inflammatory diseases, such as gout, rheumatoid arthritis, hydroxyapatite deposition, and calcium pyrophosphate deposition, and with patients undergoing chronic dialysis. Infection with *Staphylococcus aureus* as well as a rare case of tuberculosis can also be present.

20.4.1 Radiologic Imaging of Olecranon Bursitis

Radiographs may show soft tissue swelling and, in chronic cases, calcification as an expression of an old bleeding. A cortical destruction of the olecranon in the case of the infectious involvement of the bone may also be visible.

US findings include hypo- or anechogenic fluid collections superficial to the olecranon. The olecranon bursa is a typical superficial bursa with a synovial membrane supported by dense irregular connective tissue interposed in the loose areolar tissue between the skin and bone; this causes an irregular lining with internal septations specific for distended subcutaneous bursae on ultrasound images (Fig. 20.6).

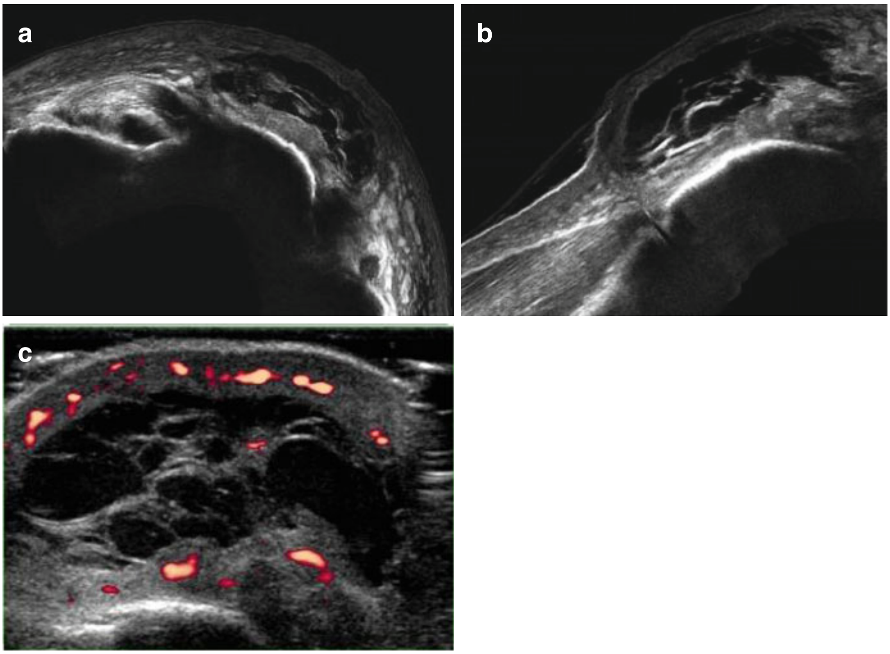

Fig. 20.6 Olecranon bursitis. (**a**) Transverse and (**b**) longitudinal 12-7 MHz US reveals distended bursa with multiple internal septations. (**c**) Colour Doppler 12-5 MHz US shows typically peribursal hypervascular pattern and septations with irregular lining specific for subcutaneous bursae

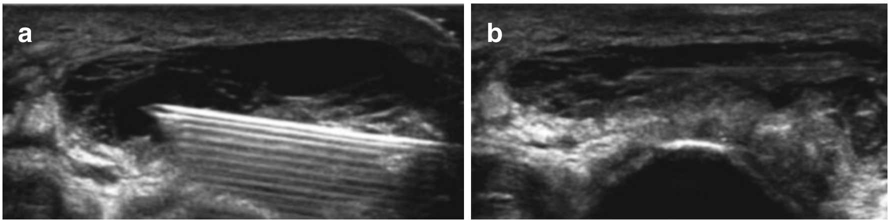

Fig. 20.7 US-guided aspiration of the chronic inflammatory olecranon bursitis. (**a**) Longitudinal and (**b**) axial 12-5 MHz US shows needle aspiration of the bursal fluid (same patient as 20.6)

Fluctuating hyperechoic particles can be seen in crystal deposition disease. Colour Doppler imaging can visualise thick synovium with rim-like hypervascularisation and soft tissue hyperaemia of the subcutaneous fat.

In chronic haemorrhagic or septic bursitis, homogeneous predominant hyperechoic content is present, resulting in a complex image of the bursitis. US-guided aspiration can easily be performed in combination with corticosteroid injection in non-infectious inflammatory diseases (Fig. 20.7).

MRI demonstrates localised fluid signal intensity lesions which in the case of haemorrhage get a more complex aspect. Marked enhancement of the bursal synovium and subcutaneous fat is present in septic bursitis after intravenous gadolinium DTPA administration. Oedema and infectious impairment of the underlying olecranon and eventually oedema and other abnormalities of the triceps tendon can be seen on MR imaging. Although complete differentiation between septic and non-septic olecranon bursitis is not possible, the septic bursitis is excluded in the absence of bursal and soft tissue gadolinium DTPA enhancement (Floemer et al. 2004).

20.5 Distal Biceps Tendon Injuries

The biceps brachii has a distal tendinous insertion at the tuberositas brachii and a second distal insertion, the lacertus fibrosus, on the volar side of the superficial fascia of the forearm flexor muscle compartment. Distal biceps tendon injuries primarily involve the tendon and secondarily the lacertus fibrosus. They vary in range from tendinopathy to partial and complete tears. Distal biceps tears occur in weight-lifters, bodybuilders, and manual labourers. It happens predominantly in men in their fourth decade. Smokers have a 7.5 times higher risk of getting a distal biceps rupture than non-smokers (Safran and Graham 2002). Possible locations of the injury are at the distal musculotendinous junction, midsubstance of the tendon, and, the most common one, the avulsion from the radial tuberosity. The latter is associated with increasing pain anterior at the elbow during pronation movement. During pronation the radial tuberosity rotates posterior, eventually resulting in impingement of the biceps tendon at its distal insertion together with the peritendinous bursae (bicipitoradial bursa and interosseous bursa) between the proximal radius and ulna metaphysis. Enthesophytes or hypertrophic tuberositas radii, distended bursa, and tendinopathy reduce the interosseous space and cause or increase impingement of the tendon. In complete tear of the tendon, the lacertus fibrosus is overloaded and may become tendinopathic causing specific tenderness during biceps muscle activity against resistance at the site of its insertion on the proximal volar side of the flexor muscle compartment. Operative tendon repair within two weeks shows good long-term results.

20.5.1 Radiologic Imaging of Distal Biceps Tear

Both radiographs and US may show intratendinous calcification in chronic cases of tendinopathy (Fig. 20.8).

In the case of (sub)acute biceps tendon tears, US shows hypoechoic fluid in the tendon bed and proximal retraction of the complete torn tendon. The tendon insertion at the tuberositas radii is not easily demonstrated on ultrasound examinations. If anterior-medial angled view is not successful, posterior evaluation in pronated position with elbow flexion (cobra position) may add to the evaluation of the distal 1 cm of the tendon (Figs. 20.9, 20.10, and 20.11). Thickening, thinning, or waving

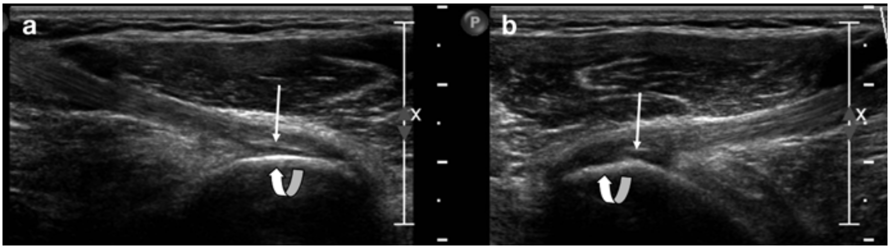

Fig. 20.8 (**a**, **b**) 12-5 MHz US, bilateral biceps insertion tendinosis with linear calcification (*arrow*) and minor thickening; *curved arrow*, tuberositas radii

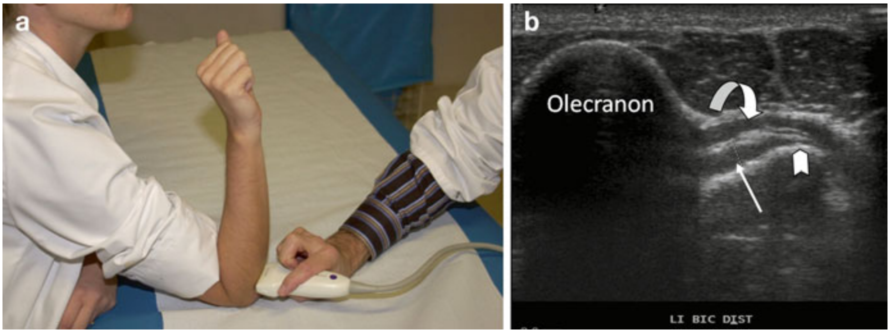

Fig. 20.9 Cobra position with elbow flexion and pronation for ultrasonographic evaluation of the distal biceps tendon at the level of the tuberositas radii insertion. (**a**) Probe position in cobra position. (**b**) 13-5 MHz US, biceps tendon (*arrow*), tuberositas radii (*arrowhead*), supinator muscle (*curved arrow*)

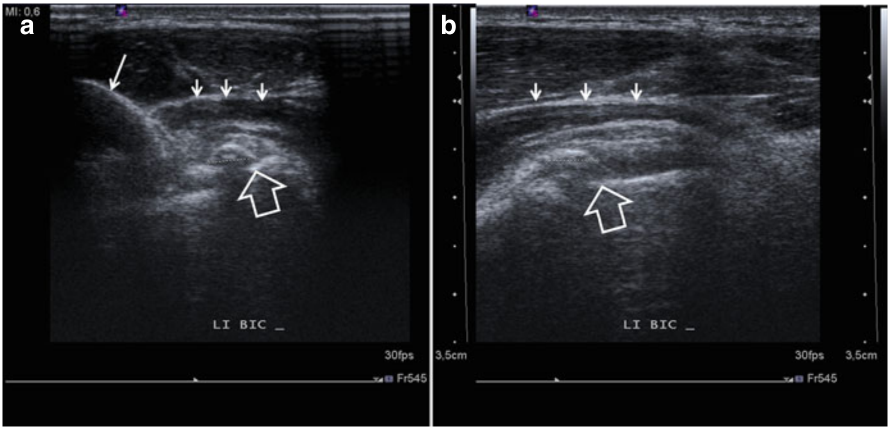

Fig. 20.10 Male patient, 33 y, painfull pronation movement at the left elbow. US 13-5 MHz ultrasound examination in cobra position with thickening of the distal biceps related to intratendinous calcification, 3.5 mm, with acoustic shadowing (calcification between marks) (**a**) axial imaging plane, (**b**) oblique axial imaging plane. Supinator muscle (*small arrow*), olecranon (*long arrow*), radial tuberosity (*big arrow*)

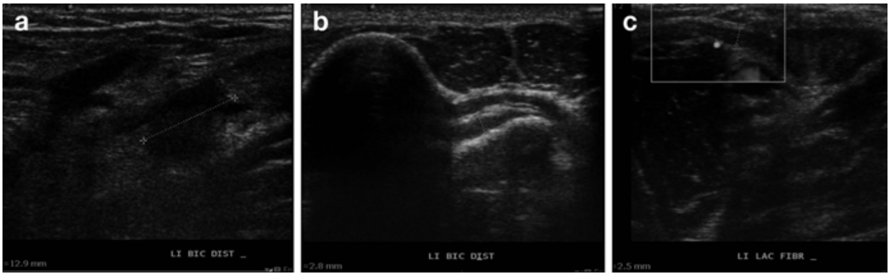

Fig. 20.11 Male patient, 56 y, painful snap at the left cubital fossa 5 days ago with residual pain at the level of the proximal ulnar flexor compartment. (**a**) US 13-5 MHz, longitudinal view at cubital fossa, demonstration of full-thickness tear of the biceps with minor retraction of 13 mm, between marks. (**b**) US 13-5 MHz, cobra view, normal distal biceps tendon with normal insertion at the tuberositas radii. (**c**) US 13-5 MHz, transverse view at the level of the ulnar flexor compartment, proximal third. Thickening of the lacertus fibrosus (2.5 mm) insertion on the superficial fascia of the flexor muscle compartment with localised pain during compression and elbow flexion against resistance

of the tendon without discontinuity can be seen in the case of partial tears (Miller and Adler 2000) (Fig. 20.12). Distension of the interosseous and bicipitoradial bursa is also demonstrated. Complete or partial fatty infiltration of the muscle belly is seen in a chronic stadium (Fig. 20.13) of tendon tear.

MRI is performed with the patient lying prone on the imaging table and with the arm extended over the head in 90° of elbow flexion, abduction, and supination

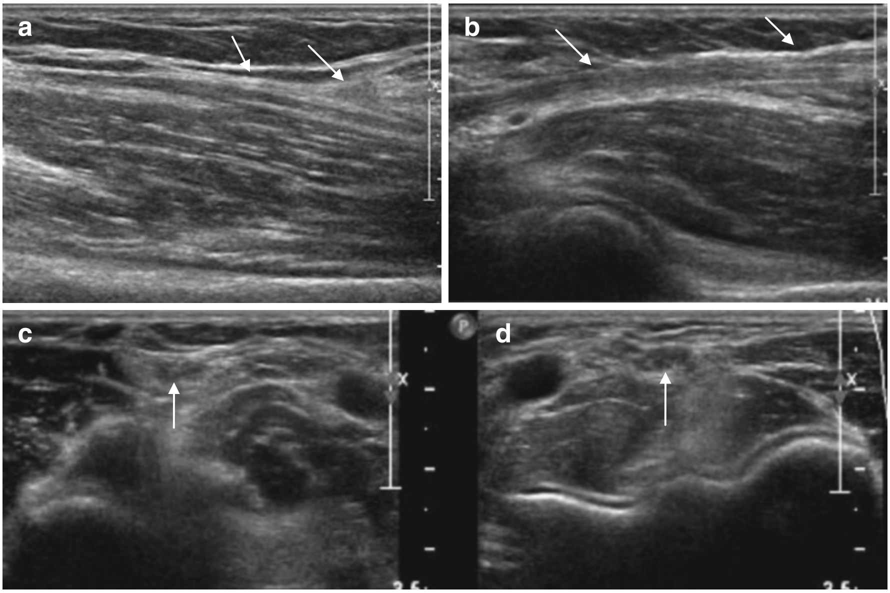

Fig. 20.12 Chronic distal biceps tendon rupture at the mid-portion of the tendon. (**a**) Longitudinal and (**c**) transverse 12-5 MHz US reveals proximal retracted muscle without distal tendon visualisation (*arrow*). (**b**) Longitudinal and (**d**) transverse 12-5 MHz US shows normal tendon (*arrow*) at the opposite side

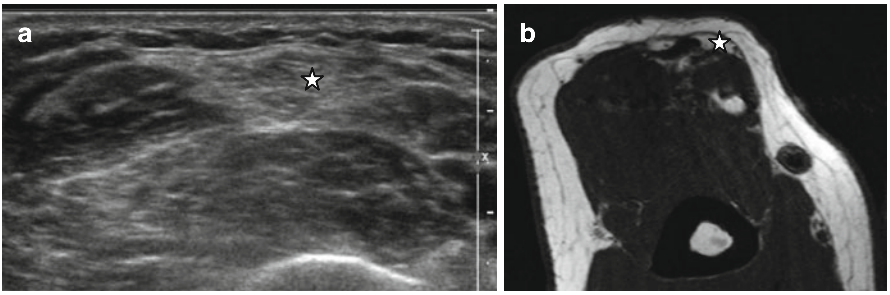

Fig. 20.13 Chronic rupture of the tendon of the caput breve of the biceps. (**a**) Axial 12-5 MHz US and (**b**) axial T2-weighted MR image show fat degeneration of the caput breve muscle belly (*asterisk*) and normal structure of the caput longum muscle, the so-called black and white sign

(FABS) position (Giuffrè and Moss 2004) (Fig. 20.14). Coronal T1 and fluid-sensitive T2 sequences show the distal biceps tendon in the longitudinal axis.

Differentiation between partial and complete tears can be made. In the case of a rupture, fluid collection in the position of the lacertus fibrosus can be identified. Bursal widening is demonstrated.

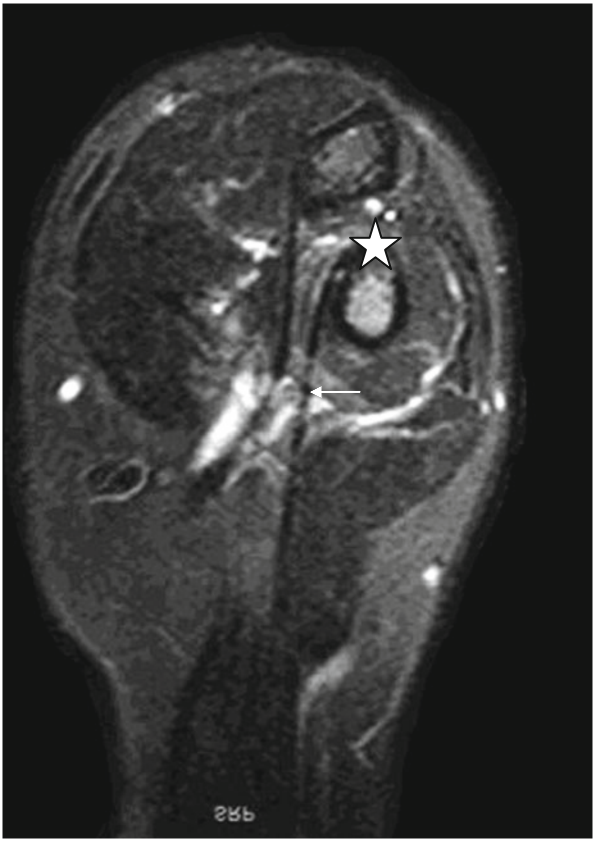

Fig. 20.14 Coronal T2-weighted fat-suppressed image of the elbow in flexion, abduction, and supination (FABS) position. Distal biceps tendon (*arrow*) is longitudinally presented till its attachment on the radial tuberosity (*asterisk*)

20.6 Medial Collateral Ligament Complex Injuries

Medial collateral ligament (MCL) injuries are the result of chronic repetitive valgus trauma related to throwing activities but can also be seen in posterior elbow dislocation. The MCL consists of anterior, posterior, and transverse bundles. The anterior bundle connects the medial epicondyle and sublime tubercle of the ulna and is most prone to injury.

Complete ruptures are often the result of acute trauma, while partial ruptures are often seen in throwing athletes. Tears occur proximally, distally, or at the level of the midsubstance. They can be associated with tears of the flexor digitorum superficialis due to the close relation with this muscle.

Posteromedial impingement syndrome has been seen in the setting of existing valgus instabilities which resulted from chronic repetitive microtrauma in throwing athletes (Frostick et al. 1999). These valgus extension overloads (VEO) result in MCL injuries with inflammation and partial or complete tears. The light subluxation of the elbow leads to posteromedial impingement of the olecranon with consecutive osteophyte formation and eventually intra-articular bodies (Wilson et al. 1983) (Fig. 20.15). Associated possible injuries are flexor-pronator injury and ulnar nerve entrapment as a result of cubital tunnel syndrome. In the latest stadium of the chronic valgus instability, osteochondral defects of the radiocapitellar joint can also be seen.

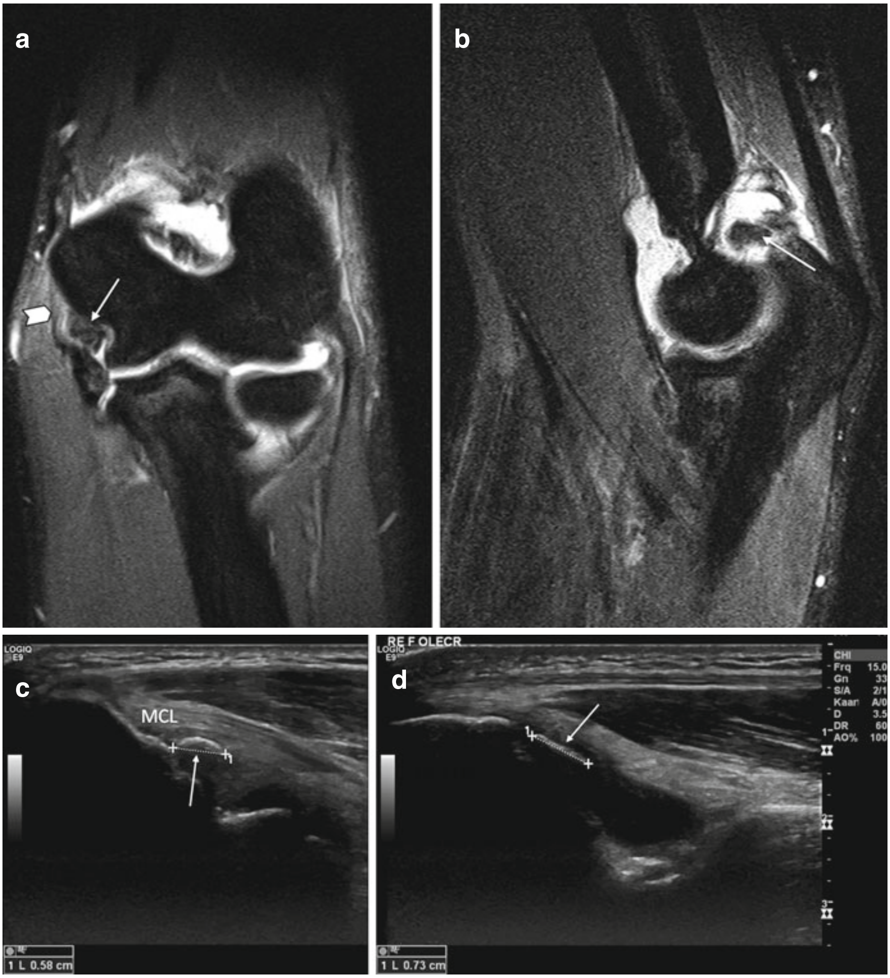

Fig. 20.15 Male, 27 y, javelin thrower with chronic complaints of posterior impingement. MRI, 1.5 T coronal (**a**) and sagittal (**b**) T2-WI with FS, ultrasound 15-5 MHz, oblique coronal US of MCL (**c**), and posterior sagittal view (**d**). Thickening of the anterior band of the MCL (*arrowhead*) with bone fragment (*arrow*) on (**a**, and **c**). Loose body at the olecranon fossa with marked joint effusion on sagittal images (**b**, **d**)

20.6.1 Radiologic Imaging of Medial Collateral Ligament Complex Injuries

Radiographs should be the first choice of imaging modality. Chronic MCL injuries can be associated with MCL ossification which is clearly visible on the radiographs. Ulnar traction spurs or avulsion of the sublime tubercle can be seen as well (Fig. 20.16). Reversed axial projection allows better visualisation of olecranon degenerative changes.

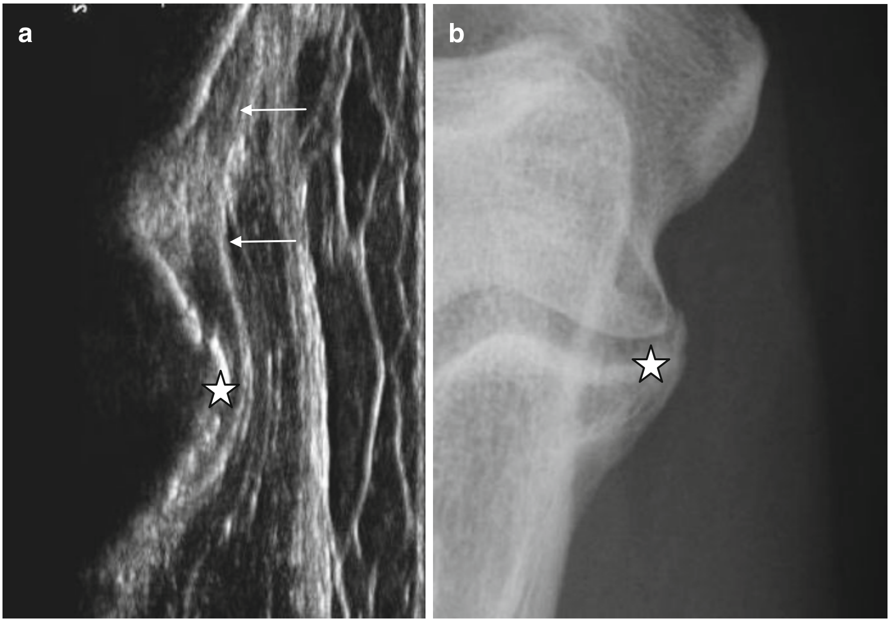

Fig. 20.16 Chronic overload stress of the medial collateral ligament. (**a**) Coronal 12-5 MHz US shows thick medial collateral ligament (*arrows*) and (**b**) frontal radiograph also shows old avulsion of the sublime tubercle (*asterisk*)

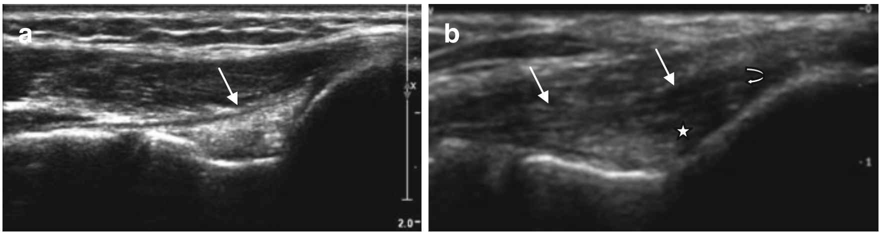

Fig. 20.17 Medial collateral ligament. (**a**) Longitudinal 12-5 MHz US of the normal, homogeneous echo pattern of the medial collateral ligament (*arrow*) which connects the medial epicondyle with the sublime tubercle of the ulna. (**b**) Longitudinal 12-5 MHz US of the chronic overuse syndrome with thick medial collateral ligament (*arrows*) showing a small origin calcification and low echogenicity of the intra-articular fat (*asterisk*)

Stress radiographs can be used to evaluate MCL insufficiency. A side-to-side difference of >0.5 mm in the joint space was consistent with a MCL tear (Rijke et al. 1994), and in throwing athletes differences of ≥2 mm in the ulnohumeral joint space required MCL reconstruction (Thompson et al. 2001).

US shows thickened hypoechoic MCL, with effusion near the medial epicondyle (Jacobson and van Holsbeeck 1998). In chronic cases calcifications and heterotopic bone can be seen (Conway et al. 1992) (Fig. 20.17).

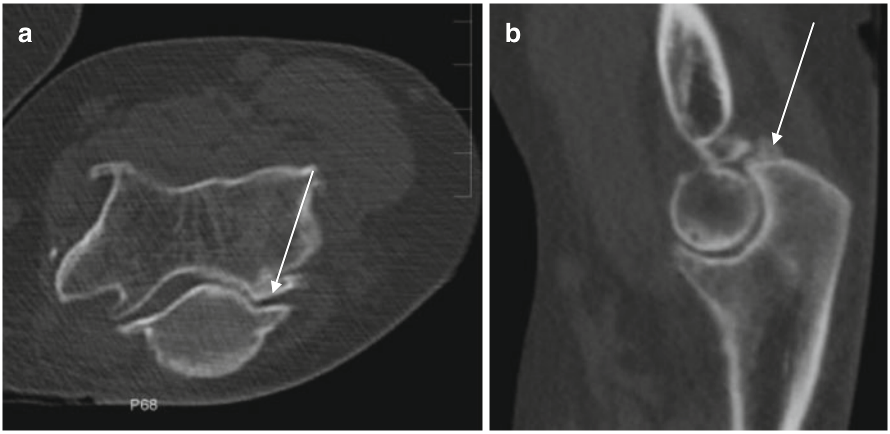

Fig. 20.18 Posterior elbow impingement. (**a**) Axial and (**b**) sagittal 2D CT reconstruction shows posterior elbow impingement with osteophyte formation (*arrows*)

Complete tears are presented as a hypoechoic gap. In throwing athletes, a dynamic valgus stress ultrasound examination can estimate medial joint laxity as well as stage partial tears (Nazarian et al. 2003). CT arthrography presents extravasations of the arthrography contrast beyond the medial aspect of the joint capsule indicating MCL injury. Posteromedial degenerative changes as olecranon osteophytes and loose bodies are best visualised with CT (Fig. 20.18).

MRI has an important role in preoperative staging for ligamentoplasty in partial ligament tears in throwing athletes. Normal MCL has a uniform low signal intensity and fat signal deep to its fibres which reflect normal intra-articular fat (Nakanishi et al 1996) (Fig. 20.19).

Partial distal MCL tears do show a "T sign" on MR arthrogram corresponding to an extension of the contrast between the distal MCL and the sublime tubercle, to >3 mm continuous with the contrast in the joint to form a "T". Other MRI findings are thickened ligament with high signal intensity on T1 and PD weight images (Fig. 20.15a), traction spur, discontinuity of the MCL in complete tears with extravasation of the contrast, and, if applicable, associated medial and lateral impaction/impingement changes as the bone bruises lateral and secondary degenerative changes posteromedial.

20.7 Lateral Collateral Ligament Complex Injury

The lateral collateral ligament complex (LCLC) consists of the radial collateral ligament, lateral ulnar collateral ligament (LUCL), and the annular ligament (Figs. 20.20 and 20.21).

Injury of the lateral collateral ligament complex is a result of chronic varus stress overload in sports or work-related activities or from acute trauma with posterior dislocation, hyperextension, or varus stress (Safran 2004). This leads to

Fig. 20.19 Medial collateral ligament. (**a**) Coronal T1-weighted SE MR image shows homogeneous low signal intensity MCL with high signal intensity deep to it representing normal intra-articular fat (*arrow*). (**b**) Coronal T1-weighted SE MR image and (**c**) coronal T2-WI FS MRI image show thickened MCL with reduced SI on T1-WI and increased SI on T2-WI of the intra-articular fat (*arrow*)

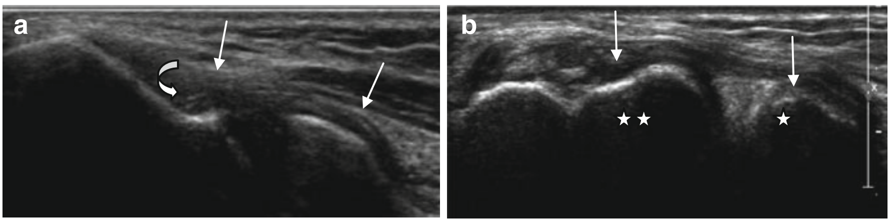

Fig. 20.20 The lateral collateral ligament (LCL). (**a**) Longitudinal 12-5 MHz US of the LCL in a chronic overuse syndrome with thick LCL (*arrows*) and proximal calcifications (*curved arrow*). (**b**) LCL reconstruction (*arrows*) from lateral epicondyle (*asterisks*) till the radius head (*asterisk*)

Fig. 20.21 T1-W coronal T1 MR image of a normal LUCL (*arrows*)

posterolateral rotatory instability (PLRI). The pathoanatomy of the PLRI develops through three stages according to the "circle of Horii"(O'Driscoll 2000):

- Stage I – disruption of the LUCL resulting in posterolateral rotatory subluxation.
- Stage II – disruption of radial-sided soft tissue and anterior and posterior capsule resulting in further dislocation of the elbow with conflict between the medial edge of the ulna and trochlea; the coronoid is perched on the trochlea, resulting in varus instability.
- Stadium III – disruption of the medial-sided ligaments, resulting in additional valgus instability. In stage III the elbow is unstable in all directions.

The proximal radioulnar joint retains its anatomical relationship in all stages.

20.7.1 Radiologic Imaging of Lateral Collateral Ligament Complex Injury

A lateral radiograph with extended elbow during stress is performed by placing the lateral side of the elbow against the x-ray plate with the shoulder and wrist in the same plane as the elbow, angulating the radiation beam from medial to lateral. Dorsal subluxation of the radius head can be seen (Fig. 20.22).

A tear of the LCL appears on US images as discontinuity of the deepest fibres of the extensor tendon origin. In the case of injury to the LCL and extensor tendons, a full-thickness interruption of the fibres is seen in combination with the soft tissue haematoma around the proximal margin of the capitellum (Conell et al. 2001).

The MRI evaluation is based on morphology, signal intensity, and continuity of the ligament structures on the lateral and medial side of the elbow. Tears occur at the lateral epicondyle and often both LCL and LUCL are disrupted at their humeral attachment. Posterior displacement of the radial head and ulna can be seen (Figs. 20.23 and 20.24).

Fig. 20.22 Subluxation of the radial head. Lateral stress radiograph is performed by placing the lateral side of the elbow against the x-ray plate with shoulder and wrist in the same plane as elbow, directing the x-ray from medial to lateral

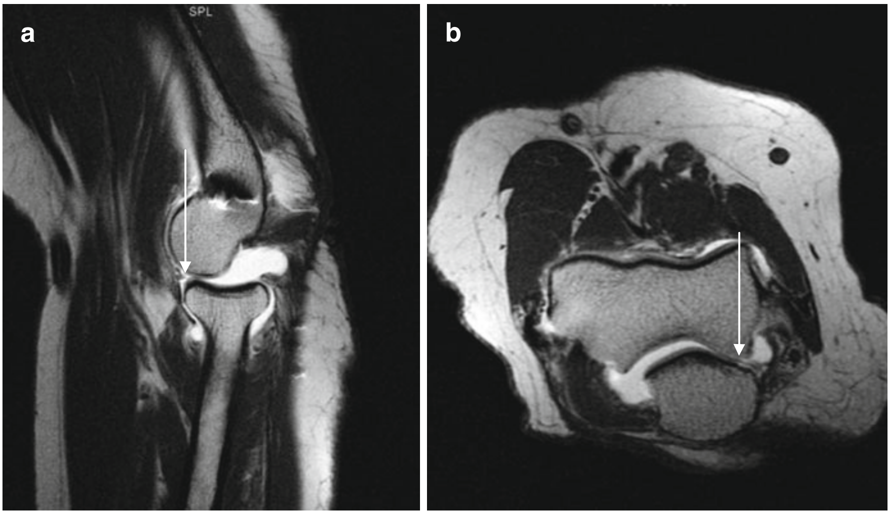

Fig. 20.23 Posterior subluxation of the radius head in a patient with lateral collateral ligament reconstruction. (**a**) T1-weighted sagittal MR arthrogram shows posterior subluxation of the radius head (*arrow*). (**b**) T1-weighted axial MR arthrogram reveals impingement between the olecranon and distal humerus as a result of posterolateral instability

Fig. 20.24 Stage III posterolateral rotatory instability. T1-weighted coronal MR arthrogram shows subtotal tear of the common extensor tendon and the lateral collateral ligament complex (*arrow*), posterolateral displacement of the radial head, and medial collateral ligament tear (*asterisk*)

MR arthrography with specific imaging reconstruction planes for the visualisation of the LUCL is suggested by Cotton et al. (1997).

20.8 Nerve Entrapment Syndromes

20.8.1 Posterior Interosseous Nerve Syndrome/Supinator Syndrome

Posterior interosseous nerve (PIN) syndrome, or supinator syndrome, consists of an entrapment of the PIN, the unique motor branch of the radial nerve just distal to the elbow running between the humeral and ulnar head of the supinator muscle. Entrapment can occur at the level of the supinator entrance level located at the proximal margin of the supinator muscle which forms a fibrous arch, the so-called arcade of Frohse, in the nerve's "intramuscular" route between the superficial and deep layers of the supinator, and at the distal margin of the supinator as well (Konjengbam and Elangbam 2004). A less common site is the region of the leash of Henry, a small recurrent vessel that crosses the PIN, or at the level of the fibrous edge of the extensor carpi radialis muscle. Behind the anatomic structures the different conditions may cause a PIN syndrome, such as radial head and neck trauma, tumours, ganglia, lipomas, extended bursas, and all intra-articular synovial diseases. The syndrome is characterised by loss of extension in the metacarpophalangeal joints, particularly the abduction and extension of the thumb. The pain can sometimes mimic a “resistant lateral tendinopathy”.

20.8.1.1 Radiologic Imaging of Posterior Interosseous Nerve Syndrome/Supinator Syndrome

Radiographs and CT can play a role in the trauma setting by showing the possible skeletal cause of the entrapment. US is suitable for demonstration of radial nerve compression, calibre change of the swollen nerve, and subsequent structural changes of the nerve (Bodner et al. 2002; Martinoli et al. 2004) (Figs. 20.25 and 20.26).

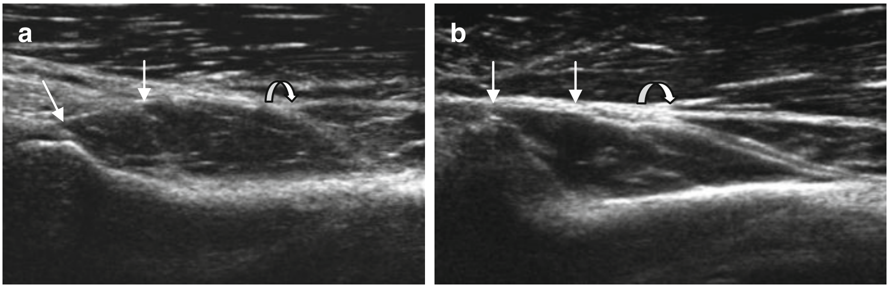

Fig. 20.25 PIN neuropathy. (**a**) Longitudinal 12-5 MHz US of the supinator muscle shows hypertrophic convex border of the supinator muscle (*arrow*) with hypoechoic compressed posterior interosseous nerve (*curved arrow*). (**b**) Asymptomatic opposite side

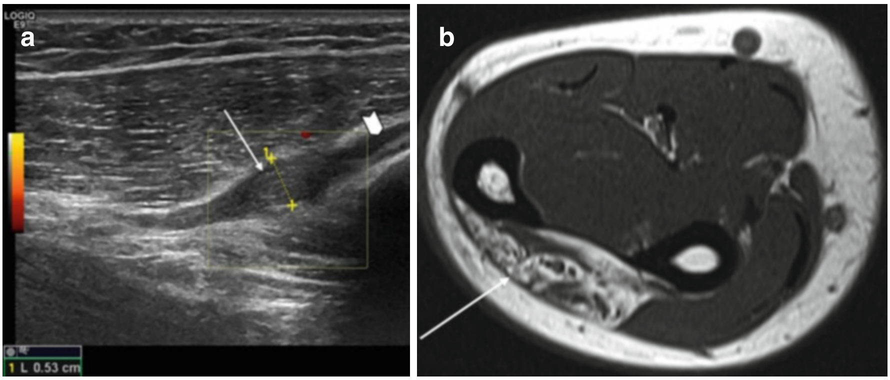

Fig. 20.26 Female patient, 39 year, right-sided chronic extension deficit of the fingers 2–5. Ultrasound and MRI examinations of advanced PIN neuropathy. (**a**) Oblique ultrasound imaging plane along the course of the PIN at the level the “arcade of Frohse”. Oval thickening of the PIN (*arrow*) representing a neuroma with absence of fibrillar structure at the nerve distal to the neuroma representing Wallerian degeneration (*arrowhead*). (**b**) MRI, T1-WI demonstration of increased SI due to lipomatous involution of extensor muscles (extensor digitorum, extensor digiti minimi, and extensor indicis proprius) (*arrow*)

Comparison with unaffected sides and scan in pronation position can be helpful. MR imaging in the forearm pronation is recommended because of the dynamic nature of compression associated with this syndrome (Chung 2010). Axial scans are best for evaluation of the neurovascular structures. The morphology and signal intensity of the nerve should be assessed. Denervation muscle oedema can be seen on fluid-sensitive T2 sequences. In a chronic stadium atrophy can be present in the region of the supinator and extensor muscles.

20.8.2 Pronator Syndrome

Pronator syndrome represents a compression of the median nerve. From proximal to distal possible sites of compression are the supracondylar process, ligament of Struthers, lacertus fibrosus of the biceps muscle, pronator teres muscle, and proximal arch of the flexor digitorum superficialis muscle. Pronator syndrome commonly occurs in weight-lifters or in people with occupations requiring pronation in combination with elbow extension. The symptoms include weakness in the thenar muscle and/or paresthesia in the skin overlying the thenar.

20.8.2.1 Radiologic Imaging

Radiographs show osseous prominence arising from the anteromedial aspect of the humerus in the case of supracondylar processes (Fig. 20.27).

US and MRI evaluation have to include all potential sites involved extending from the distal third of the arm to the flexor digitorum superficialis muscle in the proximal third of the forearm. US may show calibre change of the median nerve

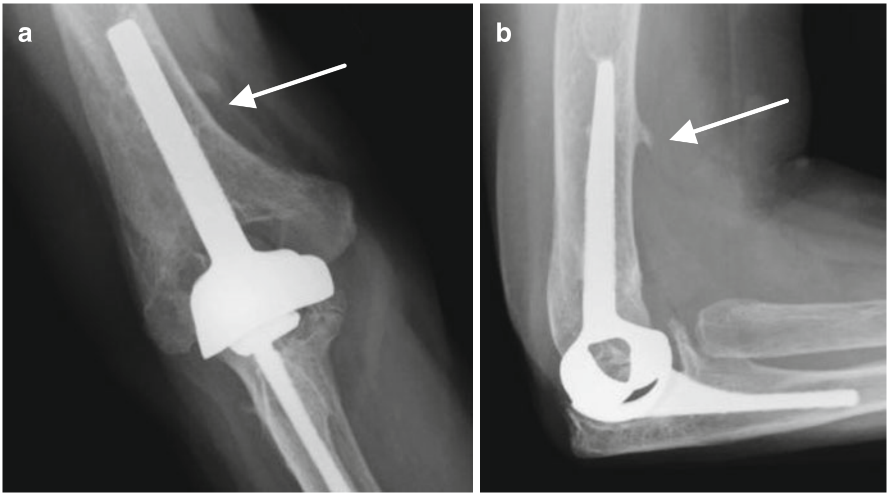

Fig. 20.27 Supracondylar process. (**a**) Frontal and (**b**) lateral radiographs show a supracondylar process (*arrow*) at the anteromedial aspect of the distal humerus diaphysis

with flattening of the nerve between two branches of the pronator muscle, suggesting neuropathy. Comparison with the unaffected side is helpful. Signal abnormalities and atrophy of the pronator teres, the flexor carpi radialis, the palmaris longus, and the flexor digitorum profundus muscle can be seen on MR imaging. A nerve may show an increased signal intensity on T2-weighted images, a well-known hallmark of the neuropathy.

20.8.3 Anterior Interosseous Nerve Syndrome

Anterior interosseous nerve syndrome (AINS), or Kiloh-Nevin syndrome, affects the anterior interosseous nerve (AIN), the motor branch of the median nerve, which supplies the flexor pollicis longus and the second flexor digitorum muscle. Patients with AINS present clinically with a weak pinch between the thumb and index finger and loss of function of the distal phalanx suggestive of flexor tendon rupture. Possible aetiological factors include fibrous bands at the origin of the flexor digitorum superficialis, an anomalous artery, compression by the ulnar head of the pronator teres muscle, accessory muscle, or an enlarged bicipital bursa.

20.8.3.1 Radiologic Imaging of AINS

US shows loss of muscle volume and an increase of echogenicity due to denervation and atrophy of the muscles and a lack of active contraction of the affected muscle (Martinoli et al. 2004). Common MR findings are oedema and atrophy of the affected muscle group.

20.8.4 Ulnar Neuropathy

Ulnar neuropathy results from the narrowing of the cubital tunnel. It has been classified into physiologic seen in sleep palsy and compressive syndrome. Compression includes direct extrinsic compression of the nerve against a shallow condylar groove, bone abnormalities such as cubitus valgus, deformities from previous elbow fractures, osteoarthritis with medial osteophytes and loose bodies, heterotopic ossification, and a variety of space-occupying soft tissue lesions including inflammatory synovitis and thickening of the capsule and accessory anconeus epitrochlearis muscle (Bianchi and Martinoli 2007) (Fig. 20.28).

Clinically semiflexion deformity of the ring and little finger can be seen. Ulnar neuropathy can also be seen secondary in the case of the ulnar nerve instability.

Snapping elbow syndrome can be caused by the torn annular ligament, synovial folds, free intra-articular bodies, snapping of the ulnar nerve from the cubital tunnel, and snapping of the medial head of the triceps muscle. In this condition the dislocation of the muscle is often combined with dislocation of the ulnar nerve.

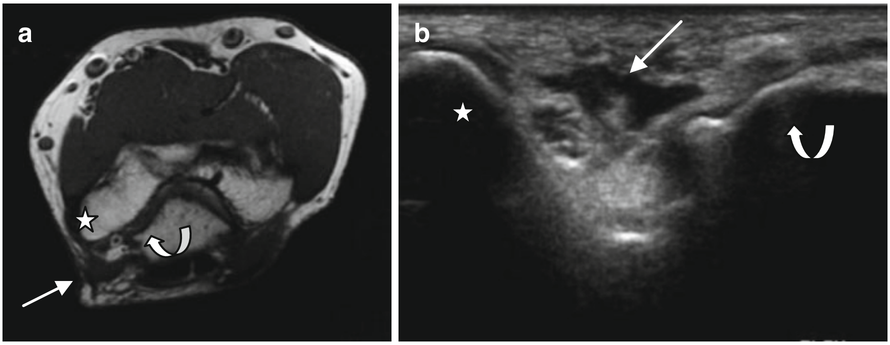

Fig. 20.28 The accessory anconeus epitrochlearis muscle. (**a**) Axial T1-weighted MR image and (**b**) axial 12-5 MHz US image of the cubital tunnel. The retinaculum is replaced by anomalous anconeus epitrochlearis muscle (*arrow*) which connects the medial epicondyle (*asterisk*) and olecranon (*curved arrow*)

20.8.4.1 Radiologic Imaging of Ulnar Neuropathy

Radiographs may show bony changes in the region of the cubital groove. Better visualisation of this region can be achieved by reversed axial projection of the olecranon.

US may show the cause of the entrapment and proximal to the compression thickened nerve, loss of typical fascicular echo pattern, and in some cases hypervascularisation (Fig. 20.29).

The most appropriate imaging for the diagnosis and differential diagnosis of the snapping elbow syndrome is dynamic US imaging during active flexion and extension of the elbow (Jacobson et al. 2001).

Dynamic US during elbow flexion may show partial or complete migration of the ulnar nerve over the medial epicondyle (Jacobson et al. 2001). Dynamic examination should include full flexion of the elbow (Fig. 20.30).

MRI presents increased signal intensity of the nerve on fluid-sensitive sequences and detects other morphologic and anatomic malformations as a cause of the compression (Fig. 20.31).

20.9 Fractures: Classification and Imaging Findings

Regardless of the used classification system for elbow fractures, it is crucial to define the presence and location of all fracture lines, including the intra-articular fractures and the degree of the displacement of the bone fragments, to define the stability and degree of comminution.

Post-traumatic myositis ossificans presents on the radiograph as soft tissue and periosteal calcification as early as 3–4 weeks after the fracture occurred with gradual ossification. Especially dislocations accompanied with soft tissue injury do develop myositis ossificans (Fig. 20.32).

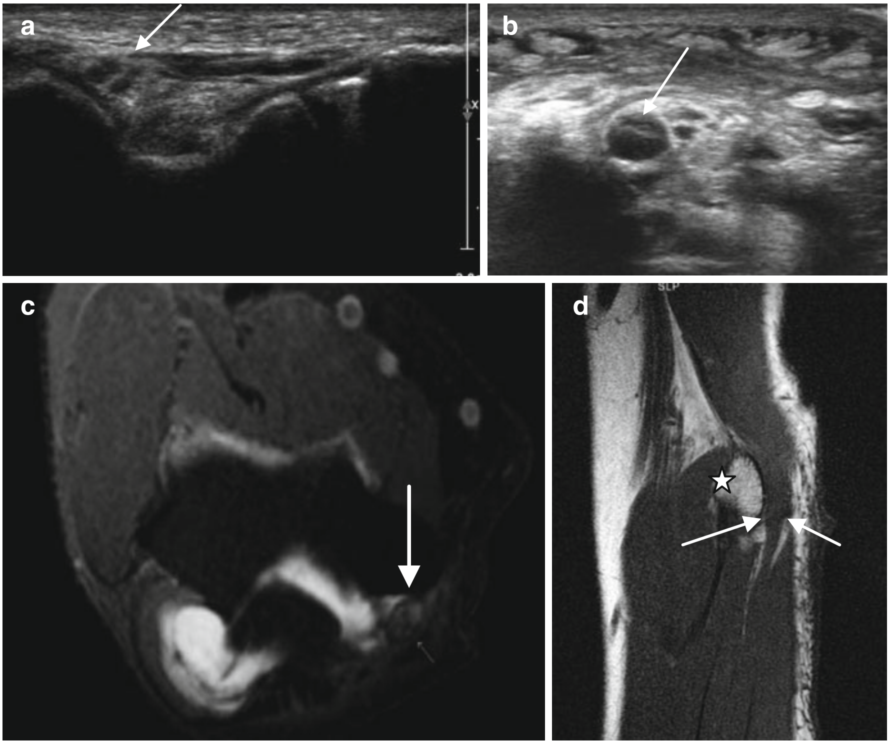

Fig. 20.29 The ulnar nerve. (**a**) Axial 12-7 MHz US of a normal ulnar nerve (*arrow*) with fascicular pattern. (**b**) Thickened ulnar nerve in the case of ulnar neuropathy. (**c**) Proton density-weighted fat-suppressed axial MR image shows abnormal increased signal intensity and thickened ulnar nerve as expression of the neuropathy. (**d**) T1-weighted sagittal MR image of the swollen ulnar nerve (*arrow*) in the cubital tunnel; asterisk, medial epicondyle

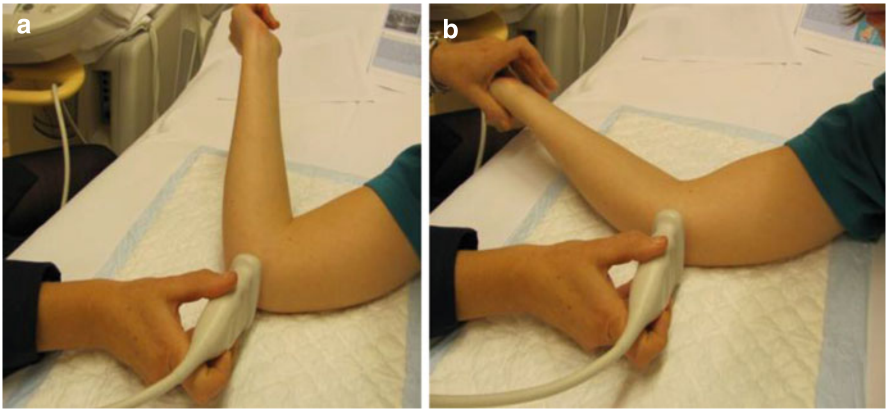

Fig. 20.30 Ulnar nerve instability. (**a**, **b**)_Dynamic scan with flexion and extension of the elbow. (**c**, **d**) Axial 12-5 MHz US of the anterior dislocation of the ulnar nerve (*arrow*) over the margin of the medial epicondyle (*asterisk*) during elbow flexion movement. (**d**) Reposition of the anterior ulnar nerve (*arrow*) during the elbow extension movement

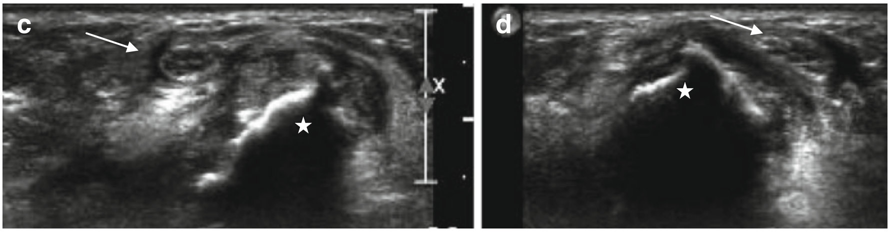

Fig. 20.30 (continued)

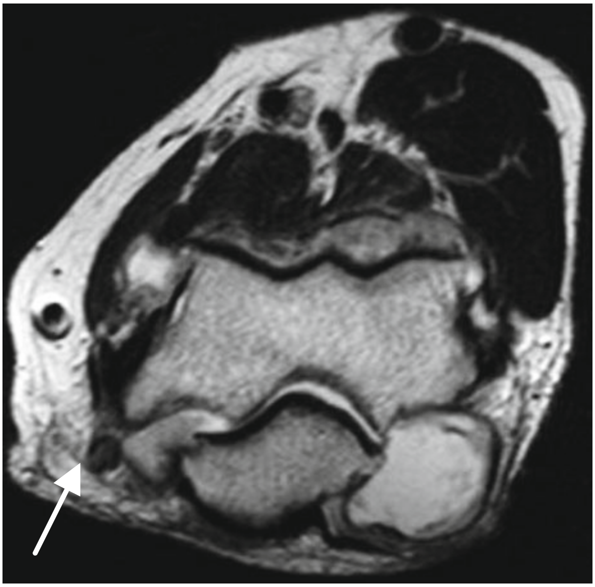

Fig. 20.31 Axial T2-weighted MR image demonstrating subluxation of the ulnar nerve (*arrow*) in a case with hydrops of the elbow

Radiographs in two directions are the first imaging choice. An elevation of the fat pad in the setting of acute trauma indicates a haemarthrosis and suggests a fracture. In some cases additional views such as radiocapitellum view or Coyle trauma view, oblique AP view with internal and external rotation, or reversed olecranon view may be necessary to show the fracture. Coyle elbow trauma or axial lateromedial radiographs are made with the elbow flexed 90° and if possible pronated hand with radiation angle 45° towards the shoulder. CT with multiplanar reformation and three-dimensional volume renderings demonstrates optimally bone structure and morphology of fractures. Both MRI and US play a role in identifying soft tissue injuries around the elbow joint in case of fractures and dislocations. MRI can be used for the assessment of occult elbow fractures and, particularly in the paediatric age group, to determine the type of fracture.

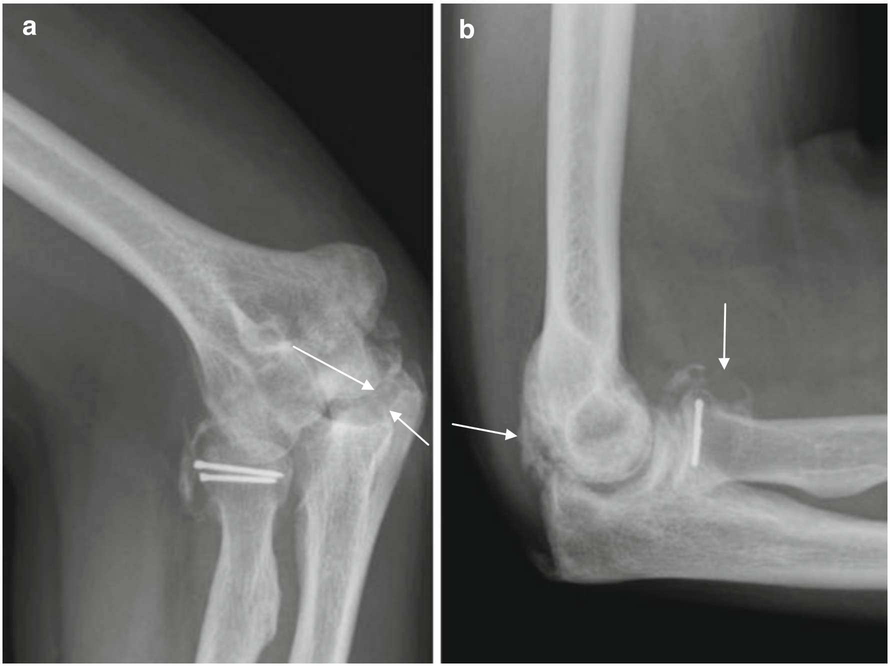

Fig. 20.32 Post-traumatic myositis ossificans with medial collateral ligament instability. (**a**) Anteroposterior radiograph shows mild opening of the medial joint space (*arrows*). (**b**) Lateral radiograph shows myositis ossificans in the capsular region anterior and posterior to the elbow joint (*arrows*)

20.9.1 Supracondylar Fractures

Supracondylar fractures are the most common fractures in the paediatric group and are the result of a fall on an outstretched arm with extended elbow. The Gartland classification is based on the integrity of the posterior humeral cortex (Gartland 1959):

- Type I is non-displaced and is often only present as a fat pad displacement on lateral radiographs. Treatment consists of splinting in 90° flexion.
- Type II is a hyperextension injury with the posterior cortex still intact but radiographically a rotational and hyperextension deformity is detected.
- Type III is a fully displaced fracture, often in posterior direction, with complete cortical disruption.

Both types II and III require operative management. Possible complications are entrapment of the median, ulnar, and radial nerve, including possible stretching of the anterior interosseous nerve and injuries to the brachial artery and vein. MRI identifies these injuries in an early stage. US plays a role in elbow injuries in skeletally immature patients (neonates and children) (Dias et al. 1988).

20.9.2 Intercondylar Fractures

The classification of intercondylar fractures is based on their radiologic assessment (Riseborough and Radin 1969):

- Type I: Non-displaced fracture extending between the capitellum and trochlea
- Type II: Slight displacement with no rotation between the condylar fragments in the frontal plane
- Type III: Displacement with rotation of the fragments
- Type IV: Severe comminution of the articular surface, “bag of bones” fracture

Pure post-treatment result is often related to fixation failure and non-union. Types II and III are treated by open reduction and internal fixation.

20.9.3 Lateral Condylar Fractures

These are the most common physical injuries of the elbow. It typically occurs between the age 2 and 14 and is commonly associated with hyperextension varus trauma. The Rutherford classification is based on displacement (Anderson et al. 1998):

- Type I is characterised by a hinged and stable fracture with intact articular cartilage.
- Type II is characterised by involvement of the articular cartilage with potentially minimal displacement.
- Type III fractures involve the articular cartilage, often with completely rotated fracture fragments.

Both types II and III are unstable. As the intra-articular fragment runs through the cartilage, it is not visible on the radiographs or CT. MRI shows joint effusion, fracture lines, and signal intensity changes of the structures involved (Fig. 20.33).

20.9.4 Medial Condylar Fractures

Hyperextension with valgus stress and a direct blow on the elbow are the main causes of medial condyle injuries.

Isolated medial condyle fractures are not very common. Epiphyseal component of Salter-Harris type III or IV including the trochlea occurs. The status of the ulnar nerve should be assessed as part of the elbow dislocation.

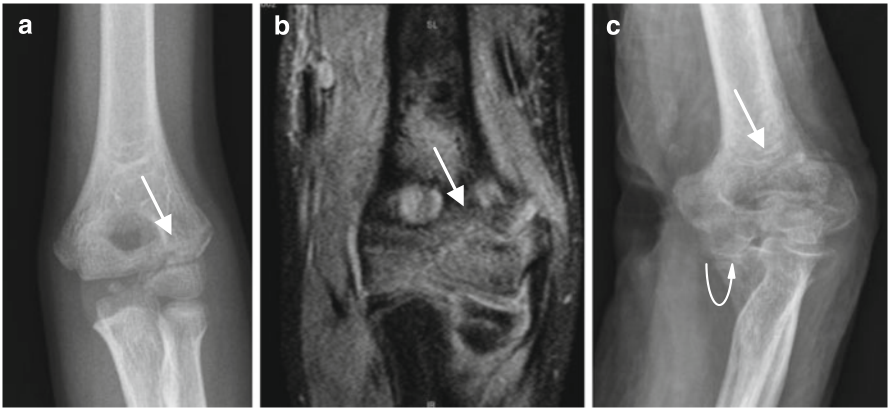

Fig. 20.33 Lateral condylar fracture in two patients. (**a**) Frontal radiograph and (**b**) coronal proton density-weighted fat-suppressed MR image of the minimal displaced fracture (*arrow*). (**c**) Frontal radiograph shows moderate displaced lateral condylar fracture (*arrow*) with laterally subluxed radius and ulna and discongruent joint (*curved arrow*)

20.9.5 Medial Apophysitis and Avulsion Fractures of the Medial Epicondyle

Chronic valgus stress applied to the elbow results in age-dependent changes of the region of the medial elbow such as distraction apophysitis in childhood and epycondylar avulsion in the more adult athlete.

Medial apophysitis, or "Little League elbow", occurs in children at the age of 10 or younger involved in throwing sports such as baseball. Valgus stress causes fragmentation, subchondral bone resorption, or delayed closure of the medial epicondylar apophysis of the non-fused epicondylar ossification centre. Radiographs show fragmentation and separation of the ossification centre. MRI demonstrates an area of separation through the epicondylar region with possible changes in signal intensity in the adjacent bone and apophysis.

Avulsion fractures of the medial epicondyle occur primary in adolescents after medial epicondylar physeal fusion has taken place. It is the result of the force generated by acute valgus stress with simultaneous forearm contraction of the flexor muscle. Woods and Tullos (1977) divide those injuries in:

- Type I – patients under 15 years of age; a large, often rotated fragment with concomitant injury of the UCL
- Type II – patients above 15 years of age; a small fracture fragment with concomitant injury of the common flexor tendon

Displacements over 2 mm require operative fixation (Klingele and Kocher 2002; Ireland and Andrews 1988). As the epicondyle may be pulled distally and may be trapped in the elbow joint, a typical misdiagnosis is loose body or trochlea

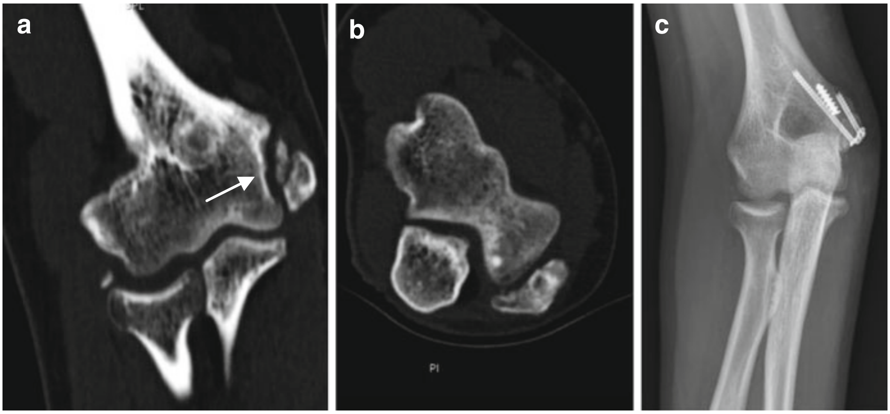

Fig. 20.34 Medial epicondyle avulsion fracture. (**a**) 2D coronal CT reconstruction and (**b**) axial CT image show chronic fracture and fragmentation of the medial epicondyle (*arrow*) with dislocation >than 2 mm. (**c**) Frontal radiograph after open reduction and internal fixation of the fracture

ossification centre. Comparison with the asymptomatic elbow is recommended. In this overuse injury, the role of the MRI also is the evaluation of associated pathology, including radial-sided lesions (osteochondritis dissecans of the capitellum and, respectively, radial head), olecranon apophysitis, and posteromedial impingement (Klingele and Kocher 2002) (Fig. 20.34).

20.9.6 Coronoid Process Fractures

Most coronoid fractures are part of a complex injury with posterior elbow dislocation. Isolated coronoid fractures are the result of a fall on the outstretched hand, with direct coronoid process shear injury on the trochlea. Regan and Morrey's classification of coronoid process fractures is based on the amount of articular surface involved and the resulting instability (Regan and Morrey 1989):

- Type I is a small shear fracture of the tip of the coronoid and is an indirect indicator of injury of the anterior band of the MCL.
- Type II represents fractures involving less than 50 % of the coronoid, which is the minimum required for the stability of the elbow.
- Type III involves more than 50 % of the coronoid resulting in gross ulnohumeral instability related to involvement of the anterior band of the MCL and the annular ligament.

Aside from radiographs, additional information, especially in the case of the comminution, can be gathered by CT (Fig. 20.35).

US and MRI have a specific role in avulsions of the sublime tubercle of the ulna, documented in throwing sports as part of MCL injuries.

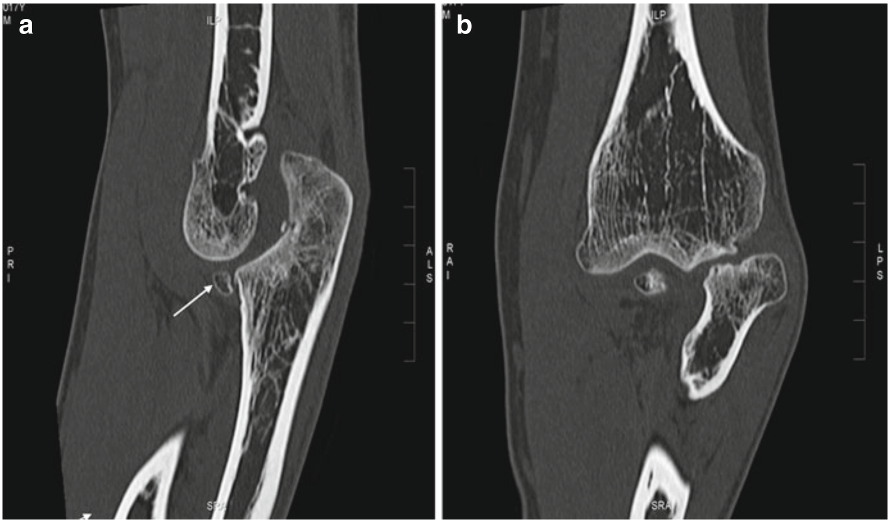

Fig. 20.35 Chronic posterior dislocation of the left elbow. (**a**) 2D sagittal CT reconstruction presents Regan and Morrey type I small shear fracture of the coronoid (*arrow*), indirect sign of collateral ligament injury. (**b**) 2D coronal CT reconstruction shows associated Mason type IV radial head fracture with dislocation

20.9.7 Radial Head Fractures

Radial head fractures are the most common elbow fractures in the adult athlete. The injury can be associated with coronoid fracture and MCL injury resulting in a "terrible triad" injury of the elbow (Blease et al. 1997). Radial head fractures are the result of a fall on the outstretched arm with the forearm in pronation and typically are located at the anterolateral margin of the radial head. Mason classification divides radial head fractures in (Blease et al. 1997):

- Type I with less than 2 mm displacement
- Type II with more than 2 mm displacement
- Type III comminuted
- Type IV fracture with associated elbow dislocation

Next to AP and lateral views, radiographs also include a radiocapitellum view or Coyle trauma view. CT adds additional information in the case of type III and IV fractures (Figs. 20.36 and 20.37).

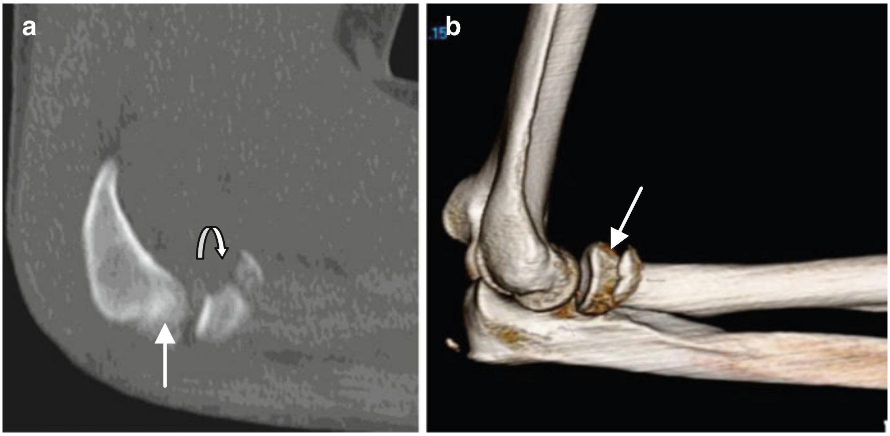

Fig. 20.36 Mason type II displaced radius head fracture. (**a**) 2D sagittal CT reconstruction shows radial fracture fragment displacement over 2 mm (*curved arrow*) with associated type 2 capitellum fracture characterised by a small shell of bone (*arrow*). Instable radius head fracture with avulsion fracture of the capitellum (**b**) 3D CT reconstruction of the radius head fracture (*arrow*)

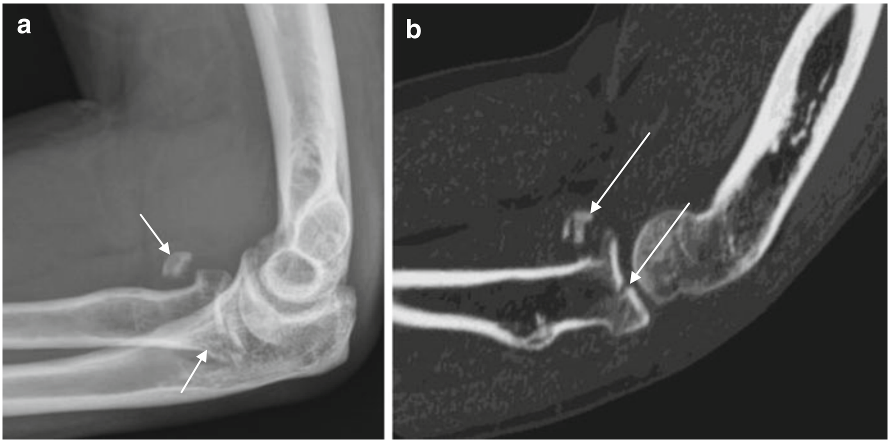

Fig. 20.37 Radial head Mason type III comminuted fracture. (**a**) Lateral radiograph and (**b**) 2D CT sagittal reconstruction reveals comminuted radial head fracture with anterior displacement of the fragment (*arrows*)

MRI assesses soft tissue ligament injuries (MCL and LCLC). A rare but serious complication is the disruption of the interosseous membrane and distal radioulnar joint dislocation – the so-called Essex-Lopresti lesion (Hughes and Chung 2010a). Additional radiographs of the wrist are in this case necessary. Conservative treatment is only for type I fractures indicated.

20.9.8 Olecranon Fractures

Olecranon fractures may be the result of a direct blow on the proximal ulna or of a distraction injury from triceps contractions and avulsions of the olecranon. It is often the result of high-energy injuries and those resulting from minor trauma should raise suspicion about the metabolic status of the bone (Blease et al. 1997). Mayo classification divides olecranon fractures into (McKay and Katarincic 2002):

- Type I – less than 2 mm displacement of the fragments, generally involving the proximal third of the articular surface
- Type II – more than 2 mm displacement, usually involving the middle third of the articular surface
- Type III – displaced, unstable fracture, usually involving the distal third of the articular surface (Fig. 20.38)

Complications are ulnar nerve neuropathy, post-traumatic arthritis, and development of an os supratrochlear dorsale.

20.9.9 Capitellum Fractures

Even though these are rare injuries seen in less than 6 % of elbow fractures, the fracture of the capitellum is the most common pure intra-articular fracture of the elbow. On lateral radiograph joint effusion is seen in combination with displaced fragments of the capitellum above the radial head and coronoid process. The fractured segment is typically rotated with the convex articular contour facing anterior.

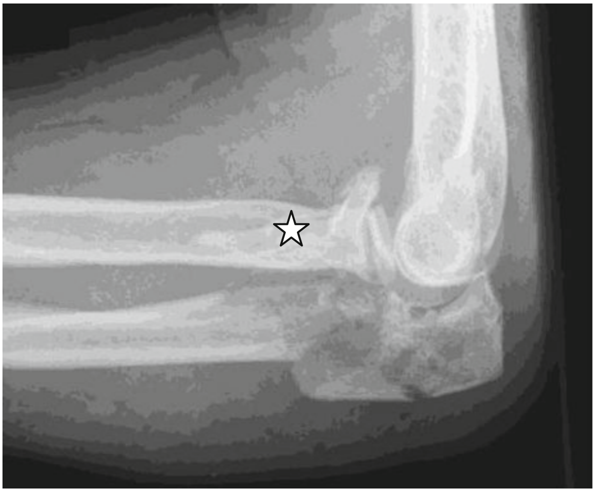

Fig. 20.38 Mayo classification type III olecranon fracture. Comminuted, displaced, unstable fracture of the distal third of the articular surface of the olecranon is associated with fracture and of the radial head (*asterisk*)

20.10 Dislocations

The elbow is the third most common site of dislocations in adults after the shoulder and the interphalangeal joints (Shankum and Liu 2008). They are divided into acute, chronic (unreduced), and habitual dislocations. The classification is based on the position of the radius/ulna in relation to the distal humerus. Most are posterior, of which 90 % are posterolateral (Fig. 20.39). The remaining types are posteromedial, anterior, medial, lateral, and the extremely rare divergent type.

20.11 Osteochondritis Dissecans

Osteochondritis dissecans is a condition associated with separation of a bone fragment together with the overlying cartilage from its mother bone. This condition is typically seen after ossification of the capitellum has occurred in adolescents of 12–16 years of age. The dominant side is usually affected although in 20 % of patients it is bilaterally present. It is most common in pitchers, gymnast, and weightlifters. Most authors believe that the condition is related to repetitive valgus stress and a relatively tenuous blood supply to the capitellum (Bradly and Petrie 2001).

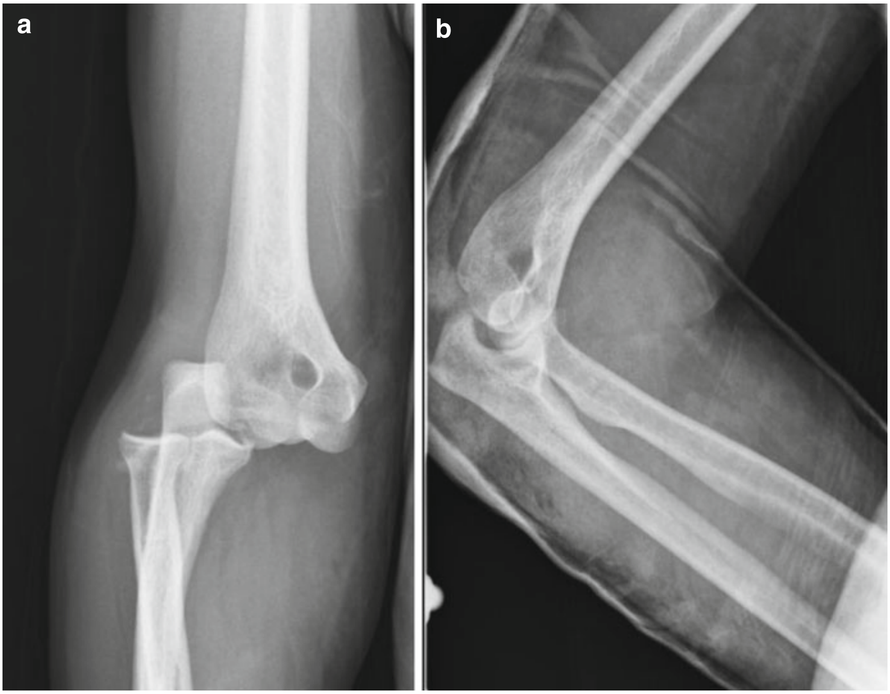

Fig. 20.39 Posterolateral dislocation of the elbow. (**a**) Frontal and (**b**) lateral radiographs showing posterolateral elbow dislocation with fracture of the radial head

20.11.1 Radiologic Imaging of Osteochondritis Dissecans

Radiographs show cortical irregularity, subchondral lucency, flattening of the capitellum, and loose bodies (Fig. 20.40). Secondary elbow degeneration is the result in 50 % of the patients (Bradly and Petrie 2001). US may document the integrity of the cartilage and detect defects of the subchondral bone and the presence of loose bodies (Takahara et al. 1998).

MRI is very sensitive when it comes to disease detection (Takahara et al. 1998) and is often used in disease staging. The main elements of the MRI evaluation are lesion size, stability, viability, and location (Hughes and Chung 2010b).

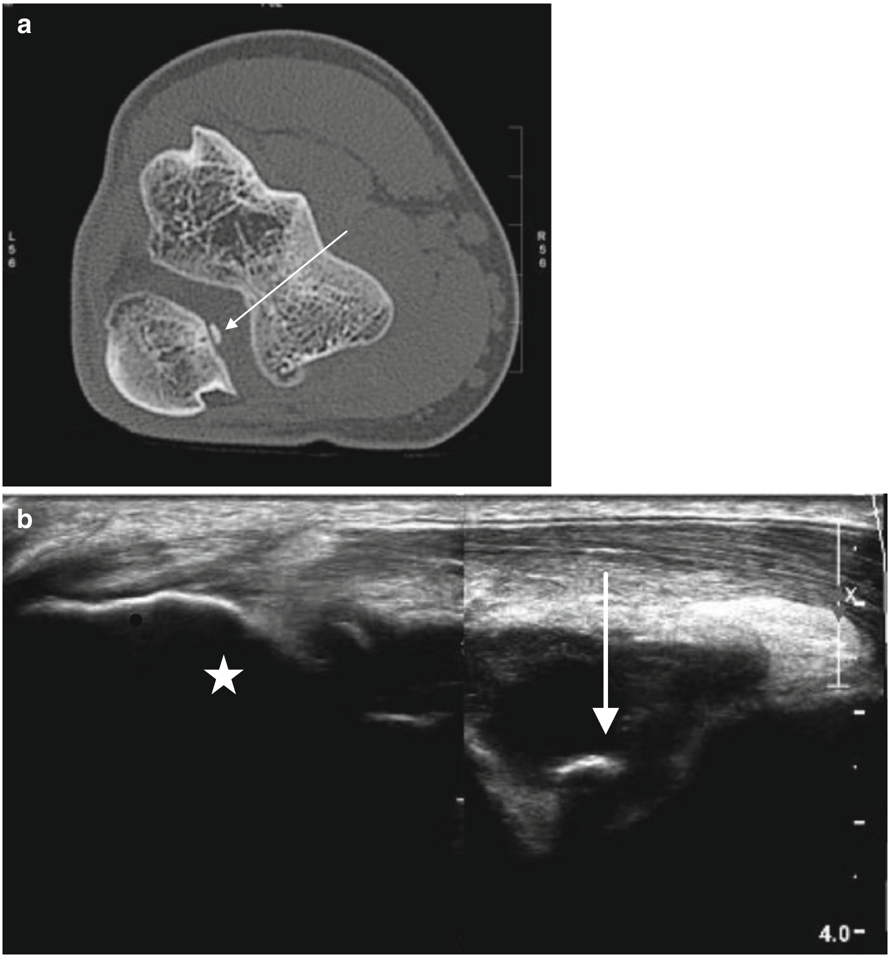

Fig. 20.40 Intra-articular corpora libera. (**a**) Axial CT image of the elbow shows intra-articular corpus liberum (*arrow*) between the olecranon and the humerus. (**b**) 12-5 MHz longitudinal US of the olecranon (*asterisk*) shows corpus liberum posterior to the humerus; hydrops in the joint

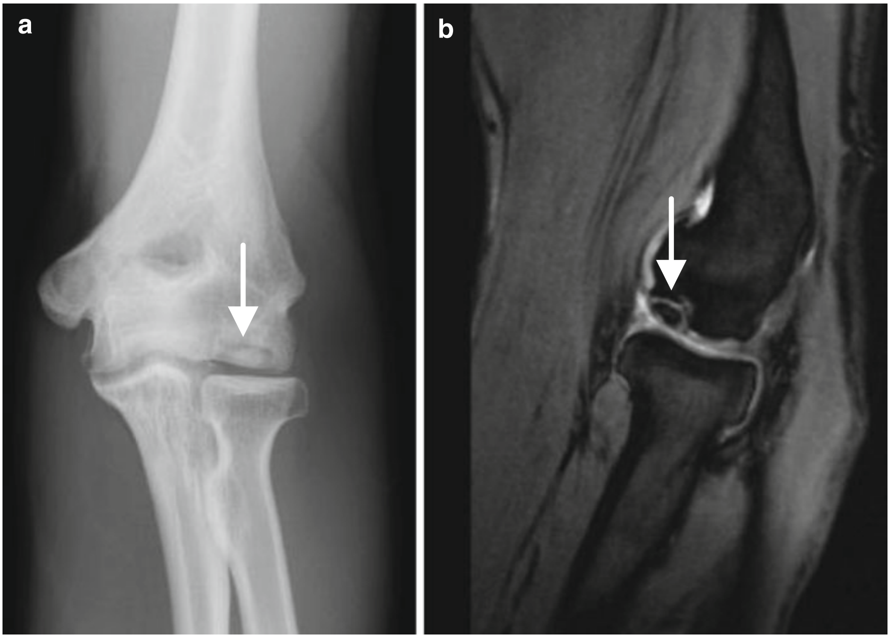

Fig. 20.41 Osteochondritis dissecans of the capitellum. (**a**) Anteroposterior radiograph shows fragmentation of the capitellum (*arrow*). (**b**) T2-weighted gradient MR image shows an in situ osteochondral lesion (*arrow*). A high signal intensity region surrounds the bone fragment suggesting an unstable fragment. MRI without arthrogram is unable to discriminate in situ stable and unstable fragments due to poor discrimination on T2 of granulation tissue and joint fluid

On fluid-sensitive sequences (T2, T2-FS, STIR), unstable lesions are characterised by fluid or intra-articularly injected contrast encircling the osteochondral lesion. The osteochondral fragment can have variable signal intensity depending on the stage of the oedema, necrosis, and sclerosis (Fig. 20.41).

Unstable lesions are often larger than 1 cm. Perilesional cyst-like lesions accompany unstable osteochondral fragments (Bowen et al. 2001). A typical location for osteochondritis dissecans is the anterior aspect of the capitellum and should be differentiated from the capitellar pseudodefect, which is typically located posterolateral and represents the transition of the articular cartilage to the more irregular surface of the lateral epicondyle.

20.12 Chronic Exertional Compartment Syndrome

Chronic exertional compartment syndrome (CECS) of the forearm is an exercise-induced neuromuscular condition that causes pain, swelling, and disability in affected muscles of the arms. It is common in athletes who participate in sports that involve repetitive movements, such as weight-lifters, climbers, motorcyclists, rowers, and swimmers, as well as violinist and piano players. The flexor forearm compartment is

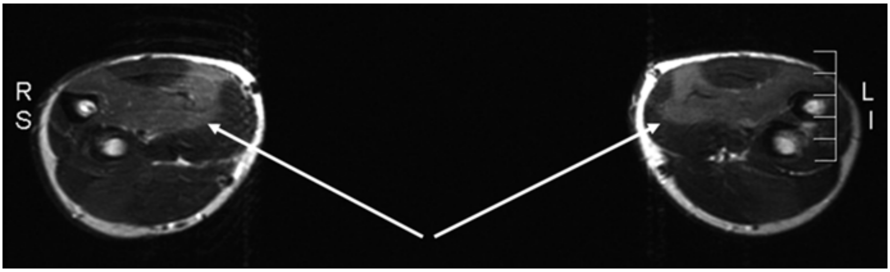

Fig. 20.42 Motor racer with bilateral CECS at the forearm. Bilateral axial T2-WI at the proximal third of the right and left forearm immediately after bilateral eccentric exertion. Marked increased SI at the right and left flexor digitorum superficialis and profundus muscles

usually involved. The syndrome occurs when the interstitial pressure in a closed fascial compartment increases to such a degree that local blood flow is compromised, resulting in tissue ischaemia. In general symptoms disappear within an hour of stopping the activity but recur when exercise resumes. Intracompartmental hydrostatic pressure testing before and after exercise is considered the gold standard for the confirmation of CECS. These measurements must be performed before and during pain-provoking actions and then again after 1 and 5 min of rest. Fasciotomy is the treatment of choice.

20.12.1 Radiologic Imaging of CECS

A non-invasive alternative to hydrostatic pressure measurement in the initial screening for the athletes with dullness and pain in the forearm during exertion is MRI (Gielen et al. 2009). MRI after exercise shows a diffuse increase in signal intensity and increased SNR on T2-weighted sequences in the flexor compartments, specifically in the flexor digitorum superficialis and profundus muscles (Fig. 20.42). If oedema is documented on MRI, a preoperative hydrostatic pressure measurement is recommended. In untrained individuals a minor increase in muscle SI caused by eccentric training is found and may mimic findings in CECS.

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Nuclear Medicine Imaging of Elbow and Forearm Injuries

21

Walter Noordzij and Andor W.J.M. Glaudemans

Contents

Abstract

The elbow is a joint subject to significant mechanical stress. In general, injuries in sports medicine involving the elbow joint can be identified with a patient's history and adequate physical examination. The role of nuclear medicine in elbow and forearm injuries is rather limited. A specific diagnosis can rarely be made on bone scintigraphy solely, mainly due to the complexity of the elbow joint, in which several structures overlap each other in a small area. Only in very specific diagnoses, including (stress) fractures, lateral and medial epicondylalgia, osteochondritis dissecans, and (a)septic loosening of prosthetic implants, nuclear medicine is able to play an additional role in imaging the elbow. A three-phase bone scintigraphy, using a technetium-99m (^{99m}Tc)-labeled diphosphonate complex, is the cornerstone within nuclear medicine imaging and can detect fractures, prosthesis loosening, and inflammation. The exact role of bone scintigraphy in loosening of elbow prostheses is still a matter of debate. For imaging

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infections after elbow arthroplasty, leukocyte scintigraphy in combination with three-phase bone scintigraphy is the nuclear imaging method of choice. However, anti-granulocyte monoclonal antibody imaging has shown good results in elbow prostheses and may be considered to be an adequate alternative in institutions without of the opportunity to label leukocytes ex vivo. This chapter highlights the role of nuclear medicine in injuries of the elbow and the forearm.

21.1 Introduction

The elbow is a joint subject to significant mechanical stress. In general, injuries in sports medicine involving the elbow joint can be identified with a patient's history and adequate physical examination. Acute fractures are usually obvious, with or without conventional radiological images. For other pathologies, the main modality of investigation is plain radiography, CT, and/or MRI as described in the previous chapter. The role of nuclear medicine in elbow and forearm injuries is rather limited and is only (poorly) defined in medial and lateral epicondylalgia and possibly in osteochondritis dissecans of the capitulum (Van der Wall et al. 1999a). A specific diagnosis can rarely be made on bone scintigraphy solely, mainly due to the complexity of the elbow joint, in which several structures overlap each other in a small area (Fig. 21.1). In fact, significant overlap is present in all standard views: the distal humerus over the proximal ulna in anteroposterior view and proximal radius over the proximal ulna in lateral views (Van der Wall et al. 2001). In the past, special projections as the skyline view (elbows flexed to 110° with the posterior humeral aspect placed on the face of the camera) have been proven to minimize overlap by moving the radial head behind the attenuating mass of the capitellum of the humerus (Van der Wall et al. 1999a). The introduction of hybrid SPECT/CT camera systems leads to better anatomic localization due to the exact fusion of scintigraphic images over anatomic CT images. However, SPECT/CT of the elbow can be difficult to perform, since it necessitates a prone position of the patient. This is usually not a problem for young patients but not an ideal position in elderly.

Only in very specific diagnoses, including (stress) fractures, lateral and medial epicondylitis, osteochondritis dissecans, and (a)septic loosening of prosthetic implants, nuclear medicine is able to play an additional role in imaging the elbow. A three-phase bone scintigraphy, using a technetium-99m (^{99m}Tc)-labeled diphosphonate complex, is the cornerstone within nuclear medicine imaging and can detect fractures, prosthesis loosening, and inflammation. The exact role of bone scintigraphy in loosening of elbow prostheses is still a matter of debate. Uptake around the prosthesis can be physiological due to "recent" surgery, up to 2 years after implantation, in accordance with total knee arthroplasty. An additional leukocyte scintigraphy, usually with ^{99m}Tc-labeled hexamethylpropyleneamine oxime (^{99m}Tc-HMPAO), is able to distinguish between no infection, inflammation, or infection (Fig. 21.2). A negative leukocyte scan excludes an infection. This chapter highlights the role of nuclear medicine in injuries of the elbow and the forearm.

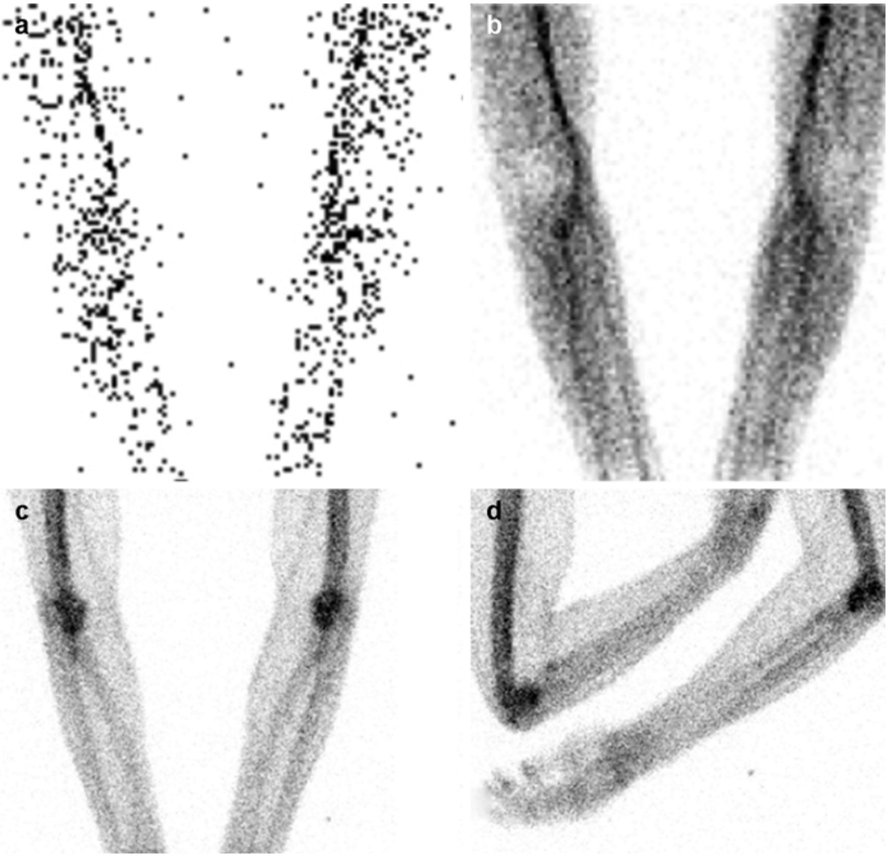

Fig. 21.1 Normal aspect of the elbows on a three-phase bone scintigraphy using ^{99m}Tc-HDP (injection site of the foot). Normal flow (**a**) and blood pool phase (**b**). Normal distribution of bone tracer in the osseous structures of the elbow joint (late images, **c** posterior view, **d** lateral view)

21.2 Lateral and Medial Epicondylalgia

As described in Chap. 19, lateral epicondylitis, also known as lateral epicondylalgia or "tennis elbow," is defined as an overuse injury of the common extensor tendon, which originates from the lateral epicondyle of the humerus. Medial epicondylitis, also known as medial epicondylalgia or golfer's elbow, concerns a (degenerative) tendinopathy of the common tendinous origins of the flexor muscles of the fingers, thumb, and wrist, which is inserted into the medial epicondyle of the humerus (Rineer and Ruch 2009). Also, this epicondylalgia is described in detail in Chap. 19.

These both indications are the most common reasons for making a three-phase bone scintigraphy of the elbow joint. However, only few data are available in literature. In fact, only one large study is published that reported the use of three-phase

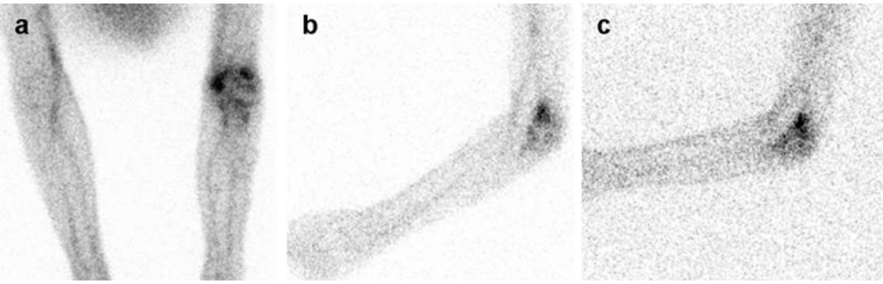

Fig. 21.2 Leukocyte scintigraphy, using ^{99m}Tc-HMPAO-labeled autologous white blood cells, in a patient after a distal humeral fracture on the right side with complaints of functional restrictions. Early (after 3 h) images of the elbow region, posterior view (**a**) and lateral view (**b**), showing abnormal uptake in the proximal part of the right elbow. Late image (**c**, after 24 h), lateral view showing persisting increased uptake at the right elbow. The ratio of abnormal uptake to the contralateral normal side increases, indicating an active infection, in this case, osteomyelitis

bone scintigraphy in patients with chronic epicondylalgia, with poor response to or failure of traditional conservative treatment (Pienimäki et al. 2008). In this study, 59 patients with unilateral chronic epicondylalgia underwent history and pain questionnaires, physical examination including manual testing, and bone scintigraphy using 550 MBq ^{99m}Tc-labeled hydroxy methane diphosphonate (^{99m}Tc-HDP). A semiquantitative method was used to determine the ratio between the uptake in the affected epicondyle and the ipsilateral humerus, as well as in the unaffected healthy epicondyle and the humerus.

Flow (perfusion) and blood pool images, available in 52 and 54 patients, respectively, were abnormal in 7 (13 %) and 12 (22 %) patients and indicate increased soft tissue uptake suggested to be a consequence of vasodilatation due to chronic prolonged inflammation. Tracer uptake on late static images was categorized as low, slightly elevated, moderately elevated (15 patients in all three categories), and high (14 patients). At the affected epicondyles, tracer uptake was significantly higher compared to the corresponding healthy epicondyle: epicondyle-to-humerus ratio was 33 % ($p<0.001$) higher in men and 17 % ($p=0.007$) in women. However, in men, the uptake in the affected epicondyle was higher than in women. High bone tracer uptake was present in 14 patients and was associated with significantly better reported work ability, better function of the arm, and less muscle tenderness. Therefore, the authors concluded that high tracer uptake might reflect a regenerative healing process of epicondylitis. Furthermore, they concluded that bone uptake might enable subclassification of patients with epicondylitis, which could be of value in designing treatment interventions for this highly prevalent disorder.

In general daily practice, three-phase bone scintigraphy in epicondylalgia is mainly used to confirm or exclude this diagnosis when the referring clinician is in doubt about the diagnosis. Three phase bone scan may help in localizing the site and severity. Depending on severity of inflammatory response, increased uptake may be seen both on early and late phases (Patel 1998). A statement on prognosis is regularly not reported.

21.3 Other Elbow and Forearm Injuries

Other elbow and forearm injuries are mentioned only in case reports or small case series and sometimes even not. The following contains an overview of the role of nuclear medicine in these different diagnoses.

Olecranon bursitis may show positive flow and blood pool images on the bone scan due to inflammation of the bursa but is not supposed to give positive results on the late images, since those images only reflect bone metabolism. On FDG-PET, however, it is sometimes seen as an occasional finding in patients. Uptake of FDG around the elbow joint may indicate that the patient suffers from bursitis.

One report describes the use of three-phase bone scintigraphy in diagnosing *triceps tendinopathy* in amateur weight lifters (Van der Wall et al. 1999b). Twelve patients with different upper arm complaints after weight lifting underwent three-phase bone scintigraphy using 850–900 MBq ^{99m}Tc-MDP. Two patients were reported to have triceps tendinopathy, one patient bilaterally. In both patients, it was different from the clinical diagnosis, by history and physical examination. One patient, a male runner, was clinically diagnosed with tendinopathy of the supraspinatus muscle; the other patient, a female tennis player, was suspected of having synovitis of the elbow. This report showed that nuclear medicine is able to play a diagnostic role in confirming clinically suspected injuries of the elbow and, additionally, detect unsuspected disease.

Posterior impingement is an uncommon disorder in the general population, however, not in athletes with repetitive stretching of the elbow. CT can be used to evaluate the posterior compartment for osteophytes. MRI with intra-articular contrast is even more sensitive, with sensitivity reported for posterior soft tissue or loose bodies nearly 90 % (Eygendaal and Safran 2006). Bone scintigraphy – with SPECT-CT – will also be able to visualize these osteophytes and may be helpful to determine viability of the loose fragment. This technique was found useful for localizing and characterizing impingement syndrome and soft tissue pathology in the ankle and foot region (Chicklore et al. 2012). Literature studies that describe the use of nuclear medicine imaging techniques in posterior impingement of the elbow are not available.

Osteochondritis dissecans (OD) typically affects the humeral capitellum of the dominant elbow in athletes engaged in repetitive overhead or upper extremity weight-bearing activities. As mentioned before, MRI is the gold-standard imaging technique since it shows osteochondral lesions of the capitellum at an earlier stage, is more accurate in showing the presence of loose bodies, and appears to be more valuable in determining the stability and viability of the OD fragment (Van der Ende et al. 2011). Reports mentioning the use of bone scintigraphy for OD are scarce and mostly older publications (Hall and Galea 1999; Van der Wall et al. 1999a; Woodward and Bianco 1975). However, bone scintigraphy could be of use for this indication, since it may show positive results in all three phases. SPECT imaging and correlation with CT may show high accuracy for viability of loose fragments.

Stress injuries to the medial elbow are well documented. Magnetic resonance imaging is the modality of choice. The role of nuclear medicine, especially bone scintigraphy, is limited to the situation in which conventional imaging is not able to identify a lesion. However, bone scintigraphy can be of value since injured or degenerative medial collateral ligaments may show calcifications (Mirowitz and London 1992). A stress lesion to the proximal medial ulna, in the region of the medial collateral ligament, seen on a three-phase bone scan was reported once (Mamanee et al. 2000). This 14-year-old baseball player (pitcher) suffered from increasing pain in his right medial elbow since three months. After a short period of rest, the complaints disappeared, and he was able to pitch with no symptoms.

Stress fractures in throwers are generally located proximal to the elbow, whereas weight lifters usually suffer from stress fractures distal to the elbow. Bone scintigraphy is able to visualize fractures in these patients when conventional imaging is indecisive (Sinha et al. 1999).

Little leaguer's elbow is described as an apophysitis of the medial epicondyle in young athletes, due to repetitive valgus stress of the elbow (Cassas and Cassettari-Wayhs 2006; Shanley and Thigpen 2013). The diagnosis is made primarily clinically and should be considered in throwers with medial elbow pain. Plain radiograph imaging will suffice, however, may also be normal. MRI provides additional detail and is considered to be a helpful tool as well (Benjamin and Briner 2005). So far, no reports of nuclear medicine modalities are available for this specific indication.

Nuclear medicine modalities are regularly not performed in patients suspected of an *acute and chronic forearm compartment syndrome*. No reports are available which discuss the diagnostic value for these indications. One case report mentions uptake of ^{99m}Tc-labeled methylene diphosphonate (MDP) in the forearm due to an acute compartment syndrome (Gerard et al. 2008). Initially, the bone scan in this patient was performed to detect osseous metastases in a patient with bladder cancer. The compartment syndrome was caused by infiltration of high-volume intravenous contrast, administered during a CT scan the day before.

21.4 Elbow Arthroplasty

Rheumatoid arthritis is the leading cause of prosthetic implantation in the elbow. The elbow can also be affected in other inflammatory arthropathies, as primary degenerative osteoarthritis, crystalline arthropathy, and hemophilia. The indications have expanded to include posttraumatic injuries as comminuted distal humerus fractures and instability. After placement of a total elbow arthroplasty (TEA), the elbow is splinted in extension for 24–36 h. Thereafter, active range of motion exercise begins. Patients are encouraged to move the elbow through a range of motion and participate in activities of daily living. Sports activities such as golf and tennis are not allowed anymore after TEA. In fact, persistence of these activities is a contraindication for surgery (Bernadino 2010).

In concordance to other arthroplasties, the most often reported complications are loosening (Fig. 21.3), periprosthetic fracture, infection, and ulnar nerve complications (Kim et al. 2011; Voloshin et al. 2011). Complications of TEAs, especially (a) septic loosening, are reported with an incidence around 1–5 % (Little et al. 2005b).

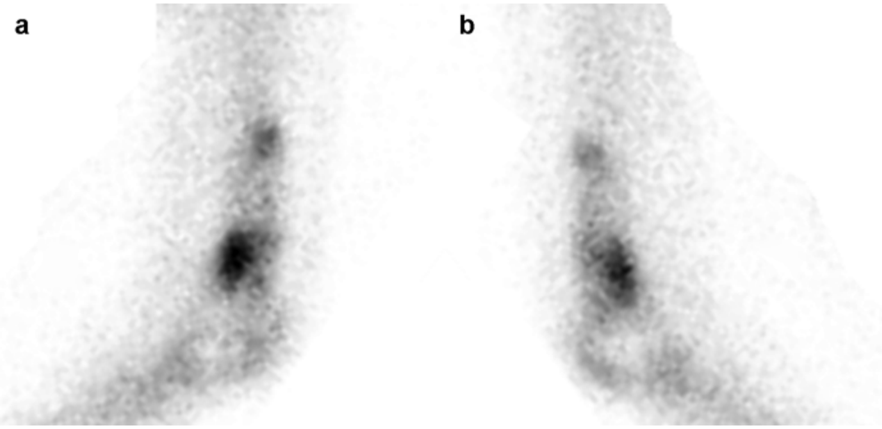

Fig. 21.3 Left lateral (**a**) and right lateral view (**b**) of an elbow arthroplasty in a patient with destructive rheumatoid arthritis, visualized with ^{99m}Tc-HDP. The distribution of uptake indicates loosening of the humeral part of the prosthesis

Long-term survival of elbow implants in patients with rheumatoid arthritis approaches that of total knee arthroplasty (Van der Lugt and Rozing 2004; Little et al. 2005a).

Nuclear medicine imaging modalities are able to distinguish septic prosthesis loosening from aseptic loosening. The differentiation is very important, since the surgical management of aseptic loosening is a single-step procedure, but infection may require multiple admissions. Conventional serum tests as increased leukocytes, C-reactive protein, and erythrocyte sediment rate are neither sensitive nor specific for infection. Also, plain radiographs are not sensitive and specific. The best test characteristics are derived from the combined use of three-phase bone scintigraphy followed by leukocyte scintigraphy, with or without bone marrow imaging (Love et al. 2009). Therefore, at present, this combination is the method of choice.

As alternative to the leukocyte scintigraphy, in which leukocytes are obtained from a blood sample and labeled ex vivo, ^{99m}Tc-labeled anti-granulocyte monoclonal antibodies (e.g., sulesomab) were introduced to diagnose prosthetic joint infections (Harwood et al. 1994). The exact mechanism of imaging infection with these antibodies is still unclear. The rationale was the direct binding of these antibodies to granulocytes. However, the majority of the antibodies concentrate in an infected area through nonspecific leakage as a result of increased permeability. This modality has also been used in elbow prostheses (Iyengar and Vinjamuri 2005). In this study, 38 patients with the suspicion of an infected prosthesis were investigated by scintigraphic imaging with ^{99m}Tc-sulesomab (LeukoScan®). In four of these patients, a TEA was placed earlier. All patients also underwent serum testing, radiographs, three-phase bone scintigraphy, microbiology/histology, and supportive imaging (CT, MRI, and/or ultrasound). A true positive finding on ^{99m}Tc-Sulesomab scintigraphy was defined as abnormal uptake correlated or confirmed by microbiology/histology and supportive imaging. Three TEAs were found true positive infected, and one was true negative. So, the authors concluded that this modality had an accuracy of 100 % in diagnosing infected TEA. This modality may be a good alternative to leukocyte scintigraphy, especially for hospitals without the opportunity to label leukocytes ex vivo.

Positron emission tomography using fluorine-18-labeled fluorodeoxyglucose (^{18}F-FDG-PET) has the potential to detect infections in hip and knee prostheses (Zhuang et al. 2007). However, uptake around the neck of the prosthesis may be due to a noninfectious reaction after surgery and influence the specificity of the diagnosis (Glaudemans and Signore 2010). This nonspecific FDG uptake can be seen until 20 years after prosthesis placement. Therefore, ^{18}F-FDG-PET, either with or without additional CT, should not be routinely performed for the assessment of infected arthroplasties in a clinical setting until the criteria for differentiation between septic and aseptic loosening are more defined (Signore and Glaudemans 2011).

Despite this limitations, there is increasing interest in the use of ^{18}F-FDG-PET(/CT) for infected prostheses. Its use in TEA is described in one case report (Harisankar et al. 2010). This 35-year-old female patient suffered from pain in the right elbow since one month, occuring one year after placement of the TEA. Conventional radiographs were within normal limits. She was referred for an ^{18}F-FDG-PET/CT to exclude infection of the prosthesis. The authors reported slightly elevated FDG uptake around the distal humeral part of the prosthesis, without obvious uptake in the interface between bone and prosthesis. According to the low uptake and the location, the authors concluded an aseptic loosening of the TEA, without evidence for infection. Gram staining and cultures of joint aspiration were performed and were negative for infection. In retrospect, the uptake could also indicate a reactive origin, moreover, because this patient was treated conservatively.

So, in conclusion, bone and leukocyte scintigraphy may play an additional role in (a)septic TEA loosening, when conventional imaging is unable to confirm the diagnosis. At this moment, ^{18}F-FDG-PET/CT should not be performed routinely for this indication until the criteria for interpretation are better defined.

Conclusions

The use of nuclear medicine modalities for imaging elbow and forearm injuries is limited. Three-phase bone scintigraphy may be used to identify medial and lateral epicondylitis, stress reactions, and fractures, especially when conventional imaging is inconclusive. The introduction of hybrid cameras (SPECT-CT) leads to better diagnostic accuracy. This technique may show added value in osteochondritis dissecans, posterior impingement syndrome, and avulsion fractures. At the moment, literature studies for these indications are scarce. Large prospective studies, comparing conventional imaging methods with SPECT-CT, are worth to perform and may show surprising results.

For imaging infections after elbow arthroplasty, leukocyte scintigraphy in combination with three-phase bone scintigraphy is the nuclear imaging method of choice. However, anti-granulocyte monoclonal antibody imaging has shown good results in elbow prostheses and may be considered to be an adequate alternative in institutions without the opportunity to label leukocytes ex vivo. At the moment, ^{18}F-FDG-PET/CT should not be performed routinely for this indication until the criteria for interpretation are better defined.

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Part VII

The Musculoskeletal System Topographically: Wrist, Hand, and Fingers

Injuries of Wrist, Hand and Fingers

22

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Abstract

Sports injuries of the hand and wrist are common. Wrist injuries occur mostly due to a fall on the outstretched hand. Distal radius fractures and scaphoid fractures are the most frequently seen fractures of the wrist. Ligament injuries of the wrist may not always be that obvious at first sight, but may lead to serious secondary consequences, such as carpal collapse and osteoarthritis. Next to acute injuries, overuse injuries are also frequently encountered. Overuse injuries mainly affect tendons and nerves, such as in M. de Quervain, the intersection syndrome, carpal tunnel syndrome or the cyclist's wrist.

Injuries to the hand comprise fractures, dislocations, contusions, sprains and overuse injuries. In this chapter, fractures such as the boxer's fracture, PIP joint injuries, injuries to the thumb such as the skier's thumb and pulley injuries are described. A thorough evaluation of the injury mechanism and a systematic clinical examination are the keys to successful treatment and return to sporting activities.

Abbreviations

APL	Abductor pollicis longus
CMCJ	Carpometacarpal joint
DIPJ	Distal interphalangeal joint
DISI	Distal intercalated segment instability
DRUJ	Distal radioulnar joint
ECRB	Extensor carpi radialis brevis
ECRL	Extensor carpi radialis longus
ECU	Extensor carpi ulnaris
EPB	Extensor pollicis brevis
EPL	Extensor pollicis longus
FCR	Flexor carpi radialis
FCU	Flexor carpi ulnaris
FDP	Flexor digitorum profundus
FDS	Flexor digitorum superficialis
FPL	Flexor pollicis longus
IPJ	Interphalangeal joint
MCPJ	Metacarpophalangeal joint
PIPJ	Proximal interphalangeal joint

PL	Palmaris longus
PQ	Pronator quadratus
PT	Pronator teres
TFCC	Triangular fibrocartilaginous complex
UCL	Ulnar collateral ligament

22.1 Introduction and Epidemiology

Hand and wrist injuries in sports are frequently reported. Three to 9 % of all athletic injuries involve the hand and wrist (Rettig 2003). Sytema et al. analysed over 25,000 sports injury cases attending at an emergency department and found that the upper extremity holds a substantial part (35 %) in sports injuries (Sytema et al. 2010). Furthermore, they revealed that nearly 70 % of upper limb injuries occurred to the hand or wrist (Sytema et al. 2010). Most upper extremity injuries are caused by a fall or by getting struck by a ball. Sports with a high risk on sustaining upper extremity injuries due to falling are horse riding, speed skating, (inline) skating, skiing, snowboarding and school sports. Ball sports cause less upper limb than lower limb injuries, but the number of hand injuries due to getting struck by a ball is still substantial (17 % of all upper limb sports injuries). Compared to lower extremity, the upper extremity contains a very high fracture rate, especially in adolescents and children (Sytema et al. 2010; Conn et al. 2003; Cuddihy and Hurley 1990; Court-Brown et al. 2008; Flood and Mina 1985; Wood et al. 2010). Fractures, sprains and contusions most frequently occur, followed by wounds and dislocations (Sytema et al. 2010). Forty percent of all sports-related upper limb fractures are located in carpus, metacarpus or fingers (Court-Brown et al. 2008). Males are more affected than females (Sytema et al. 2010; Wood et al. 2010). Although nearly 90 % of the world population is right-handed, this is not reflected in the side of the athletes' injured upper extremity, since there is an equal distribution of left- and right-sided injuries (Sytema et al. 2010). Many injuries are sports specific, such as Guyon's canal syndrome in cyclists, the intersection syndrome in rowers, fractures of the hook of the hamate in golf, tennis or baseball or distal physeal injuries in gymnasts.

Not only acute injuries to the hand and wrist but also overuse syndromes are quite common. Such syndromes are mostly encountered in racquet sports, rowing, volleyball, handball and gymnastics (Rettig 2004). Of all sports injuries, it is estimated that 25–50 % are caused by overuse (Rettig 2004).

22.2 Functional Anatomy

22.2.1 Anatomy of Hand and Wrist (ASSH 2001)

Bones, Joints and Ligaments The skeleton of the hand and wrist consists of 27 bones. These bones are located in the carpus, metacarpus and phalanges. From the radial to the ulnar side, the carpus consists of a proximal row of four bones (scaphoid, lunate, triquetrum and pisiform) and a distal row of four bones (trapezium, trapezoid, capitate and hamate). The metacarpus consists of five bones, and the thumb contains two phalanges, whereas the remaining fingers consist of three phalanges.

The stability of the wrist is provided by ligaments connecting radius, ulna and carpus. The most important wrist stabilisers at the radial side are the scapholunate ligament, the radioscaphocapitate ligament and the radioscapholunate ligaments. The TFCC combined with the ulnolunate ligament and the ulnar collateral ligament stabilise the ulnar side of the wrist. The stability of the metacarpophalangeal (MCP) joint and the interphalangeal (IP) joints is provided by collateral ligaments and, on the volar side, by fibrocartilaginous volar plates.

Muscles The muscles of hand and wrist can be divided into extrinsic and intrinsic muscles. The extrinsic muscles have their origins outside the hand and their insertions within the hand, whereas the intrinsic muscles have their origins and insertions within the hand. The tendons of the extrinsic extensors are arranged in six tendon compartments over the dorsum of the wrist. The flexor tendons enter the hand at the carpal tunnel. At the level of the MCP joint and more distally, the flexors lie anterior to the volar plates and are surrounded by the flexor tendon sheath. The flexor tendon sheath is thickened by annular and cruciate fibres, the so-called pulleys, which act as stabilisers for the flexor tendons. The pulleys also facilitate tendon excursion and provide for nutrition. The intrinsic muscles consist of the thenar and hypothenar groups and the lumbrical and interosseous muscles.

Nerves The hand is innervated by the radial, median and ulnar nerves.

The radial nerve is innervating the muscles that extend the wrist and MCP joints and that abduct and extend the thumb. The sensory branches innervate the dorsum of the hand and thumb, except for the ulnar side of the hand. The posterior interosseous nerve innervates the dorsal wrist capsule.

The median nerve innervates part of the flexors of the wrist (pronator teres (PT), pronator quadratus (PQ), m. flexor carpi radialis (FCR), m. palmaris longus (PL), m. flexor pollicis longus (FPL), m. flexor digitorum superficialis (FDS) and the radial part of the m. flexor digitorum profundus (FDP)). The median nerve enters the hand through the carpal tunnel. The motor branch innervates various muscles of the thenar and the lumbrical muscles of the second and third ray. The sensory branches of the median nerve innervate the volar side of the palm, thumb, index finger, long finger and radial side of the ring finger. The anterior interosseous nerve is a branch of the median nerve and innervates the volar wrist capsule.

The ulnar nerve innervates the remaining flexors of the hand and wrist (m. flexor carpi ulnaris (FCU)) and the ulnar part of the FDP. The ulnar nerve accompanies the ulnar artery when entering the wrist through Guyon's canal. This tunnel is located radial to the pisiform bone and ulnar to the hook of the hamate. The ulnar nerve also

innervates the thenar muscles, the ulnar part of the lumbrical muscles, the interosseous muscles and the adductor muscle of the thumb. Distal from Guyon's canal, the sensory branches innervate the volar and dorsal sides of the small finger and the ulnar part of the ring finger.
Vessels The blood supply of the hand is provided by the radial and ulnar arteries through an arterial arch system.

22.2.2 Clinical Examination of Hand and Wrist (ASSH 2001)

Clinical examination of the hand and wrist starts with exposure of the entire upper extremity. The active and passive shoulder and elbow motion should be examined. These proximal joints are essential in positioning of the hand. Always compare the affected hand with the contralateral side.

Further physical examination of the hand and wrist consists of inspection, the active and passive range of joint motion, muscle testing, palpation, evaluation of the cutaneous sensibility and evaluation of the arterial circulation.
Inspection When inspecting the hand, one should observe abnormal posture or position, colour, skin moisture, swelling and oedema, scars, skin lesions, abnormalities of the nails and muscle atrophy.
Active and Passive Range of Joint Motion The active range of motion of the wrist, thumb and fingers should be measured using a goniometer. The usual way to note joint mobility is extension-neutral-flexion and radial deviation-neutral-ulnar deviation. Wrist movements are flexion, extension, ulnar and radial deviation, pronation and supination. Flexion and extension as well as radial and ulnar deviation result from radiocarpal and intercarpal motion. Pronation and supination occur through the proximal and distal radioulnar joints. The MCP movements are flexion, (hyper)extension, abduction and adduction. The thumb movements are flexion and (hyper)extension, abduction and adduction and opposition or combinations of these movements. IP movements are flexion and (hyper)extension.
Muscle Testing Extrinsic as well as intrinsic muscles should be systematically evaluated; its strength should be graded and recorded.
Palpation Most tendons of hand and wrist are palpable, especially when they are examined against resistance. The bones and joints of the hand are easy to palpate. Palpation of the wrist is somewhat more complicated, although the styloid processes of the ulna and the radius are easy to palpate on the lateral aspects of the wrist. Lister's tubercle, also called tuberculum dorsale, is the most apparent dorsal prominence of the radius. The lunate is located just distally from Lister's tubercle, and the capitate is positioned proximally from the lunate. The scaphoid is palpable on the floor of the anatomic snuff box, which is formed by the tendons of the m. extensor pollicis longus (EPL, ulnar side)

and the m. abductor pollicis longus (APL) and m. extensor pollicis brevis (EPB, radial side).

Neurological Evaluation: Cutaneous Sensibility Sensibility can be evaluated by static and moving two-point touch discrimination or the Semmes-Weinstein Aesthesiometer monofilament testing (SWMT) set (Jerosch-Herold 2003; Bell-Krotoski et al. 1993). The SWMT testing set includes 20 monofilaments of different thicknesses. When a monofilament buckles on the skin, a predefined force is applied. The starting filament is the 2.83 filament, which reflects normal sensibility. If that filament is sensed, a thinner filament is tested, and if not, a thicker filament is tested. Low cutaneous sensibility is related to the thicker monofilaments of the SMWT testing set.

Circulation The circulation of the hand is evaluated by examining the colour of the skin and nails and testing the capillary refill. To test the patency of the radial and ulnar arteries, the Allen test can be performed: The examiner occludes the radial artery for several minutes and compares the hand colour to the other hand. If there is sufficient collateral circulation through the ulnar artery, no change in colour should be observed. The procedure can be repeated by occluding the ulnar artery.

22.3 Bone Injuries of the Wrist

22.3.1 Distal Radius Fractures

Distal radius fractures are common sports injuries (Court-Brown et al. 2008; Chen et al. 2009). The mechanism of injury is mostly a fall on the outstretched hand, which might be sustained during hockey, soccer, gymnastics, snowboarding, badminton, ice-skating or in-line skating (Court-Brown et al. 2008; Chen et al. 2009). There are various types of distal radius fractures, which need different therapeutical approaches. Physical examination reveals swelling of the wrist, possible deformities, pain and tenderness at the distal part of the radius and restricted range of motion. Distal radius fractures may be accompanied by other injuries, such as carpal fractures, ligament injuries of the carpus or of the distal radioulnar joint or injuries at the elbow region.

22.3.2 Scaphoid Fractures

Scaphoid fractures are the most common fractures (60–70 %) among carpal bone fractures (Rettig 1998a, b; Steinberg 2002). Basketball, hockey, field hockey, soccer, boxing, cycling and skating are the sports with the highest risk for scaphoid fractures. The injury mechanism is a fall with the wrist in hyperextension and ulnar deviation (Green and Strickland 1994). Clinical features are pain with extension and swelling in the anatomic snuffbox or at the tuberositas of the scaphoid at the volar side. The diagnosis of an acute scaphoid fracture is sometimes difficult due to the fact that initial radiographs may not show the fracture. All contact-sport athletes who have radial wrist pain should be considered to have a scaphoid fracture until proven otherwise (Rettig 2003). Frequently encountered complications in scaphoid fracture healing are malunion, nonunion or avascular necrosis. Fracture consolidation depends on the stability and localisation of the fracture. Instable fractures show slower consolidation than stable fractures. Fractures in the distal part of the scaphoid consolidate faster than in the more proximal parts. Nonunion or malunion of the scaphoid may lead to dorsal intercalated segment instability (DISI deformity) of the lunate. DISI deformities may result in osteoarthritis, which is painful and causes deterioration of wrist function. Nonunion may lead to scaphoid nonunion advanced collapse (SNAC-wrist), which is also a cause of posttraumatic osteoarthritis.

22.3.3 Lunate Fractures and Kienböck's Disease

Fractures of the lunate are uncommon, nearly 1–6.5 % of all carpal fractures occur in the lunate. The fracture is mostly the result of a fall on the outstretched hand, whereby the lunate is compressed between the distal radius and the capitate. Five fracture types are described: fractures in the volar or dorsal pole, chip fractures and transversal and sagittal fractures (Teisen and Hjarbaek 1988; Dana et al. 2010).

There does not seem to be a direct relation between lunate fractures and avascular necrosis of the lunate (Kienböck's disease). However, repetitive trauma may lead to microfractures which may affect the vascularisation. Such traumata are related to handball, volleyball, golf, gymnastics or boxing.

Mostly, Kienböck's disease is seen in adults 20–40 years of age, who do not have a trauma in their medical history. They present with mild to severe pain at the dorsum of the wrist, swelling, deterioration of wrist mobility and less power grip. Kienböck's disease may be bilateral. The precise aetiology remains uncertain, although different patterns of arterial vascularisation, disruption of venous outflow, a relatively short ulna (ulna minus) and a decreased radial inclination in combination with a small lunate have been mentioned as risk factors for Kienböck's disease (Lutsky and Beredjiklian 2012). Radiographic studies are necessary to diagnose Kienböck's disease.

22.3.4 Hook of Hamate Fractures

Fractures of the hook of the hamate are rare, 0.2–5 % of all carpal fractures (Rettig 2003; Teisen and Hjarbaek 1988). Such fractures are mostly seen in racquet sports, such as tennis, or in golf or baseball. The injury mechanism can be a fall, a direct trauma or striking of balls when using racquets, bats or clubs. Patients present with ulnar wrist pain. Physical examination shows pain when palpating the hypothenar distal to the pisiform and a painful grip. Chronic fractures have been associated with ruptures of the flexor tendons of the ring and little fingers and ulnar nerve neuropathy since the hook of the hamate makes up the radial wall of Guyon's canal (Green and Strickland 1994).

22.3.5 Pisiform Fractures

Pisiform fractures are uncommon (less than 1 % of all carpal fractures) and result from direct trauma to the volar ulnar aspect of the wrist (Lichtman and Alexander 1997). Often, pisiform fractures occur in combination with other injuries, such as distal radius, hamate and triquetrum fractures or dislocations. Pisiform fractures may be transverse, longitudinal or comminuted. Patients suffer from pain, swelling and tenderness in the proximal hypothenar. Damage of the ulnar nerve or ulnar artery may occur, since the pisiform makes up the ulnar wall of Guyon's canal (Lichtman and Alexander 1997). The pisiform can undergo chondral changes from overuse, leading to pisotriquetral osteoarthritis (Rettig 2003).

22.3.6 Triquetrum Fractures

Up to 14 % of all carpal fractures are located in the triquetrum (Green and Strickland 1994; Lichtman and Alexander 1997). In the majority of cases, a dorsal chip fracture is diagnosed. The mechanism of injury is an impaction of the dorsal part of the triquetrum against the ulnar styloid when falling on the outstretched hand with the wrist in ulnar deviation. A fracture of the body of the triquetrum is rare, and mostly the result of a high-energy trauma. Such fractures are associated with perilunate dislocations. Physical examination reveals painful dorsiflexion and ulnar deviation and pain when palpating the dorso-ulnar side of the wrist.

22.3.7 Capitate Fractures

Fractures of the capitate (1–2 % of all carpal fractures) can result from a direct blow to the dorsum of the wrist or from dorsiflexion of the wrist. A direct trauma to the heads of the second and third metacarpal in palmar flexion of the wrist may also lead to a capitate fracture. Fractures can be isolated or associated with a perilunate dislocation. Due to a delicate blood supply, avascular necrosis and nonunion of the proximal pole occur rather frequently, especially in proximal pole fractures (Lichtman and Alexander 1997). The patient has pain on the dorsum of the wrist, with swelling at the base of the third or fourth ray.

22.3.8 Trapezium and Trapezoid Fractures

Trapezium fractures account for 3–5 % of all carpal fractures. Two main fracture types are distinguished: a split fracture with subluxation of the first metacarpal and a fracture of the trapezial ridge (base or tip) (Lichtman and Alexander 1997). The injury mechanism is a fall on a hyperextended wrist in radial deviation. The trapezium gets compressed between the radial styloid and the first metacarpal or the first metacarpal compresses the trapezium in such a way that it splits. The fracture of the body is associated with ligament injuries, mostly of the thumb. The patient presents with pain and tenderness of the base of the thumb. Pain is elicited by resisted wrist flexion. The trapezoid has a protected position in the wrist, and as such, fractures hardly occur.

22.4 Ligament Injuries of the Wrist

22.4.1 Scapholunate Dissociation

The scapholunate ligaments are important stabilisers of the wrist. Three ligaments are involved in scapholunate instability: the interosseous scapholunate ligament, the dorsal scapholunate ligament and the volar radioscapholunate ligament (Green and Strickland 1994). Disruptions may be partial, which leads to dynamic instability, or they may be complete, which leads to static deformities. The mechanism of injury is a fall on an outstretched hand, which may occur in several collision or contact sports (Rettig 2003). Pain, swelling over the dorsoradial aspect of the wrist and limited joint mobility are the clinical features. The *scaphoid shift test (Watson's test)* may be positive, especially in chronic cases: the examiner's thumb is placed over the palmar aspect of the distal pole of the scaphoid. A constant pressure is maintained. The wrist is moved from extension-ulnar deviation to flexion-radial deviation. At the end of the radial deviation, the compression at the scaphoid is diminished. A positive test reveals dorsal pain or a clunk. In acute cases, the wrist is mostly too painful to perform the Watson's test. The dissociation of the scapholunate ligaments results in flexion of the scaphoid and extension of the lunate and triquetrum. A DISI pattern occurs (Rettig 2003). If untreated, a scapholunate dissociation may lead to advanced collapse and osteoarthritis of the wrist.

22.4.2 Lunotriquetral and Triquetrohamate Injuries

The lunotriquetral ligament is much thinner than the scapholunate ligament, but not as frequently involved in sports injuries. Triquetrohamate instability is the most common ulnar instability. In both occasions, a fall on the outstretched hand is the mechanism of injury. Patients complain about ulnar pain and sometimes a clunk is audible or palpable. In LT dissociations, the *lunotriquetral shear manoeuvre (Reagan's test)* may be positive: the examiner stabilises the lunate between the thumb and the index finger of one hand and the triquetrum between thumb and index finger of the other hand. Both bones are mobilised in an anteroposterior plane and any discomfort of the patient is observed.

22.4.3 TFCC Lesions and Distal Radioulnar Joint Instability

The TFCC is an important stabiliser of the ulnar side of the wrist, especially of the distal radioulnar joint. The TFCC consists of a central, avascular disc, dorsal and volar radioulnar ligaments and volar ulnocarpal ligaments. The latter connect the TFCC and ulnar styloid with lunate and triquetrum. The ECU subsheath and the ulnar collateral ligament (UCL) are also parts of the TFCC (Rettig 2003). TFCC lesions may be the result of acute trauma or repetitive use, such as racquet sports, golf, boxing, waterskiing or gymnastics. TFC tears can be classified as either traumatic (class 1) or degenerative (class 2) (Palmer 1989; Friedman and Palmer 1991). The traumatic class consists of four subclassifications based on the location of the tear. The tear may be central or peripheral. Peripheral tears may cause distal radioulnar joint (DRUJ) instability. The degenerative group consists of five subclassifications based on the magnitude of the tear and the severity of concomitant chondromalacia or osteoarthritis (Lichtman and Alexander 1997; Sachar 2012). The degenerative TFC tears are often associated with the ulnocarpal impaction syndrome, which is a result of a relative overlength of the ulna, the so-called ulnar-positive variance (Sachar 2012). Patients complain about ulnar-sided wrist pain. Palpation reveals pain in the soft spot between the ulnar styloid, FCU, volar surface of the ulnar head and pisiform. *The TFC stress te*st may be useful to reveal ulnar pathology: The examiner holds the forearm of the patient with one hand. With his other hand, he grasps the hand of the patient on the metacarpal level. The wrist is ulnarly deviated and pronated and axial compression is performed. The test is positive when there is pain, clicks or crepitance.

DRUJ instability can be assessed with the piano key test, although the diagnostic value is doubtful (Wijffels et al. 2012).

Piano Key Test The examiner holds the distal radius with one hand and takes the ulnar head between the thumb and the index finger of his other hand. To check freedom of motion in the anteroposterior plane, excessive motion, pain and crepitus are evaluated. The patient can also be asked to push the pronated hand on a table. Instable DRUJ will produce pain and increased ulna mobility when compared to the opposite side (Sachar 2012). Clinical features are pain at the dorsoulnar side of the wrist and restricted pronation and supination.

22.4.4 Carpal Dislocation

A high-energy trauma due to collision or contact sports may lead to carpal dislocation or perilunate dislocation. Such a dislocation is the result of the disruption of the scapholunate and lunotriquetral ligaments, radial collateral ligament failure and disruption of the capito-lunate articulation (Rettig 2003; Chen et al. 2009). Swelling and deformity can be seen, but may be limited. Paraesthesias or numbness in the distribution of the median nerve may be present, as compression of the median nerve is a frequent complication of the injury.

22.5 Overuse Syndromes of the Wrist

22.5.1 De Quervain's Syndrome

The most common tenosynovitis of the wrist in athletes is De Quervain's disease. It is a disorder of the first dorsal compartment tendons, the APL and the EPB. The tenosynovitis occurs as a result of microtraumata due to repetitive gliding of these tendons beneath the sheath of the first dorsal compartment over the radial styloid (Rettig 2004). Activities that require a forceful grip, with the wrist in ulnar deviation, predispose for this disorder. Sports involved are badminton, squash, rowing, fly fishing, volleyball and golf. Clinical features are pain and swelling over the first dorsal compartment. *Finkelstein's test* is considered pathognomonic in making the diagnosis: Flexion of the thumb and ulnar deviation of the wrist produces pain in the first dorsal compartment (Green and Strickland 1994).

22.5.2 Intersection Syndrome

The intersection syndrome is characterised by pain, crepitus and swelling of the dorsoradial side of the wrist, about 6 cm proximal from Lister's tubercle. Pain can be elicited by frequent flexion and extension of the wrist against resistance. The intersection syndrome is located at the crossing point of the APL and EPB muscles with the extensor carpi radialis brevis and longus (ECRB and ECRL) tendons. The syndrome is frequently seen in oarsmen, racquet sporters and weight lifters. If crepitus is found, the term squeakers syndrome is also used (Rettig 2004; Green and Strickland 1994).

22.5.3 Tendinopathy of the FCR and FCU

Chronic repetitive trauma may cause tendinopathy of the FCR or FCU. FCU tendinopathy is more common than FCR tendinopathy. Patients complain about pain and tenderness over the tendons, increasing with passive dorsiflexion or resisted palmar flexion. FCU and FCR tendinopathy have been reported in golf and racquet sports.

22.5.4 Tendinopathy of the Extensor Carpi Ulnaris (ECU) and ECU Subluxation

ECU tendinopathy is quite common among oarsmen and tennis players. Especially tennis players with a two-handed backhand suffer from ECU tendinopathy in the nondominant hand (Rettig 2004), since an excessive ulnar deviation is needed to produce a two-handed backhand. If the ulnar septum of the sixth dorsal compartment is ruptured or attenuated, the ECU tendon may subluxate, mainly when the wrist is supinated. The patient then experiences a painful snap over the dorsoulnar side of the wrist. ECU subluxation has been reported in tennis players, golfers and weight lifters (Rettig 2004; Green and Strickland 1994).

22.5.5 Radial Epiphyseal Injury: The Gymnast's Wrist

Gymnasts frequently use their wrists to bear their body weight, which may lead to distal radial epiphyseal injuries (Frush and Lindenfeld 2009). The growth plate is most vulnerable to injury during the adolescent growth spurt. Physical features are a gradual onset of wrist pain, which gets worse during weight-bearing activities, while the wrist is in extension, as in tumbling, vaulting or back walkovers (Wijffels et al. 2012). Patients complain about wrist pain that deteriorates with repetitive hyperextension and axial forces on the wrist. Mostly, a normal range of motion can be found with slight swelling of the distal radius and diminished grip force (Webb and Rettig 2008). Pain can be found over the distal radius during palpation.

22.5.6 Median Nerve Entrapment: Carpal Tunnel Syndrome

The carpal tunnel syndrome, compression of the median nerve, is the most frequently seen entrapment neuropathy in sports. It is seen in archery, wheelchair basketball, bicycling, bodybuilding or weightlifting, football, golf and wrestling (Toth et al. 2005). A carpal tunnel syndrome can also be associated with acute trauma, such as a distal radius fracture. Clinical features are paraesthesias or numbness in the first three rays of the hand, mainly at the volar side. Patients may have nocturnal pain. *Phalen's test* may be positive: The patient holds his forearms vertically and allows both hands to drop into complete flexion at the wrist for about one minute. This manoeuvre may cause numbness and paraesthesias in case of a carpal tunnel syndrome. *Tinel's test* can also be applied: Percussion of the median nerve at the carpal tunnel may cause paraesthesias.

22.5.7 Ulnar Nerve Entrapment: Cyclist's Wrist

Entrapment of the ulnar nerve in Guyon's canal leads to paraesthesia or numbness in the fourth and fifth finger. Cyclists are at risk for this disorder, due to compression of the ulnar nerve when holding the handlebars. The disorder is called the cyclist's wrist or handlebar palsy. The entrapment can also be seen in other sports with frequent compression at the ulnar side of the palm, such as basketball (wheelchair), weightlifting, football, cross-country skiing or snowmobiling (Toth et al. 2005). The deep motor branch as well as the superficial sensory branch may be affected. When the motor branch is involved, atrophy of the interosseous and adductor pollicis muscles may be present. In the latter case, Froment's sign may be positive: The patient is unable to hold a piece of paper between an extended and adducted thumb and index finger. *Tinel's sign* can be also positive: Percussion of the ulnar nerve at Guyon's canal may cause paraesthesias.

22.6 Injuries of the Hand

22.6.1 Fractures

Distal phalangeal fractures are mostly the result of crush injuries and are often associated with nail or nail bed injuries. Direct trauma may cause fractures of the middle phalanges, mainly resulting in transverse or comminuted fractures. Deviating forces exerted on a flexed finger may lead to unstable, spiral fractures of the proximal phalanges or the metacarpals (Rettig 2004). Since sports injuries are mostly low-energy injuries, the majority of fractures is stable. In case of unstable fractures, complications are rotation deformities or clawing of the digit.

The most common fracture to the carpometacarpal joint (CMCJ) of the thumb is the Bennett's fracture, which is an intra-articular fracture of the base of the first metacarpal with dislocation of the CMCJ. One third of all fractures to the first metacarpal concern a Bennett's fracture (Brownlie and Anderson 2011). The injury mechanism is a fall on an outstretched hand or the hitting of a jaw or helmet of an opposing player with a flexed and adducted thumb (Brownlie and Anderson 2011). The patient presents with pain at the base of the thumb, restricted range of motion of the first ray and diminished grip force.

A second common fracture is the boxer's fracture, which is a fracture of the neck of the fifth metacarpal. Such fractures are associated with punch or closed fist injuries. Young males of 15–24 of age are affected in more than 90 % of the cases (Jeanmonod et al. 2011).

22.6.2 PIP Joint Injuries

In sports, the PIPJ is the most frequently injured joint (Rettig 2004). PIPJ injuries include volar plate injuries, collateral ligament injuries, dislocations and intra-articular fractures. Due to axial loading and hyperextension forces, for example, in ball sports, the collateral ligaments of the PIPJ are commonly injured. Most injuries are of minor severity.

PIPJ dislocations may be volar, dorsal or lateral. The volar plate ruptures from its distal attachment, and in some cases, there is also an avulsion fracture of the middle phalanx. The injury mechanism is also axial loading and hyperextension, mostly during ball-contact sports, such as basketball, baseball or volleyball. The term 'coach's finger' is referred to as a PIPJ injury that was treated by the coach, but appeared to lead to a stiff painful finger after a while, due to underestimation of the severity and complexity of the injury (McCue et al. 1974).

22.6.3 Extensor Tendon Injury: Mallet Finger or Baseball Finger

A mallet finger is a rupture of the extensor tendon at its insertion on the distal phalanx. Such injuries are referred to as baseball finger or drop finger. The injury may occur if the extended fingertip is struck by a ball, such as in basketball, baseball or volleyball. The mallet finger concerns only the extensor tendon or may be associated with bony avulsion of the distal phalanx. Several types of mallet fingers are distinguished (Scalcione et al. 2012). The patient has pain at the distal phalanx, and there is a flexion deformity at the DIP joint. Improper treatment may lead to extensor lag, since 1 mm of lengthening of the terminal tendon may lead to an extension lag at the DIP joint of 25° (Scalcione et al. 2012).

22.6.4 Flexor Digitorum Profundus Injury: Jersey Finger

In football or rugby, the player may grasp the jersey or the pants of his opponent in such a way that the finger is forcibly extended while the FDP contracts. An avulsion injury of the FDP from its insertion on the distal phalanx may occur. Such injury is referred to as a jersey finger (Rettig 2004). A second injury mechanism is catching a finger on the rim of the goal while dunking a basketball (Green and Strickland 1994). The ring finger is involved in 75 % of the cases (Rettig 2004). Patients are unable to flex the DIP joint of the affected finger. Clinical examination should distinguish the flexion function of the FDP from the FDS. The FDP function can be tested by stabilising the PIPJ by the examiner, while the patient actively tries to flex the DIPJ.

22.6.5 Ulnar Collateral Ligament Injury: Skier's Thumb

The skier's or gamekeeper's thumb results from an UCL injury of the metacarpal joint of the thumb. This may occur from a direct radial force on the abducted thumb, such as in skiing, football, basketball or other contact sports (Rettig 2004). It is important to distinguish partial from complete ruptures of the UCL. Complete ruptures may be complicated by a Stener's lesion, which is an indication for surgery. A Stener's lesion is caused by herniation of the distal part of the UCL through the adductor aponeurosis.

Patients present with pain over the ulnar aspect of the MCPJ of the thumb. Pinch grip is often painful, and with palpation, a painful mass may be felt proximal to the adductor aponeurosis in a Stener's lesion (Anderson 2010). Examination of the UCL consists of applying a valgus force with the thumb in 30° of flexion. If there is more than 30° laxity, or 15° more laxity than on the noninjured side, rupture of the UCL is likely. This procedure should be repeated with the thumb examined in full extension to assess a possible rupture of the accessory collateral ligament.

22.6.6 Pulley Lesions

Pulley injuries are seen in rock climbers, since they exert a substantial force to the pulley system. Most climbers report an acute onset due to a hard grip or an unexpected slipping off of their feet (Schoffl et al. 2003). Patients experience pain, swelling and tenderness with gripping, especially hook gripping (Scalcione et al. 2012), at the level of the proximal or middle phalanges. Bow stringing of the flexor tendons and loss of flexion function may occur. The crimping finger position (DIP and MCP joints in extension and PIP joints in flexion) is especially responsible for pulley injuries (Schoffl et al. 2003). In this position, the FDP is maximally contracted and generates a large force on the A2 and A4 pulleys.

Conclusions

Sports injuries of the hand and wrist are frequently seen. Not only acute sports injuries but also chronic injuries due to overuse or repetitive movements need attention of medical professionals. Although most injuries described in this chapter can also be caused by other trauma mechanisms than sports, a lot of sports are related to specific injuries. It is therefore not a coincidence that many injuries of hand and wrist have received sport-related names, such as skier's thumb, basketball finger, boxer's fracture, cyclist's wrist or gymnast's wrist. Specific knowledge about trauma mechanisms within high-risk sports and the way sports are executed is necessary for a proper diagnosis, treatment and advice on preventive measures.

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Radiologic Imaging of Wrist, Hand, and Finger Injuries

23

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Abstract

Acute and overuse injuries to the wrist and hand occur with a higher frequency in specific sports utilizing the hand and wrist. Wrist lesions may sometimes be difficult to diagnose on physical examination. Proper clinical and radiological diagnosis of injuries in this region requires a thorough knowledge of the anatomy and biomechanics of the wrist. Knowledge of the sports activity aids in the diagnosis of these injuries as sporting activities may be associated with specific injury patterns. Important acute injuries that should not to be missed are any type of carpal dislocation especially lunate and perilunate dislocation. Special considerations are made in preadolescent and adolescent athletes, as hand and wrist injuries are more common in these age groups compared to adults.

Fractures are primarily examined radiographically; complex intra-articular fracture components are evaluated with multiplanar or cone beam CT. Despite the fact that nondisplaced fractures are a radiological challenge and occult fractures are frequent, radiography remains the first imaging modality in the initial evaluation and follow-up. If clinically suspected, additional examinations are mandatory, whether repeated radiographs after 1 week of immobilization, or bone scintigraphy, or MRI. Because of its sensitivity, specificity, absence of radiation exposure, and lower cost, MRI is the imaging modality of choice over nuclear imaging techniques for depiction of radiographic occult fractures. Multislice CT or cone beam CT with its high spatial resolution and multiplanar two-dimensional reconstructions in three orthogonal imaging planes improves visualization and characterization of the fracture line and the amount of displacement and angulation of the fracture fragments or staging. AVN is studied with contrast-enhanced MRI. Stress fractures are lately recognized on radiographs related to endosteal spongious callus with bandlike increased bone density. On MRI they are early and easily demonstrated. On MRI, the presence of edema without a visible fracture line may represent a bone bruise or a stress reaction recognized as forestage of stress fracture.

About 10 % of carpal injuries result in instability. Clinical findings are often nonspecific. Imaging is important as diagnosis of a significant injury will dictate treatment. Wrist instability most commonly results from ligamentous disruption

between bones of the proximal carpal row. The presence or absence of carpal instability on radiographs depends on the association between intrinsic and extrinsic ligament tears – even partial ones – rather than on the presence of intrinsic ligament tears alone, even when the tears are complete. An instability pattern in the radiocarpal or midcarpal joint with carpal dissociation is called carpal instability dissociative (CID); carpal instability without carpal dissociation is known as carpal instability nondissociative (CIND).

Imaging evaluation of patients with ulnar-sided wrist pain is mandatory because of its broad clinical differential diagnosis comprising DRUJ, TFCC, LT, and ECU lesions, pisotriquetral instability, ulnoradial impingement, and ulnocarpal impaction-abutment. Radiographs demonstrate the variance of the ulna, distal radioulnar joint dislocations, and signs of chronic ulnar impaction-abutment syndrome related to ulna majus or ulnoradial impingement related to ulna minus. TFCC evaluation is done with MRI.

Overuse tendon injuries are more frequent compared to acute tendon lesions. Inflammation of tendon sheaths is the most frequent abnormality found on US of the wrist. Ultrasound or MRI is only indicated in chronic recidivism. Tendon rupture and its severity can also be detected on US.

Peripheral nerve injuries of the upper extremity in sports are rarely reported; however, they can be most debilitating to an athlete. Peripheral nerves are prone to various types of injury in sport owing to their superficial location. Most commonly, direct blows or repetitive microtrauma is implicated as a mechanism of injury. Hypothenar hammer syndrome (HHS) is related to repetitive trauma of the ulnar-volar aspect of the wrist. Doppler ultrasound along is an accurate noninvasive test to determine the presence, size, and extent of HHS. Bicyclists develop ulnar nerve impingement at Guyon's canal.

Abbreviations

AP	Anteroposterior
AVN	Avascular necrosis
CID	Carpal instability dissociative
CIND	Carpal instability nondissociative
CMC(J)	Carpometacarpal joint
CT	Computerized tomography
CTA	Computerized tomography combined with arthrography
DIP	Distal interphalangeal joint
DRU(J)	Distal radioulnar (joint)
DTPA	Diethylene triamine pentaacetic acid
ECR	Extensor carpi radialis (brevis and/or longus)
EPL	Extensor pollicis longus
FCR	Flexor carpi radialis
FCU	Flexor carpi ulnaris
FOOSH	Fall onto the outstretched hand

FS	Fat saturation
GE	Gradient echo
HHS	Hypothenar hammer syndrome
IP	Interphalangeal
LT	Lunotriquetral ligament
MCI	Midcarpal instability
MCP	Metacarpophalangeal
MHz	Megahertz
MRA	Magnetic resonance imaging combined with arthrography
MRI	Magnetic resonance imaging
MTU	Musculotendinous unit
N Med	Median nerve
OA	Osteoarthritis
PA	Posteroanterior
PD	Proton density
PIN	Posterior interosseous nerve, deep branch of the radial nerve
PIP	Proximal interphalangeal joint
PL	Palmaris longus
RC	Radiocarpal
RLT	Radiolunotriquetral ligament (volar)
ROM	Range of motion
RSC	Radioscapholunate ligament (volar)
SE	Spin echo
SI	Signal intensity
SL	Scapholunate ligament
SLAC	Scapholunate advanced collapse
STIR	Short tau inversion recovery
STT	Scapho-trapezio-trapezoid
T	Tesla
TFC(C)	Triangular fibrocartilage (fibrocartilaginous complex)
TSE	Turbo spin echo
WI	Weighted imaging

23.1 Introduction and Epidemiology

Injuries to the wrist and hand occur with a frequency between 3 and 9 % (Geissler 2001). This injury incidence is higher in specific sports utilizing the hand and wrist, resulting in an increased potential for trauma. Acute and overuse trauma to the wrist may cause bone or soft tissue lesions, which may sometimes be difficult to diagnose. Pain, limited joint function, and swelling are usual complaints. Physical examination may be difficult due to the multiple small bony and soft tissue structures involved. Proper diagnosis of injuries in this region requires a thorough knowledge of the anatomy and biomechanics of the wrist (Halikis and

Taleisnik 1996). Sporting activities may be associated with specific injury patterns related to the associated actions and stresses. Knowledge of the sports activity therefore aids in the diagnosis of these injuries. Early diagnosis of the injury and proper referral of these patients can help prevent complications, including prolonged pain and discomfort, surgery, and lost time from sports participation. Failure to diagnose sports injuries may lead to permanent disability (McCue et al. 1979). Wrist injuries can be divided into four categories, namely, acute traumatic, overuse, neurovascular, and weight-bearing injuries (Howse 1994). Traumatic injuries are the most common. These acute wrist injuries are often caused by accident and are hard to prevent. They are due either to indirect trauma, most often to a fall onto the outstretched hand (FOOSH) with hyperextension, or a combination of a rotatory and torsional force and otherwise a direct blow to the wrist (Howse 1994). Fractures, dislocations, sprains (ligamentous injuries) and strains (muscle injuries), contusions, and hematomas do exist. Examples of common acute traumatic injuries are metacarpal bone fractures, ulnar collateral ligament sprain of the CMC of the thumb, distal radius fracture (often intra-articular in athletes), scaphoid fracture, and minor intercarpal scapholunate (SL) ligament sprain or tear. Less common injuries include fracture of the hook of hamate, TFCC tear, DRUJ instability, scapholunate dissociation, and frost bite injury. Important acute injuries that should not to be missed are any type of carpal dislocation especially lunate and perilunate dislocation and traumatic arterial thrombosis. Hypoxia in the soft tissues may give rise to dystrophic calcifications. The major symptom is pain that usually develops gradually. Periostitis, stress reactions/fractures, tendinopathy, and (stenosing) tenovaginitis are lesions found in adults. Special considerations are made in preadolescent and adolescent athletes as hand and wrist injuries are more common in these age groups compared to adults (Geissler 2001). Epiphyseal growth plate injuries are examples of overuse injuries in children and adolescents. It is particularly important to recognize wrist injuries that occur in the immature skeleton, such as gymnast's wrist as continued sports participation in affected children may result in growth arrest and long-term problems. Common overuse injuries of type II tendons with tenovaginitis include de Quervain's syndrome, proximal intersection syndrome at the crossing of the first (ECR compartment) and second compartment (de Quervain compartment) in the distal forearm proximally from the extensor retinaculum, the distal intersection syndrome at the crossing on the second and third (EPL) compartment distally from the extensor retinaculum, (sub) luxation of the extensor carpi ulnaris tendon in a tennis player that plays double-handed backhand, and the common dorsal carpal impingement syndrome (Rettig 2001). Other overuse injuries in athletes include Kienbock's disease (lunatomalacia) associated to ulna minus; pisotriquetral syndrome; ligamentous injuries such as scapholunate, lunotriquetral, and midcarpal instability injuries; and injuries to the DRUJ and TFCC (Rettig 1998). The cycling-related nerve injury is a chronic compressive neuropathy of the ulnar nerve in Guyon's canal. Vascular injuries are uncommon; in the acute setting, they are usually a result from high-velocity impact from balls, and in the occupational setting, the result of repetitive contact trauma in combat sports (karate, golf, and occasionally in tennis players or hockey players) (Zayed et al. 2013; Ablett and Hackett 2008; Noël and Hayoz 2000). Weight-bearing injuries are more specific to gymnasts, and they result from excessive compressive and rotational forces across the wrist (Howse 1994). The six most common sports causing injuries in children are basketball (19.5 %), football (17.1 %), baseball/softball (14.9 %), soccer (14.2 %), rollerblading/skating (5.7 %), and hockey (4.6 %). Sprains/strains (32.0 %), fractures (29.4 %), contusions/ abrasions (19.3 %), and lacerations (9.7 %) account for 90 % of injury types. The most common injury location is the wrist/hand (28 %). Contact with another person or object is the mechanism for more than 50 % of the sports-related injuries (Taylor and Attia 2000). Most ball-related injuries occur during soccer and rugby (86 %), while the majority of fractures occurring during wheel sports are in cycling (63 %). The radius/ulna is the most frequent fracture location (36 %) (Lyons et al. 1999). Hassan and Dorani (2001) found that soccer, rollerblading, cycling, and netball injuries are the most frequent causes of fractures. Soccer and rollerblading are the commonest cause of fractures among boys, while rollerblading and netball injuries are most frequent cause among girls. Brudvik and Hove (2003) found that scaphoid fracture, an infrequent fracture in children, is seen in 9 % of all fractures due to rollerblading/skating, with a doubled risk of fracture in boys aged 13–15 years compared with girls.

23.2 General Technical Considerations on Radiological Imaging

With technical advances in imaging systems, injuries of the wrist, hand, and fingers can be accurately evaluated with ultrasound and/or magnetic resonance in addition to radiographs and CT (Fig. 23.1). Wrist injuries are less well evaluated clinically; although hand and finger injuries can be assessed by expert clinical examination, additional information obtained from imaging can help in diagnosis and staging and thus optimizing treatment planning. For ultrasound, linear transducers should be used. Transducers of 15 MHz or higher offer the high spatial resolution that is needed. Examination in a waterbed may improve the quality of static and dynamic ultrasound. Clinical suspicion of radiographic occult fracture is a well-established indication for plain CT or MRI; CT after arthrography (CTA) can be used to study ligament integrity but has the drawback that only the injected compartment(s) is studied. For MRI, high-resolution images with thin slices (1.5–2 mm) can be obtained only with dedicated wrist or finger coils at high magnetic field strength. Results at 3 T are far better compared to 1.5 T or lower. A drawback of these coils is the very small field of view and the limited positioning freedom. Meticulous attention to patient immobilization, choice of the smallest field of view obtainable, and optimizing signal to noise ratio by carefully selecting imaging parameters will yield the best results. Imaging sequences should include “anatomical” and “fluid-sensitive” sequences. Anatomical images will consist of either SE T1WI or TSE PD-WI (Fig. 23.2a). These sequences offer high

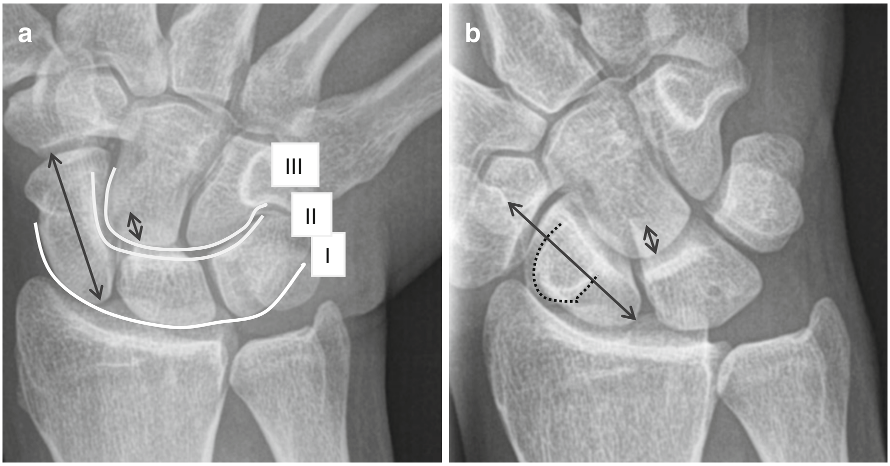

Fig. 23.1 Normal PA wrist radiographs. (**a**) Ulnar deviation, (**b**) radial deviation. A normal wrist shows no discontinuity in Gilula lines *I*, *II*, and *III* and neutral, ulnar, and radial deviation. In ulnar-sided wrist deviation, the scaphoid shows its longest diameter (*a double-sided long arrow*); in radial deviation the scaphoid rotates volarly out of the coronal plane with foreshortened projection on PA view producing a signet ring appearance at its distal half (*dotted line*); the superposition of the lunate and capitate bone is increased due to solidarity of motion of the scaphoid and lunate bone (**b** *small double arrow*)

anatomical detail; excellent knowledge of normal anatomy is essential to assess pathological changes. "Fluid-sensitive" sequences will consist of STIR-weighted images or turbo spin echo T2 or intermediate TE FS images and will emphasize high-signal-intensity changes (Fig. 23.2b, d). These sequences offer less imaging detail in the fingers due to the small field of view. At the wrist intermediately weighed TSE sequences with FS offer a good evaluation of bone marrow edema together with evaluation of the joint cartilage. GE sequences are no more regarded as an alternative to (T)SE sequences, due to susceptibility artifacts related to bone-soft tissue interfaces, and chemical shift artifact related to muscle-fat interfaces, adversely affect image quality in the hands. MR evaluation of the wrist joints is performed with (MRA) or without arthrography with, respectively, TSE intermediate TE at 3 T or with FS or T1WI with FS at 1.5 T or more in three orthogonal planes. In the indirect MRA technique with intravenous gadolinium DTPA administration, all synovial compartments are enhanced; this is regarded as a disadvantage as leakage of contrast from one compartment to the other as a sign of pathological communication is not demonstrated (Fig. 23.2c). However, communication between compartments in itself is often not clinical significant and almost regarded as physiologic above the age of 35. The major advantage of the indirect arthrography technique is that it allows simultaneous assessment of extra-articular soft tissues together with all synovial joints in a minimal invasive way (Bergin and Schweitzer 2003).

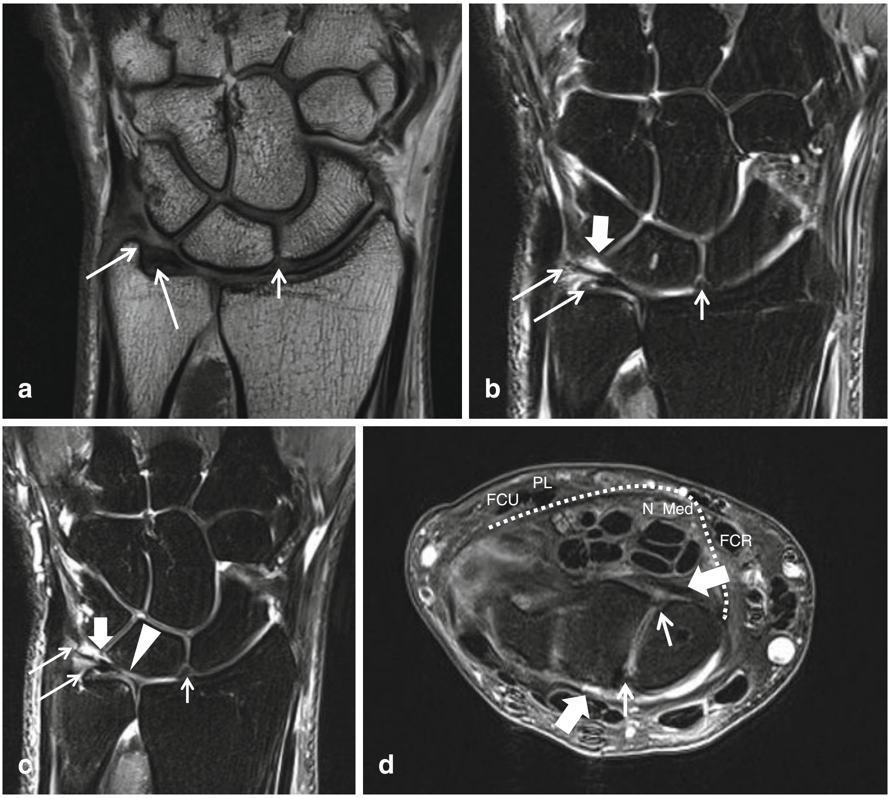

Fig. 23.2 Wrist 3 T MRA images after IV gadolinium administration (indirect arthrography), (**a**) coronal SE T1, (**b**) coronal intermediate TE FS, (**c**) coronal SE T1 FS (**d**) axial intermediate TE FS at proximal row. Intrinsic SL (*small arrow*) and LT (*thick arrow* on (**b**, **c**)) ligaments and dorsal and volar components of intrinsic SL ligament demonstrated on axial images only. Intermediate SI connection between the TFC and the low SI bone lamella of the radius is best demonstrated on **c**. Two ulnar attachments of TFC on coronal images (*long arrows*) are best demonstrated on **b**, and **c.** **c** shows broad perforation (*arrowhead*) at the central part of the TFC with minor chondromalacia (increased SI at the cartilage over the distal ulna epiphysis) (palmer type II C). Extrinsic radiocarpal volar and dorsal ligaments (*thick arrows* on axial image only). At the volar aspect the transverse ligament (*dotted line*) covering the flexor digitorum profundus and superficialis tendons, the flexor pollicis longus and median nerve is demonstrated. The median nerve (N Med) is located between the flexor carpi radialis tendon (*FCR*), palmaris longus tendon (*PL*) and flexor carpi ulnaris tendon (*FCU*)

23.3 Functional Anatomy

The wrist, hand, and fingers have the most complex human musculoskeletal anatomy. Excellent knowledge of this anatomy and its function is a condition sine qua non for radiological evaluation of wrist and finger pathology.

23.3.1 Bones, Joints, and Ligaments of the Wrist and Hand

The bones consist of the distal radius and ulna, two rows of four carpal bones, metacarpal bones, and proximal, middle, and distal phalanges (Fig. 23.1). The wrist articulations are grouped in functional entities, including: the radiocarpal, distal radioulnar (DRU), pisiform-triquetral, midcarpal, scapho-trapezio-trapezoid (STT), first carpometacarpal (CMC), intermetacarpal, and interphalangeal (IP) joints. The proximal carpal row is starting at the radius or lateral aspect formed by the scaphoid, lunate, triquetrum, and pisiform. At the radiocarpal (RC) joint, this proximal carpal row functions as an integrated entity or ellipsoid ball that articulates with the socket at the distal end of the radius and the TFCC. The radiocarpal joint has a wide multidirectional range of motion. The distal carpal row is formed by the trapezium, trapezoid, capitate, and hamate and articulates with the distal surfaces of the proximal row which is called the midcarpal joint and the proximal surfaces of the metacarpal bones also called the CMC joints. The midcarpal joint has a wide range of motion especially serving flexion and extension and to a lesser range radial and ulnar deviation; the widest range of motion is located at the lateral (radial) aspect or STT joint. The 2nd to 5th CMC joint spaces are gliding joints with very restricted range of motion (ROM) due to the shape of the epiphyseal end plate and due to the fortification by a strong ligamentous apparatus. The CMC 1 is a single joint compartment and functions as a saddle joint providing a multidirectional wide range of motion. The CMC 1 and STT joints are prone to overuse osteoarthritis (OA) related to the wide range of motion. The ulna does not articulate directly with the carpus but does with the distal radius at the DRUJ. The MCP and IP joints are hinge joints with unidirectional movement restricted to flexion and extension due to radial and ulnar collateral ligaments. Extension in these joints is restricted to 180° by the very strong palmar plate that is a ligamentous thickening of the volar capsule in these joints. The carpal bones are held together by ligaments, including the intrinsic (or interosseous) and extrinsic ligaments (Figs. 23.2 and 23.3). These strong ligaments are essential stabilizers of the wrist. The dorsal ligaments are weaker than the volar ligaments, resulting in dorsal dislocation being more common. The intrinsic (or interosseous) ligaments connect pairs of carpal bones and divides the midcarpal and RC joint compartments. In the proximal carpal row, the scapholunate (SL) and lunotriquetral (LT) ligaments join the proximal, dorsal, and volar margins of these carpal bones and separate the RC from the midcarpal compartments. Especially the volar and dorsal parts of these, SL (Fig. 23.4) and LT intrinsic ligaments are essential in the stabilization of the centrally located lunate bone; perforations at the proximal part of these interosseous ligaments have no functional consequence. The dorsal and volar extrinsic ligaments are thickenings of the inner surface of the joint capsule (Fig. 23.4). The main dorsal extrinsic ligaments are the radiotriquetral, triquetrotrapezial, and triquetroscaphoid ligaments. The main volar extrinsic ligaments are the radioscapholunate (RSC) and the radiolunotriquetral (RLT) (long radiolunate) and the short radiolunate ligaments. The TFCC is an important stabilizer of the DRUJ. Its main central component is the TFC disk, which separates the RC compartment from

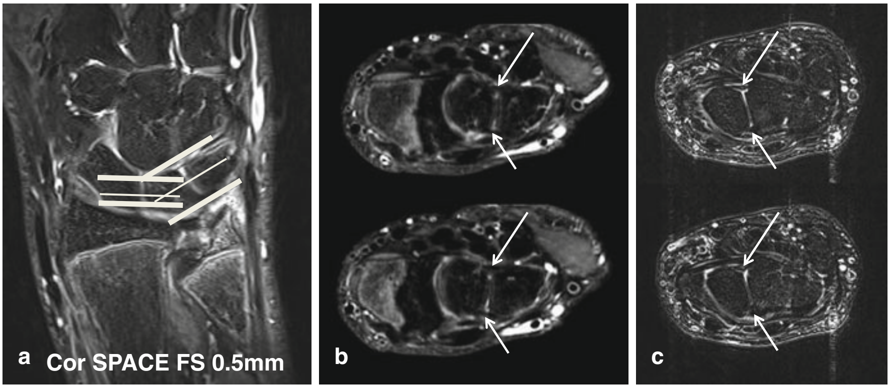

Fig. 23.3 MR demonstration of volar and dorsal components of the LT (**b**) and SL (**c**) intrinsic ligament. (**a**) Native coronal image, 3D TSE (SPACE, Siemens) intermediary TE FS, thin slice (0.5 mm), demonstrating oblique axial reconstruction plane perpendicular to the articular surface at the LT compartment of the midcarpal joint (**b**) and axial imaging plane perpendicular to the SL compartment of the midcarpal joint on TSE intermediary TE FS images (**C**). *Arrows* point to the dorsal and volar intrinsic ligament components. (**b**) Oblique axial multiplanar reconstruction with 0.5 mm slice thickness. (**c**) Axial TSE intermediary TE with FS images

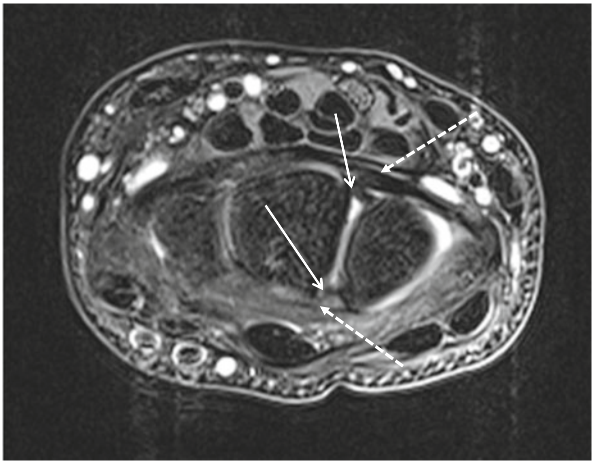

Fig. 23.4 MRI normal SL ligament. Axial TSE intermediary TE MRI at the level of the proximal carpal row. Low SI dorsal and volar functional important components of the intrinsic SL ligament (*arrows*) connecting the lunate and scaphoid bones are demonstrated on axial images only, extrinsic dorsal and volar radiocarpal ligaments (*dotted arrows*)

the DRUJ. The low SI on MRI of the TFC disk is attached to the intermediate MRI SI of the hyaline articular cartilage of the ulnar side of the distal radius and connects to the ulnar styloid through two fibrous bands (Fig. 23.2). The intermediate SI on MRI of the hyaline cartilage at the radial junction of the TFC should not be confused with a tear (Fig. 23.2c). The central and radial aspects of the TFC disk are "white" avascular, while the peripheral and ulnar aspects "red" have a blood supply. The latter regions hence have the potential to heal following injury with elongation or tear, either conservatively or after surgical repair (Bednar et al. 1991). Multiple variants of the ulnar adherence of the two ulnar connections are described, located from the top of the ulnar styloid process up to the distal ulnar epiphysis making the radiological evaluation difficult and less accurate; radiologists should carefully search for and recognize two separate ulnar TFC insertions to increase the accuracy of ulnar TFC avulsions (Palmer and Werner 1981; Benjamin et al. 1990; Totterman and Miller 1995). Other components of the TFCC are the dorsal and volar radioulnar ligaments, prestyloid recess, meniscal homologue (a fibrostyloid fold that extends into the prestyloid recess), ulnar collateral ligament, subsynovial sheath of the extensor carpi ulnaris (ECU) tendon sheath, and volar ulnotriquetral and ulnolunate ligaments (Fig. 23.2). The DRUJ consists of an articular surface that covers two-thirds of the circumference of the distal ulnar epiphysis, which in turn articulates with the sigmoid notch of the distal radius (Fig. 23.5). The DRUJ is a pivot joint with unidirectional movement providing rotation only of the radius around the ulna; this is the distal component of supination and pronation movement of the forearm. The DRUJ is stabilized intrinsically by the TFCC and extrinsically by the interosseous membrane, extensor carpi radialis (ECR) and flexor carpi ulnaris (FCU) tendons, and the pronator quadratus muscle.

23.3.2 Tendons, Arteries, and Nerves of the Wrist and Hand

The tendons of the hand originate primarily in the forearm and pass over the wrist. The dorsal aspect of the wrist is covered by the extensor retinaculum that covers the extensor tendons and attaches to the distal radius and ulna to divide the extensor

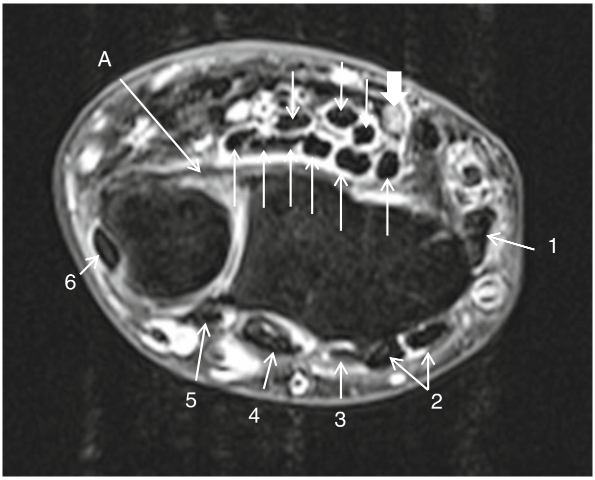

Fig. 23.5 Axial TSE intermediate SE FS at level of DRUJ in pronated joint positioning. Semicircular distal ulna epiphysis (*left*) fits in the distal radial epiphysis sigmoid notch (*right*); the volar radioulnar ligament is stretched and demonstrated as a low signal band connecting the radius and ulna (*arrow A*). Dorsal compartments numbered 1–6 (*arrows 1–6*). Volar flexor digitorum profundus and superficialis tendons with flexor pollicis longus tendons (*arrows*) and median nerve (*thick arrow*) proximal to the carpal tunnel

aspect in six type II tendon compartments, each containing one or more finger or wrist extensor tendons within a synovial sheath (Fig. 23.3). The flexor tendon compartment in the volar aspect at the level of the carpus is also called the carpal tunnel. The carpal tunnel is bounded superficially by a strong flexor retinaculum, the transverse carpal ligament (Fig. 23.2d), and contains the nine finger and long thumb flexor tendons, the distal part of the FCR tendon, the median nerve, and the radial artery but not the wrist flexor tendons and ulnar artery. The superficial and deep finger flexor tendons are surrounded by a single compartment synovial sheath at the level of the carpal tunnel; the long thumb flexor is surrounded by an independent synovial sheath at the level of the carpal tunnel up to the level of the distal phalanx. The palmaris longus and FCU tendons are located superficially to the carpal tunnel and not covered by retinaculum; they are type I tendons without synovial sheath (Fig. 23.2d). The flexor carpi radialis tendon (Fig. 23.2d) pierces the flexor retinaculum at its distal half and is therefore surrounded by a synovial sheath; it runs over the volar aspect of the scaphoid, the STT joint, subsequently in a fibro-osseous groove of the trapezium bone and inserts at the base of the second metacarpal bone. The latter tendon and tendon sheath are prone to impingement in this fibro-osseous tunnel related to overuse and STT osteoarthritis with osteophytosis, tenosynovitis, and tendinopathy. Resisted flexion at the carpus nicely demonstrates the FCR and palmaris longus tendons at the skin surface; the level of the median nerve deeply located at the carpal tunnel is between these two tendons (Fig. 23.2d). Blind infiltrations of the carpal tunnel therefore are performed at the ulnar aspect of the palmaris longus tendon to avoid median nerve injury. Guyon's canal lies superficial to the transverse carpal ligament and radial to the hook of hamate and contains the ulnar nerve, artery, and veins. The ulnar nerve runs deep to the FCU tendon and palmaris brevis muscle in Guyon's canal. The flexor FCU tendon is surrounded by a synovial sheath and inserts into the pisiform bone; it is the only tendon that inserts into one of the wrist bones. The median nerve splits distal to the carpal tunnel into the palmar common digital nerves of fingers 1–4 (radial aspect of ring finger) and branches to the thenar muscles (except flexor pollicis brevis caput profundus and adductor pollicis) at the level of the carpal tunnel. A bifid median nerve is a variant with split of the median nerve at or proximal to the carpal tunnel, an associated persistent median artery may exist, and these variants are easily detected on ultrasound with Doppler and MRI and have to be described by the radiologist as in these cases blind infiltration of the carpal tunnel may cause injury of the median nerve (Propeck et al. 2000). The ulnar nerve splits into the ramus profundus to the flexor pollicis brevis caput profundus and adductor pollicis of the thenar and hypothenar and ramus superficialis to the palmar and volar common digital nerves for the little finger and ulnar aspect of the marriage finger. The superficial branch of the radial nerve is located at the subcutaneous tissue over the radial aspect of the wrist and distal forearm and branches into the dorsal common thumb and digital nerves of the fingers 2 and 3 and radial aspect of the ring finger. The deep branch of the radial nerve also called the posterior interosseous nerve (PIN) follows the extensor digitorum tendons into the extensor digitorum fibro-osseous tunnel of the wrist together with the extensor indicis proprius tendon (extensor compartment 4) and ends into the dorsal RC joint capsule. Blood supply of the wrist and hand is very variable and complex with anastomosis at multiple levels: volarly its most important supply is via the ulnar artery, and secondary supply is via the radial artery; both arteries anastomose distally in a superficial and deep palmar arc and at the dorsal aspect via the posterior interosseous artery that ends in a dorsal arterial anastomosing network. This dorsal network connects to the deep palmar arc at the radial and ulnar side through dorsal carpal arterial branches. The scaphoid bone receives its blood supply via its distal third through a superficial palmar and dorsal branch part of the radial artery; because of this blood supply, fractures of the middle and proximal third of the scaphoid are prone to AVN. The fingers have four arteries at the four corners: the dorsal digital arteries arise from the dorsal network, the ventral digital arteries from the deep and superficial arc, and the latter anastomose at the level of the distal phalangeal tuft.

23.3.3 Anatomy and Biomechanics of Fingers, Tendons, and Ligaments

The finger joints and MCP joints are hinge joints, with full flexion capacity but extension motion restricted to 180° related to action of the volar plate that is a major thickening of the volar joint capsule. Rather thick radial and ulnar collateral ligaments resist varus or valgus deviation at these joints, the collateral ligaments have a palmar extension, the ligamentum palmaris.

Flexor digitorum superficialis musculotendinous unit (MTU) is responsible for flexion of the PIP joint and inserts on the base of the phalanx media; the flexor digitorum profundus tendon crosses the superficialis tendon at the proximal phalanx and inserts on the phalanx distalis; thus it is responsible for flexion of the DIP joint. Bowstringing of the flexor tendons relative to the phalanges is prevented by specific finger retinacula, the pulley system, annular (A) and cruciate (C) pulleys are located along the phalangeal course of the flexor tendons (Fig. 23.6). The biomechanically important annular pulleys are numbered (1–5) from proximal to distal. The odd annular pulleys (A1–3 and 5) insert on the volar plates of the MCP and IP joints; the even pulleys A2 and A4 insert on the phalanx proximalis and media, respectively; these are the strongest and most important functional pulleys (Fig. 23.6a, b). Pulley lesions are associated with overuse in climbing sports and acute trauma in baseball and in PIP dislocation (Fig. 23.6c).

The extensor apparatus of the long fingers is very complex. Extensor digitorum muscle tendons are inserting on the phalanx media 2–5; they are called the central slips and responsible for extension at the PIP joint. At the index an additional MTU, the extensor indicis proprius, is responsible for the independent extension at the PIP; also at the little finger, an additional MTU, the extensor digiti minimi, is responsible for the independent extension at the PIP. The dorsal hood is responsible for extension movement of the DIP joints 2–5; this tendinous structure is formed by the aponeuroses and tendons of the lumbrical muscles and dorsal and volar interossei muscles that run to the dorsal aspect of the phalanx on radial and ulnar side. Proximally at the level of the metacarpal heads, the dorsal

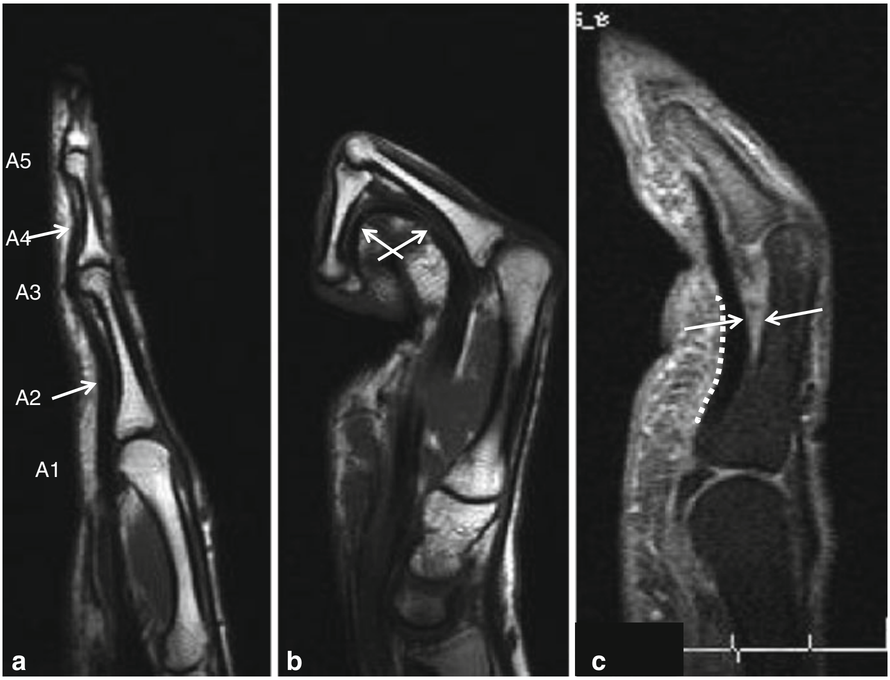

Fig. 23.6 Function of the finger pulleys. Middle finger, sagittal MR T1WI with extension (**a**) and flexion (**b**) of the finger. Bowstringing of the flexor tendons during flexion is prohibited by the pulley system on MRI demonstration of contact of the flexor tendons and the phalanx in both finger positions at the level of the A2 (proximal phalanx *arrow*) and A4 (phalanx media *arrow*) pulleys. Partial distal A2 pulley lesion (**c**) with dissociation of flexor tendons and proximal phalanx at the distal third of the A2 pulley after volar PIP dislocation (*dotted line*: extension of the A2 pulley)

hood forms a sling around the central slip; this part is called the sagittal bands; they keep the central slip centered to the central axis of the MCP joint in flexed position. The dorsal hood runs over the phalanx at radial and ulnodorsal aspect and inserts on the distal phalanx, thus responsible for the extension of the DIP joint. Lumbrical muscles with their origin at the flexor digitorum profundus tendons at metacarpal level connect the flexor and extensor apparatus of the fingers and are responsible for the complex action of the finger joints with combined flexion and extension.

At the MCP joint of the thumb, the ulnar collateral ligament is covered by the aponeurosis of the adductor pollicis; this aponeurosis is comparable to the dorsal hood of the long fingers and thus part of the extensor mechanism that forms a sling around the extensor pollicis longus tendon. Thus, the adductor pollicis muscle has a similar action to the interosseous muscles and is consequently called the missing interosseous (Mardel and Underwood 1991). The adductor pollicis tendon has a second, commonly known, insertion on the ulnar sesamoid of the first metacarpal.

23.3.4 Biomechanics of the Wrist and Hand in Sports Injuries

The wrist is a complex intercalated segment that biomechanically transmits forces generated at the hand to the forearm. An important motion component is located at the ellipsoid ball and socket radiocarpal joint; a secondary motion component is located at the midcarpal joint; the only restricted motion is located at the CMC joints 2–5. DRUJ is involved in rotation with pro- and supination. The radial side of the wrist carries 80 % of the axial load, and the ulnar side the remaining 20 %. Radial deviation of the wrist results in ventral angulation of the distal pole of the scaphoid (Fig. 23.1b) producing a round sclerotic circular line on the distal third of the scaphoid producing a signet ring aspect on radiographs; SL ligament causes solidary movement of the lunate with increased superposition of lunate and capitate (Fig. 23.1b small arrow). In neutral position and ulnar deviation, the scaphoid rotates with its long axis in the coronal plane producing the longest projection of the scaphoid on radiographs (Fig. 23.1a long arrow). In SL ligament dysfunction, a lack of solidary motion of scaphoid and lunatum results in a sustained ventral angulated position during ulnar deviation with increased scapholunate distance (SL dissociation) (Fig. 23.7).

Fig. 23.7 CR in neutral position with clenched wrist demonstrating carpal instability dissociative. CR posteroanterior view with clenched wrist. Late findings with increased scapholunar distance in neutral position (*double arrow*), increased superposition of lunate and capitate (*dotted double arrow*): Terry Thomas sign in carpal instability dissociative (CID)

23.4 Fractures

23.4.1 Scaphoid and Distal Radial Fractures

Radial, scaphoid fractures and scapholunar ligament lesions are common in sports, usually occurring during a fall on the pronated outstretched hand (FOOSH). The type of lesion depends on the patient's age, bone density, reaction time, and the angle at which the wrist hits the ground. The more dorsiflexed the wrist is, the more likely the scaphoid bone will break. With less wrist dorsiflexion, it is more likely that the radius will break. On striking a hard surface, the hand becomes fixed, while the momentum of the body produces two forces: a twisting force causing excessive supination of the forearm and a compression force which acts vertically through the carpus to the radius. The type of fracture is also dependent on whether the hand is in radial or ulnar flexion at the moment of impact. Distal radial fractures are often associated with ulnar fractures. Distal radial fractures may be extra- or intra-articular and displaced or nondisplaced. These fractures are primarily examined radiographically; complex intra-articular fracture components are evaluated with multiplanar or cone beam CT with multiplanar two-dimensional reconstructions in three orthogonal planes and three-dimensional reconstructions. Despite the fact that nondisplaced scaphoid fractures are a radiological challenge and occult fractures are frequent (Fig. 23.8a), radiography with specific scaphoid series remains the first imaging modality in the initial evaluation and follow-up of scaphoid fractures. If clinically suspected for scaphoid fracture, i.e., FOOSH with pain on palpation at the anatomical snuff box and normal radiographs, additional examinations are mandatory, whether repeated radiographs of the scaphoid after 1 week of immobilization, or bone scintigraphy, or MRI with coronal TSE FS T2 or intermediate TE sequence (Fig. 23.8c). Because of its sensitivity, specificity, absence of radiation exposure, and lower cost, MRI without contrast is the imaging modality of choice over nuclear imaging techniques (bone scintigraphy, SPECT-CT) for depiction of radiographic occult scaphoid fracture, bone contusion, and associated soft tissue injury. Multislice CT and cone beam CT with its high spatial resolution and multiplanar two-dimensional reconstructions in three orthogonal imaging planes improve visualization and characterization of the fracture line and the amount of displacement and angulation of the fracture fragments or staging that is necessary for appropriate treatment (Taljanovic et al. 2012). Malunion, nonunion, and AVN of the proximal part of the scaphoid are associated to insufficient immobilized scaphoid fractures. Increased density of the proximal part of the scaphoid on radiographs (Fig. 23.9a) is a late sign of AVN; MRI shows demarcation line between normal bone of the distal half and bone marrow edema and fat replacement in the early phases with low SI on T1 (Fig. 23.9b) and increased SI on T2WI at the proximal half of the scaphoid; in very early phases, SI on T1WI and T2WI is normal; in these cases subtracted T1WI before and after IV gadolinium administration proves absent gadolinium enhancement in the necrotic part. Contrast-enhanced MRI aids in the assessment of scaphoid fracture nonunion, AVN, fracture healing after bone grafting, and revitalization of the necrotic bone after bone grafting. Stress fractures of the scaphoid have

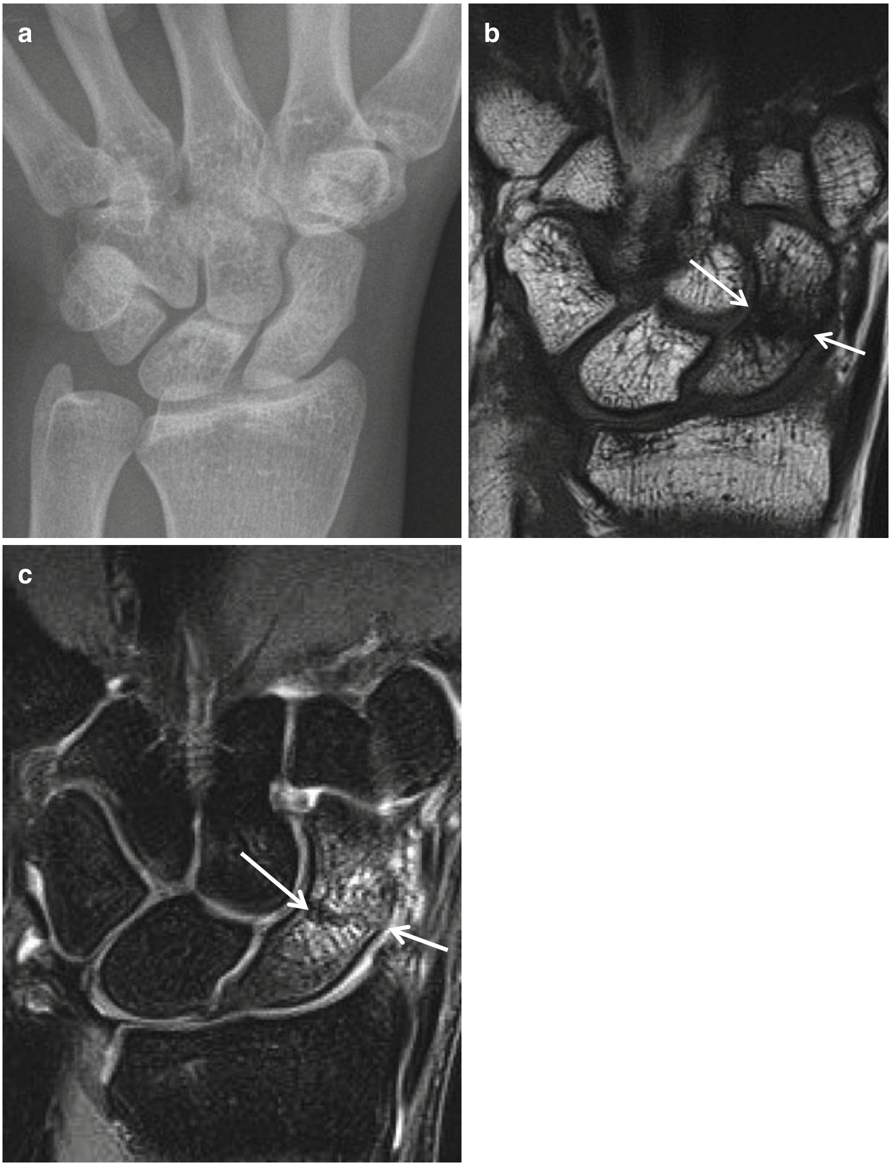

Fig. 23.8 Occult midportion scaphoid fracture. (**a**) Normal PA radiograph. (**b**) Coronal SE T1WI and C coronal TSE intermediate TE FS images demonstrating the cortical disruption (*arrows*) and fracture line surrounded with bone marrow edema with reduced SI on T1 (**b**) and increased SI on intermediate TE with FS (**c**)

been reported to be due to repetitive loading of the wrist in dorsiflexion, occurring to sportsmen such as gymnasts and shot-putters (Hanks et al. 1989). These stress fractures are recognized late on radiographs related to endosteal spongious callus

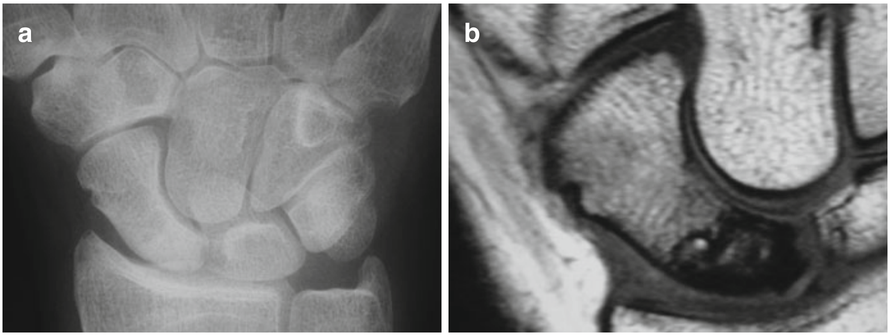

Fig. 23.9 Midportion scaphoid fracture with AVN of the proximal half. (**a**) PA radiograph demonstrating relative increased density of the proximal half related to absence of osteopenia. (**b**) Coronal SE T1WI shows decreased SI at the proximal necrotic half of the scaphoid with sharp demarcation line with the vital distal half

with bandlike increased bone density. On MRI they are early and easily demonstrated as a transverse low SI on T1- and T2-weighted coronal images of noncomplete fracture line surrounded by major bone marrow edema. On MRI, the presence of edema without a visible fracture line may represent a bone bruise or a stress reaction recognized as forestage of stress fracture.

23.4.2 Hamate Fractures

Hamate fractures are relatively common wrist fractures in athletes. They may be either isolated or in complex injury associated with carpometacarpal dislocation or pisiform fracture. They are commonly classified into hook or body of hamate fractures. A fractured hook of hamate is typically isolated and is the most common hamate fracture but less common compared to scaphoid fractures. This fracture is typically occult on radiographs and easily demonstrated on axial and sagittal multiplanar CT reconstructions or water-sensitive FS MRI sequences (Fig. 23.10). It occurs when a patient falls while clenching firm objects, and the object lands between the ground and ulnar side of the palm. Falling on an outstretched hand that impacts the ulnar side of the wrist may also result in fracture of the hamate hook. This injury occurs in individuals who are involved in a sport involving a racquet, club, or bat and is caused by the impact against the hook of the hamate. The fracture may also be through indirect force when a racquet is swung, when a golf club catches the ground, or when a bat hits a ball (Futami et al. 1993). There is some controversy as to whether these fractures result from shear forces transmitted through ligament insertions as the wrist is forcibly hyperextended while gripping an object. In racquet sports, fractures affect the dominant hand. In golf, hockey, and baseball, hamate fractures usually occur in the nondominant hand. Isolated fracture to the body of the hamate is less common and also often occults on radiographs. It is due to a direct force such as a punch-press injury, falling on a hyperdorsiflexed and ulnar-deviated wrist, or posterior dislocation or subluxation of the fourth and/or fifth metacarpal.

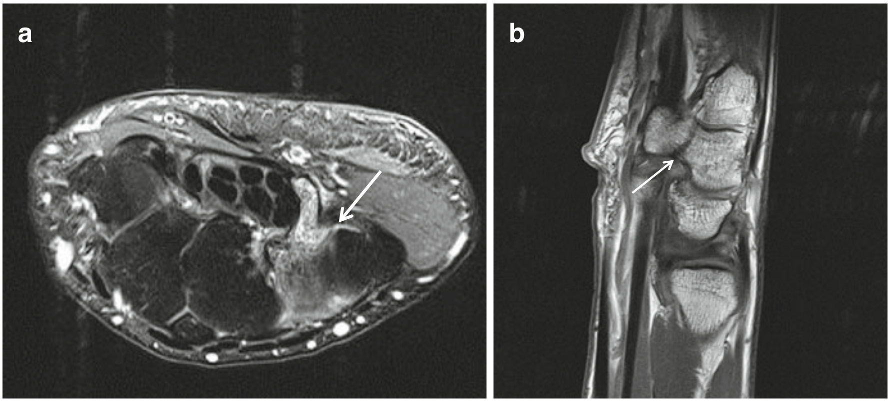

Fig. 23.10 MRI fracture hook of hamate. Axial TSE intermediate TE with FS (**a**) and sagittal TSE T1WI after intervenous gadolinium administration. Bone marrow edema surrounding the fracture (*arrow*) is well demonstrated on water-sensitive images (**a**). Fracture line (*arrow*) at the base of the hook of the hamate is demonstrated on T1WI (**b**)

23.4.3 Lunate Fractures

The lunate, being the fulcrum of the proximal carpal row, is frequently exposed to traumatic forces to the wrist. Kienbock's disease, osteomalacia, or osteonecrosis of the lunate is thought to be due to repetitive microtrauma and is associated with ulna minus. Early radiological diagnosis of Kienbock's disease is challenging as the lunate as a whole is involved, and thus the pathognomonic sign of demarcation line with double contrast that defines the necrotic bone on T2WI (well known in hip AVN) is not demonstrated. Relative homogeneous increased bone density of the lunate on radiographs (Fig. 23.23) and diffuse bone marrow edema on fluid-sensitive MRI sequences are rather late findings at a subacute stage (Fig. 23.11e) that is followed by collapse and secondary osteoarthritis. The absence of gadolinium enhancement in the very early stage of Kienbock's disease is best demonstrated by subtracting pre- and post-IV gadolinium-enhanced T1WI (Fig. 23.11c, f). Acute lunate fractures are uncommon; body fractures of the lunate are caused by axial compressive force between the radius and capitate. When occurring through one of the horns, they are due to intrinsic SL or LT ligamentous avulsion. Lunate fractures are typically occult on radiographs and may be an incidental finding on US (Fig. 23.12a); additional imaging (CT or MRI) is indicated in clinical suspicion of lunate fractures (Fig. 23.12c, d, e).

23.4.4 Other Fractures

A subcapital metacarpal five fracture is typically related to axial trauma on the clenched wrist in boxing sports. Fractures may also be caused by direct trauma, e.g., impact with a helmet during American football. Radiography is the primary imaging technique in these fractures. Additional imaging (MRI or CT) is indicated in suspicion for occult fracture or in fracture distention into the joint.

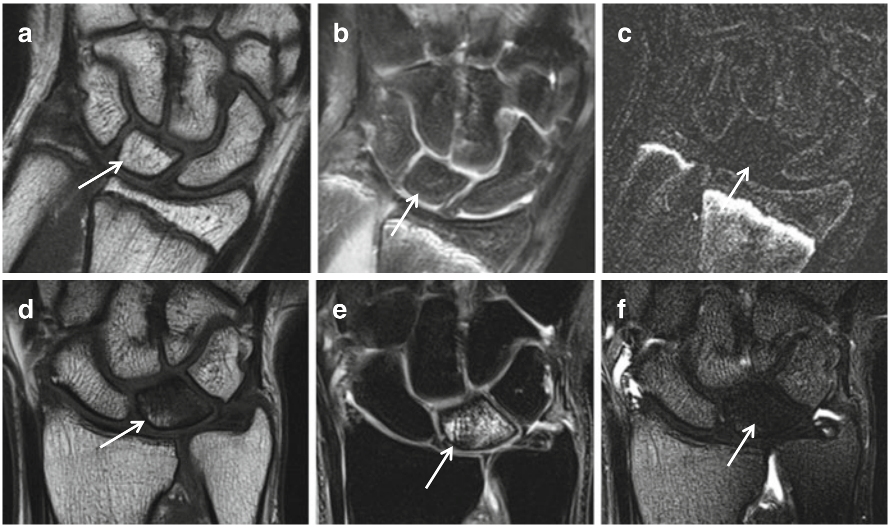

Fig. 23.11 MRI lunatomalacia, Kienbock's disease, early and later findings. Early findings AVN of the right os lunatum, coronal images (**a**–**c**) of an adolescent patient. SE T1WI (**a**), TSE intermediary TE (**b**), and subtraction image (**c**) of T1WI before and after IV gadolinium administration. No abnormalities are detected on TSE and SE WI, normal fat signal and morphology of the os lunatum on T1WI (**a**), no bone marrow edema on water image (**b**). Absence of enhancement after gadolinium administration is best demonstrated on subtracted gadolinium-enhanced image (**c**). Subacute findings of AVN of the left os lunatum, images (**d**–**f**) of an adult patient. SE T1WI (**d**), TSE intermediary TE (**e**), and subtraction image (**f**) of T1WI before and after IV gadolinium administration. Wide spread reduced SI on T1WI (**d**) with diffuse BME on water image with FS (**e**) and absence of gadolinium enhancement (**f**)

23.4.5 Special Considerations in Children

Fractures of the wrist are more common in children and young adults, especially if involved in risk-taking sports activities. Three quarters of wrist injuries are greenstick and torus fractures of the distal radius and ulna that are easily recognized on radiographs and consolidate quickly without sequel. In about 15 % of fractures in children, the metaphyseal growth area is involved; these are commonly classified according to Salter and Harris (I to IX) and need more attention (Salter and Harris 1963; Rang 1968; Ogden 1982). Especially the rare (about 1 %) Salter-Harris type V and VI lesions with crushed physis are prone to unfavorable outcome related to premature growth arrest. Diagnosis on radiographs is challenging and needs comparative images of the contralateral wrist with observant evaluation, especially the Salter-Harris types without involvement of the calcified bone (type I, V, VI, and VIII and IX) which remain occult on radiographs (Fig. 23.13a, c) and need additional MRI (Fig. 23.13b).

Fig. 23.12 Occult left lunate fracture. Incidental finding on ultrasound (**a**, **b**) and confirmation on CT (**c**) and MRI (**d**, **e**). Seventeen-year-old elite male tennis player with tennis-related chronic pain at the dorsal aspect of the wrist. Fracture line at the dorsal aspect of the os lunatum is demonstrated on axial ultrasound of the left wrist (**a** *arrow*), not demonstrated at the right wrist (**b**). Sagittal multiplanar CT reconstruction with confirmation of the fracture at the dorsal distal surface of the lunate bone (**c** *arrow*), low SI on SE T1WI sagittal MRI images surrounding the fracture line (**d**, **e** *arrows*)

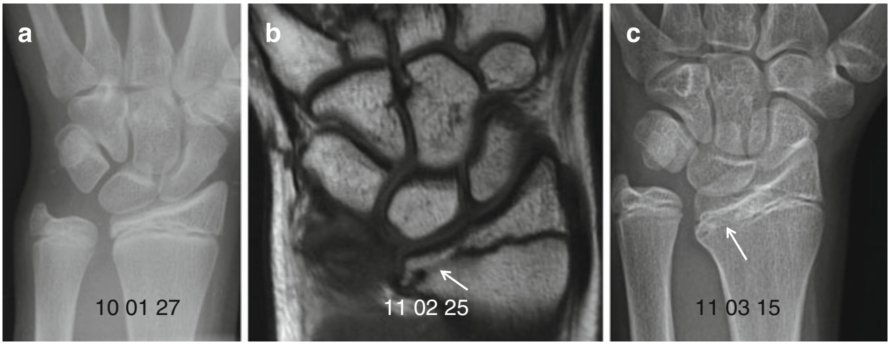

Fig. 23.13 Salter-Harris type VI fracture with partial crush of the distal radius physis. Two-year-old girl with FOOSH on the *left side*. PA radiograph shows no abnormalities (**a**). Local bony fusion of the physis (*arrows*) with growth disturbance and Madelung-like deformity is demonstrated 13 months later on coronal MRI SE T1WI (**b**) and confirmed on radiograph (**c**)

23.5 Wrist Instability and Deformity Patterns

About 10 % of carpal injuries result in instability. Scaphoid fractures and injuries to the ligaments with scaphoid subluxation can alter the wrist kinematics, leading to instability and early posttraumatic degenerative arthritis. These injuries can be the result of a single traumatic event and should be suspected in patients with wrist effusion and pain that is seemingly out of proportion to the injury even though the initial radiographs may appear normal. Clinical findings are often non-specific. Imaging is important as diagnosis of a significant injury will dictate treatment. Partial ligamentous injury is treated by cast immobilization, while complete disruptions may require early surgery to prevent long-term degenerative arthritis. Wrist instability most commonly results from ligamentous disruption between bones of the proximal carpal row. Scapholunate (SL) and lunotriquetral (LT) dissociations are forms of this instability pattern, SL instability being the most common. On the other hand, the association of SL and/or LT ligament and extrinsic ligament tears was significantly correlated ($P < .001$) with carpal instability at radiography. The presence or absence of carpal instability on radiographs depends on the association between intrinsic and extrinsic ligament tears – even partial ones – rather than on the presence of intrinsic ligament tears alone, even when the tears are complete (Theumann et al. 2006). An instability pattern in the radiocarpal or midcarpal joint with carpal dissociation is called carpal instability dissociative (CID); a carpal instability without carpal dissociation is known as carpal instability nondissociative (CIND) (Table 23.1). Treatment depends on the specific type and degree of carpal disruption and the presence or absence of degenerative changes (Cohen 1998).

Table 23.1 Classification of carpal instability patterns

Instability group	Instability entity
Dissociative (CID)	Scapholunate dissociation
	Lunotriquetral dissociation
Nondissociative (CIND)	Radiocarpal instability
	Midcarpal instability
Complex	Perilunate
	Transscaphoid perilunate
Transaxial	Radial
	Ulnar
	Radial and ulna

23.5.1 SL Instability and DISI

SL stability particularly depends on the dorsal and volar components of the intrinsic ligament. Isolated perforation of the proximal part of the SL ligament is regularly found in nonsymptomatic people above the age of thirty and should not be regarded as ligament tear. As a consequence communication of the radiocarpal and midcarpal joints on arthrography without demonstration of dorsal or ventral SL ligament lesion is not a significant finding. Major intrinsic SL ligament lesion, probably with extrinsic ligament disruption, causes non-solidary movement of scaphoid and lunate resulting in dorsal tilt of the lunate on the radius losing its linear relationship with the capitate that compensates by rotating volarly; in contrast the scaphoid rotates volarly resulting in a collapse deformity. On imaging (CR, coronal MRI, and CT), a gap exceeding 3 mm in the SL joint (Terry Thomas sign) is considered abnormal and sufficient to prove ligament insufficiency; no additional imaging is needed. A PA clenched wrist with ulnar deviation radiographs improves detection of SL dissociation (Fig. 23.7). A PA wrist radiograph in our institution is made with clenched wrist as it is more sensitive to demonstrate these signs. Also ulnar deviation PA views are more sensitive. On lateral radiographs, in neutral position, this condition is recognized by an increased scapholunate angle of 70° or more and between the lunate and capitate of 30° or more; on PA radiographs, in neutral position, shortening of the scaphoid with signet ring sign, a quadrilateral shape of the lunate with increased superposition of the lunate and capitate of more than 50 %, is demonstrated (Fig. 23.14a, b). This condition is recognized as carpal instability dissociative (CID).

In cases with negative Terry Thomas sign on radiographs, high-resolution MRA or CTA is indicated; axial imaging planes show the discontinuity of the biomechanically important dorsal and ventral parts of the SL ligaments (Figs. 23.14f and 23.15b). Recently four-dimensional computed tomography is used to demonstrate carpal instability (Troupis and Amis 2013). Sprain grade II (partial tear or elongation) of the SL (and LT) ligaments is demonstrated on axial MRI sequences only, with thickening and increased SI on T1WI and T2WI

(Fig. 23.16). Incomplete ligament rupture causes dynamic or intermittent instability with split-second SL dissociation during ulnar deviation movement of the wrist; this is only demonstrated under videofluoroscopy during radioulnar deviation movement.

This SL lesion-related instability pattern is known as dorsiflexed intercalated segment instability pattern (DISI). It generates early osteoarthritis at the midcarpal joint at capitatolunate level and radiocarpal joint at scaphoradial level known as SLAC wrist (Fig. 23.17). DISI normally occurs in unrecognized scaphoid subluxations or scaphoid fractures. The end stage of untreated scaphoid fracture with instability is called SNAC (scaphoid nonunion advanced collapse). SL CID instability is staged according to Table 23.2.

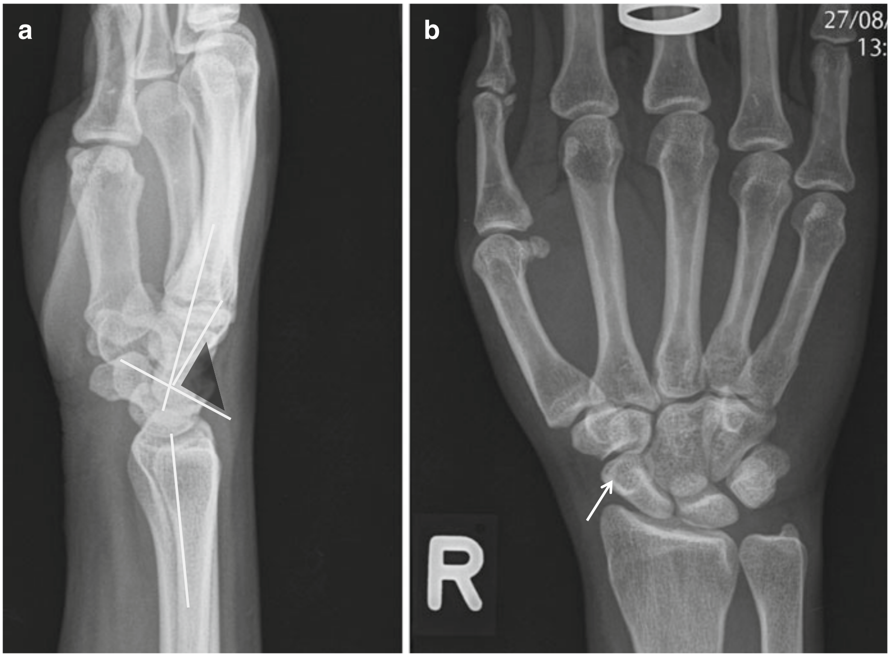

Fig. 23.14 DISI. Female, 55 years old, FOOSH, CR performed the day of trauma, MRI 4 months later. CR PA (**a**) view demonstrating shortened projection of the scaphoid with signet ring appearance, increased lunocapitate covering, lateral (**b**) view demonstrating dorsal rotation of the lunate with volar angulation of the capitate resulting in increased (>70°) scapholunate angle. The dark triangle with adjacent lines mark the distal tangent to the lunate bone with perpendicular line to calculate the scapholunate angle. Sagittal MRI images in neutral joint position at scaphoid level (**c**) and lunate (**d**) level demonstrate the dorsal rotation of the lunate with combined volar rotation of the scaphoid (*arrows*) with angle over 70°. Axial TSE intermediate TE with FS (**e**) at scapholunate level with dorsal and volar parts of intrinsic SL ligament (*arrows*). Coronal image (**f**) (coronal TSE intermediate TE with FS) shows the increased scapholunate distance (*arrows*) with discontinuity of the proximal part of the SL ligament. Axial TSE intermediate TE with FS images shows the discontinuity of the biomechanically important components of the SL ligament (*arrows*)

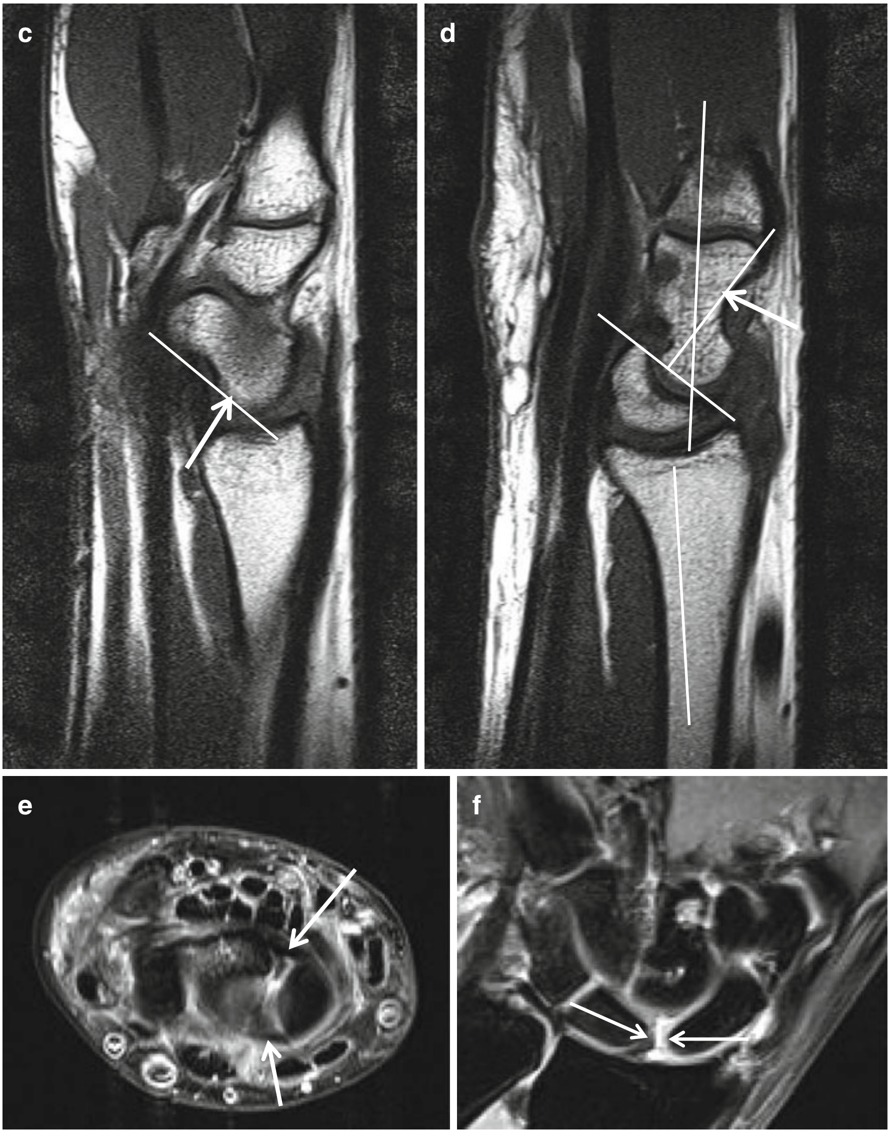

Fig. 23.14 (continued)

23.5.2 LT Instability and VISI

LT stability is, in descending order, most dependent on the palmar portion of the intrinsic LT ligament, extrinsic dorsal radiocarpal ligament, and dorsal intercarpal LT ligament. LT instability is rare. LT instability is related to acute traumatic and

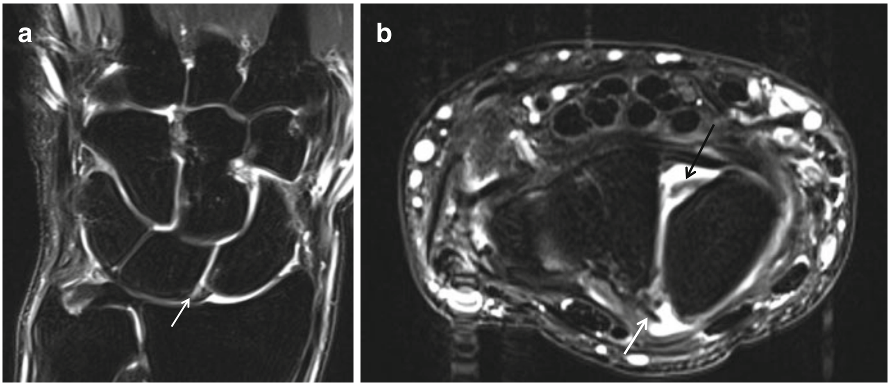

Fig. 23.15 MRI SL ligament tear. Twenty-three-year-old male soccer player with FOOSH, dorsal wrist pain with locking. Coronal (**a**) and axial (**b**) MRI TSE intermediary TE with FS. Disruption of the dorsal and volar components of the SL ligament (*arrows*) on the axial image (**b**) and on the coronal image thickening and increased SI is demonstrated (**a**, *arrow*)

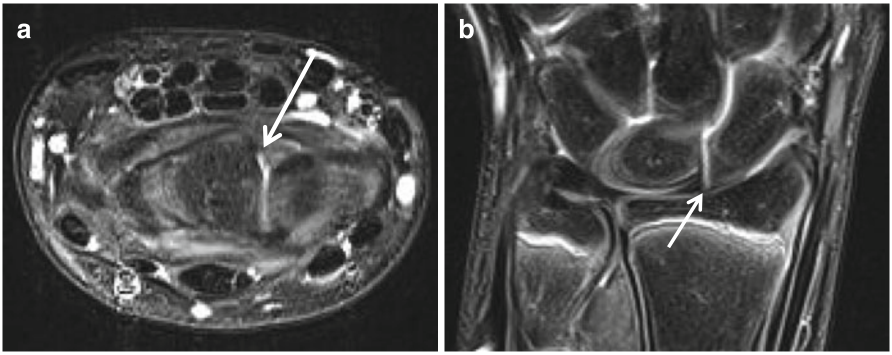

Fig. 23.16 Ten-year-old male gymnast with acute pain and giving way during hyperextension movement, chronic residual pain at the dorsal aspect of the wrist. MRI performed 4 months post-trauma. MRI after IV gadolinium administration (indirect arthrography) with coronal TSE T1WI with FS (**b**) and axial TSE intermediate TE FS (**a**). Demonstration of increased SI at the volar part of the SL ligament (**a** *arrow*), perforation at the proximal part of the SL ligament (**b** *arrow*)

chronic overuse lesions of the LT ligament (Viegas et al. 1990). Patients with LT injuries typically present with ulnar-sided wrist pain after high-energy ulnar deviation impaction to the wrist or in cases with chronic ulnotriquetral abutment. Advanced TFCC lesions include LT ligament disruption (Fig. 23.11). Imaging in CID demonstrates typically a step-off between the triquetrum and lunate (Figs. 23.18 and 23.19); LT dissociation is uncommon; however, cutoff is not as strictly defined compared to LT dissociation. Rupture of the dorsal and ventral components of the

Fig. 23.17 SLAC wrist. PA left wrist radiograph showing radiocarpal and midcarpal OA with lunatomalacia, discontinuity of the proximal and midcarpal line of Gilula

Table 23.2 SL instability staging

0	Volar SL perforation: physiologic aging phenomenon
I	Partial dorsal and/or volar SL lesion (normal radiographs)
II	Complete SL rupture (stress radiographs)
III	Complete rupture SL and extrinsic ligaments (DISI)
IV	OA

LT ligaments is best demonstrated on high-resolution axial(-oblique) CTA or MRA perpendicular to the LT joint space (Fig. 23.3b). LT injuries without instability respond well to immobilization. Acute LT injuries with instability and chronic LT injuries can be treated arthroscopically (Weiss et al. 2000). Volar intercalated segment instability pattern (VISI) can be seen in healthy patients with lax ligaments, but posttraumatically, it is due to the lunate flexing volarly on the radius as the capitate tilts dorsally (Linscheid et al. 1972). In clinical practice physiologic VISI is more frequent compared to pathologic VISI. On lateral radiographs VISI is characterized with a volar tilt of the lunate relative to the radius, dorsal tilt of the capitate relative to the lunate of 30°, or more and decreased scapholunate angle lower than 30° (Fig. 23.19b); on PA radiographic view, the scaphoid appears shortened producing a signet ring sign with triangular shape of the lunate (Fig. 23.19a) and ulnar displacement of the triquetrum with broken proximal line of Gilula (Fig. 23.19a). VISI is a sign of midcarpal instability or lunotriquetral injury. LT CID instability is staged according to Table 23.3.

23.5.3 Midcarpal Instability

Carpal instability can also occur due to loss of the normal ligamentous restraints (especially the arcuate ligament complex) between the carpal rows, for example, ulnar midcarpal instability (MCI). This is a type of nondissociative instability

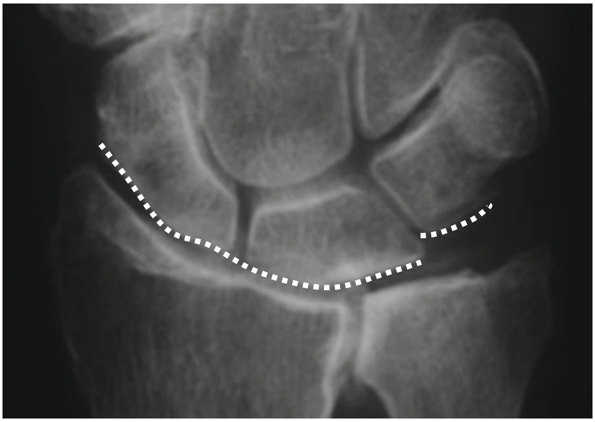

Fig. 23.18 LT lesion. Right wrist CR PA with discontinuity of the proximal (*dotted line*) and midline of Gilula

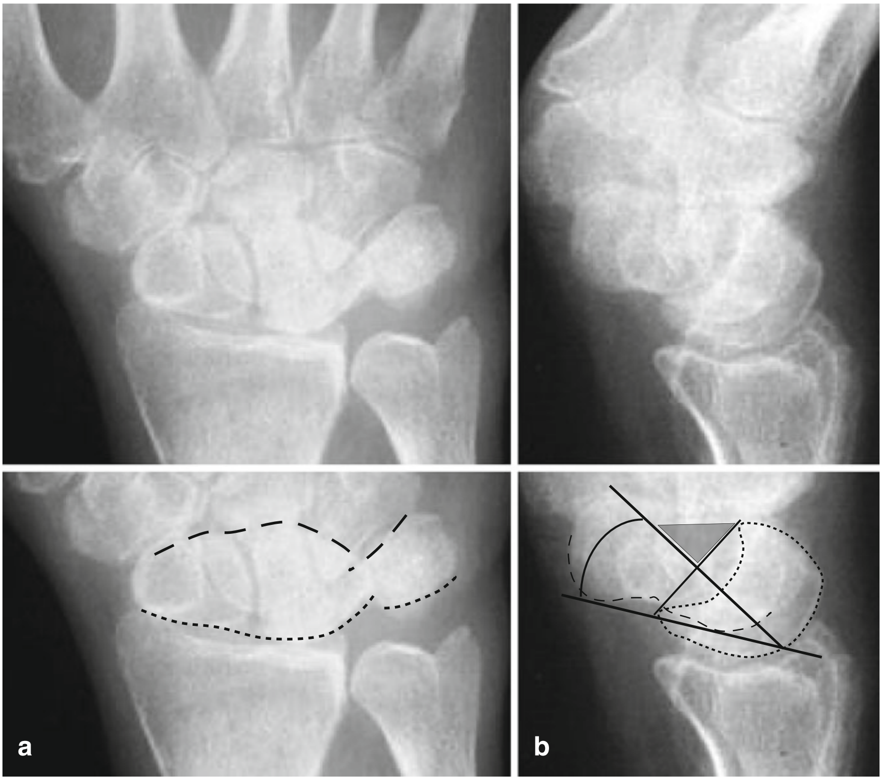

Fig. 23.19 VISI CR PA (**a**) and lateral view (**b**), images without and with drawings. Discontinuity of proximal (**a**, *dotted line*) and mid (**b**, *dashed line*) Gilula carpal lines with increased overprojection of the capitate and lunate. VISI with volar angulation of lunate bone (**b** *dotted contour*) and decreased scapholunate angle (**b**, *curved line*). Proximal lining of the scaphoid (**b** *dashed contour*)

Table 23.3 LT instability staging

I	LT tear (no VISI)
II	LT + RLT (VISI)
III	LT + RLT + RT (VISI)
IV	OA

(CIND) (Table 23.1). Midcarpal instability is usually associated with a painful and audible clunk as the distal carpal row subluxates and then reduces back against the proximal row with ulnar deviation of the wrist (Lichtman et al. 1981). Midcarpal instability is often visible as volar flexion of the entire proximal carpal row on radiographs (Lichtman et al. 1981) with VISI pattern of instability. Dynamic US can be used to confirm the diagnosis of midcarpal instability by identifying a triquetral catch-up clunk (Toms and Chojnowski 2009).

23.5.4 Perilunate Carpal Dislocation and Lunate Dislocation

Hyperextension wrist trauma may lead to dorsal perilunate radiocarpal dislocation (Fig. 23.14) and subsequently with reduction of the carpus to volar lunate dislocation (Fig. 23.15). This instability is regarded as complex (Table 23.1). These conditions are recognized on PA and lateral radiographs (Figs. 23.20 and 23.21). Prompt recognition and reduction are required. The intrinsic SL and LT ligaments are involved if respectively triquetrum or scaphoid fractures are absent. Perilunate dislocations without fractures are known as lesser arc injuries, whereas dislocations with fractures are known as greater arc injuries (Fig. 23.22).

23.6 Ulnar Wrist Pain

Imaging evaluation of patients with ulnar-sided wrist pain is mandatory because of its broad clinical differential diagnosis comprising DRUJ, TFCC, LT, and ECU lesions, pisotriquetral instability, ulnoradial impingement (Fig. 23.23), and ulnocarpal impaction-abutment. Neutral PA and lateral radiographs demonstrate the variance of the ulna, distal radioulnar joint dislocations, and signs of chronic ulnar impaction-abutment syndrome related to ulna majus or ulnoradial impingement related to ulna minus. TFCC evaluation is done with MRI.

23.7 TFCC Injuries

TFCC injuries are common in athletes in specific sports because of the high loads placed on the ulnar side of the wrist. Injuries to the TFCC can occur during acute trauma with fall or in repetitive stress in racquet and ball sports especially in ulnar-neutral and ulnar-positive variance. In over 2.5 mm ulnar variance, the load going through the ulna is doubled to 40 %. Acute tears may be due to axial loading of the

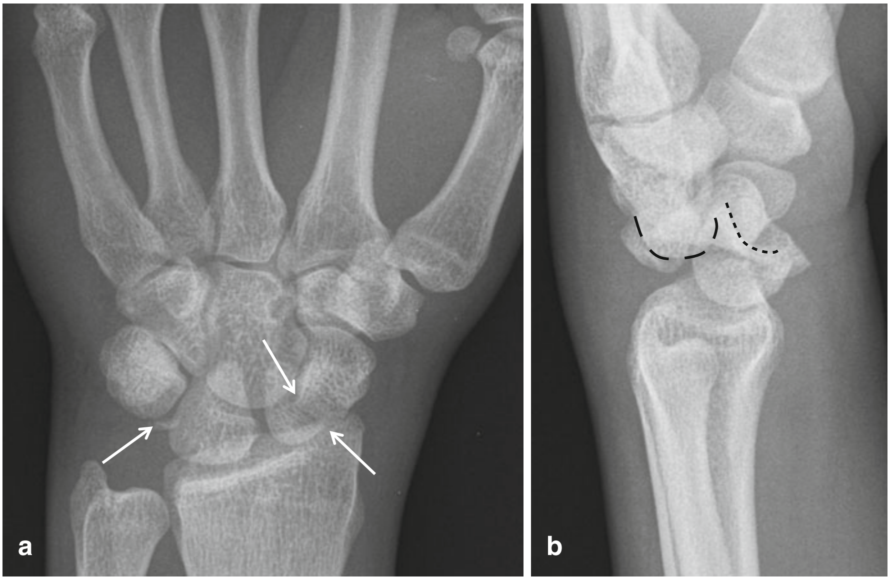

Fig. 23.20 Dorsal "transscaphoid" perilunate dislocation greater arc lesion. Dorsal dislocation of the carpus is best demonstrated on lateral radiograph (**b**) demonstrating the volar location of the lunate bone distal articular surface (**b** *dotted line*) and dorsal location of the capitate bone proximal articular surface (**b** *dashed line*). Midportion scaphoid (**a** *arrows*) and triquetrum avulsion fracture fragment (**a** *arrow*) are best demonstrated on PA view (**a**)

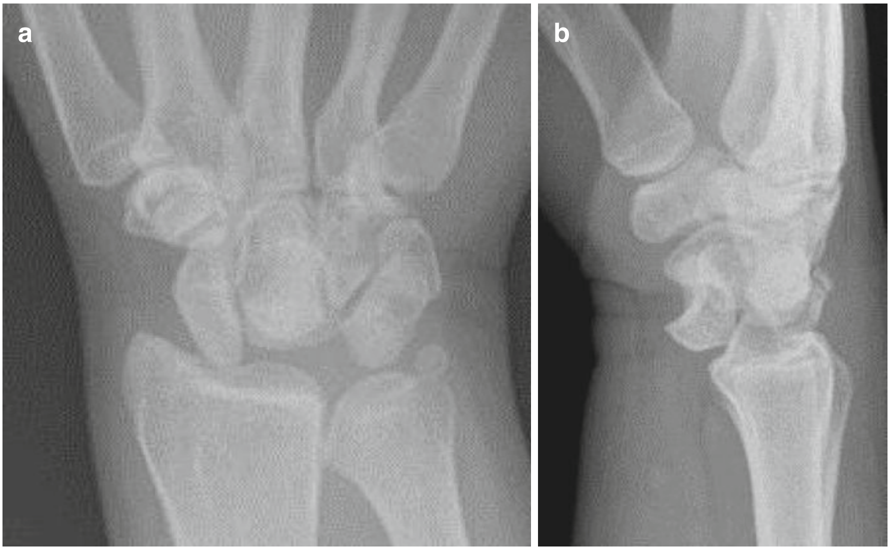

Fig. 23.21 Lunate dislocation (stage IV perilunate instability), lesser arc type. Discontinuity of Gilula lines I and II due to missing lunate at the proximal row on PA view (**a**); volar dislocation of the lunate is demonstrated on lateral view (**b**)

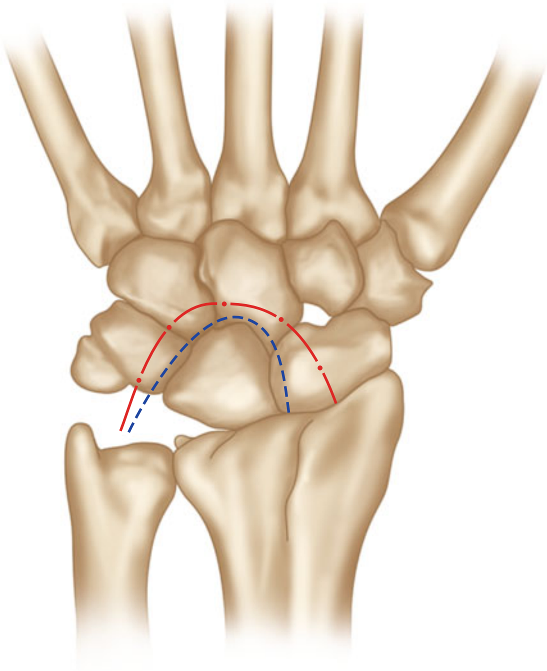

Fig. 23.22 Drawing demonstrating the lesser arc (*dashed line*) and greater arc (*dot-dashed line*) in (peri) lunate dislocations

Fig. 23.23 Ulnar (ulnoradial) impingement. Ulna minus with scalloping sclerosis at the distal radius related to chronic ulnar impingement. Increased density of the lunate bone related to AVN

distal radius, such as a FOOSH, leading to proximal radial shift and tearing of the TFCC over the ulnar head. Sudden excessive pronation or supination may also cause TFCC disruption. TFCC tears should be suspected in patients with ulnar-sided wrist pain and tenderness. On physical examination, there may be localized tenderness over the TFCC, with pain on pronation and supination. With rotation of the forearm, a palpable or audible click may be present. Lesions of the TFCC may be confined to the TFC disk or involve one or more components of the TFCC (Fig. 23.2c). There may also be associated DRUJ instability. The palmer classification of TFCC tears divides TFCC tears into traumatic (classes 1A–D) and degenerative (classes 2A–E) types (Palmer 1989) (Table 23.4). Traumatic tears are usually linear and occur at the edges of the TFCC at either the soft tissue attachments or attachment to the distal radius or ulna. The attachment to the radius and the central part of the disk, “white areas,” has no regeneration capacity due to its avascular fibrocartilaginous content; lesions in these parts are permanent and may need surgical-arthroscopical intervention. Accuracy of 3 T of these white area lesions is high. The two ulnar attachments, “red areas,” are collagenous and vascularized, regeneration is possible, and traumatic lesions at this area may be treated conservatively. Diagnosis of traumatic tears of the ulnar attachments is difficult. Accuracy of MRI in this area is low but increases if special interest is paid on 3 T MRA. Degenerative tears generally occur in ulnar impaction-abutment syndrome, in older people, and are generally located in the midportion or central nonvascularized part of the TFC disk (Fig. 23.2c). Coronal reconstructed high-resolution CTA or (in)direct MRA may demonstrate TFCC (Fig. 23.2a–c) and its lesions (Figs. 23.2c, 23.24 and 23.25). Superior contrast resolution, joint distention, and the flow of contrast facilitate the diagnosis of lesions of the TFCC and intrinsic ligaments on contrast-sensitive sequences making MRA the preferred modality for imaging internal derangements of the wrist (Maizlin et al. 2009). Special interest should be paid to the evaluation of the variability of the ulnar and the LT attachments of the TFC on coronal imaging planes and to the palmar ulnolunate and ulnotriquetral ligaments on sagittal imaging planes (Benjamin et al. 1990; Totterman and Miller 1995)

Table 23.4 Palmer classification of TFCC divides lesions into two categories according to the accurate anatomic description of tears

Class 1: traumatic
A. Central slit-like perforation
B. Ulnar avulsion – with or without styloid fracture
C. Distal avulsion (from carpus to triquetrum to LT ligament)
D. Radial avulsion with sigmoid notch fracture or without sigmoid notch fracture
Class 2: degenerative (ulnar impaction syndrome)
A. TFCC central disk wear
B. TFCC central disk wear + lunate and/or ulnar head chondromalacia
C. TFCC central disk perforation + lunate and/or ulnar head chondromalacia
D. TFCC central disk perforation + lunate and/or ulnar head chondromalacia + lunotriquetral ligament perforation
E. TFCC central disk perforation + lunate and/or ulnar head chondromalacia + lunotriquetral ligament perforation + ulnocarpal arthritis

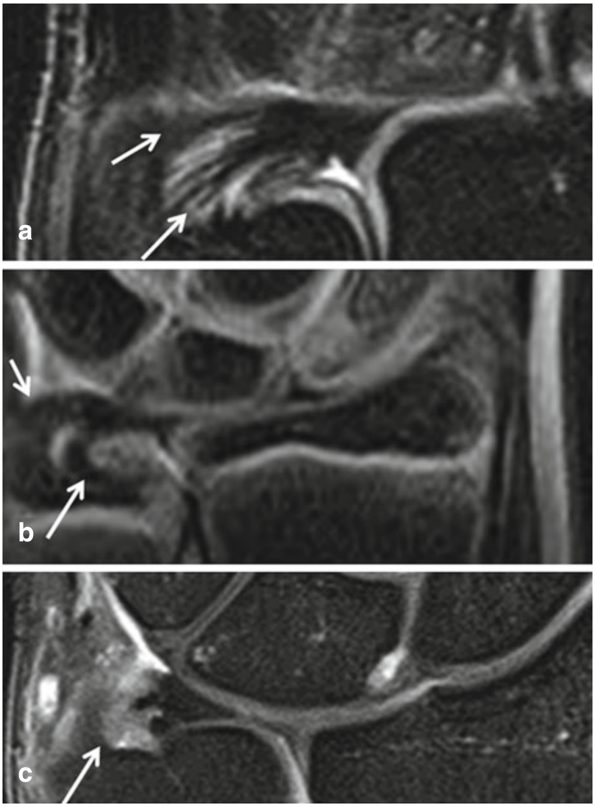

Fig. 23.24 TFC lesion MRI with coronal intermediate TE FS (**a**, **b**) of ulnar attachments and MRA coronal SE T1 FS (**c**) of ulnar-sided TFC lesion. High variability of the ulnar attachments (**a**, **b** *arrows*) of the TFC is noted; these attachments often have nonhomogeneous striated pattern (**a**) with insertion on the styloid process and sigmoid notch of the ulna. Disruption of the insertion of the sigmoid notch (*arrow*) is demonstrated in (**c**); gadolinium enhancement is demonstrated in the area of disruption

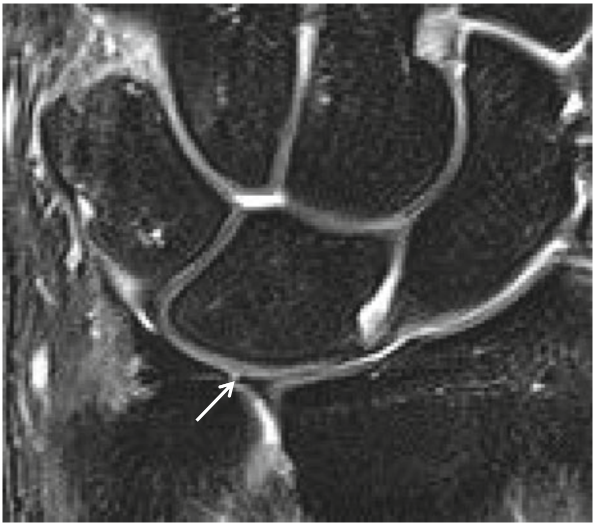

Fig. 23.25 Palmer Ia lesion, MRI with coronal intermediate TE FS demonstrating slit-like disruption with straight margins of the central "white" area of the TFC

(Fig. 23.24). Dynamic MRI examination is not routinely done but has an advantage in evaluating the stability of the TFC, ulnocarpal abutment, and ulnoradial impingement. By means of dynamic MRI, it is possible to make a preoperative diagnosis of an ulnocarpal impingement (Gabl et al. 1996).

23.8 Tendon Injuries

Overuse tendon injuries are more frequent compared to acute tendon lesions. Inflammation of tendon sheaths is the most frequent abnormality found on US of the wrist. Overuse tenosynovitis involves mainly the peritendinous synovial sheath covering type II tendons of the extensor compartments of the hand and the wrist. Hypertrophic-exudative tenosynovitis is seen as thickening of the tendon sheath that is distended by a hyposonant effusion with increased vascularity on power Doppler ultrasound of the synovial membrane (Fig. 23.26). At the first extensor compartment, this is either found at the level of the extensor retinaculum and is then called de Quervain's disease or can also be located at the crossing of the first and second compartments proximal to the extensor retinaculum and is then called proximal intersection syndrome. These conditions are related to repetitive wrist motion, especially (repetitive rotating and gripping) common in racquet sports and in athletes who use a lot of repetitive thumb motion. Clinical diagnosis with positive Finkelstein's test is straightforward. Chronic de Quervain's disease produces thickening of the extensor retinaculum resulting in stenosing tenovaginitis. Ultrasound or MRI is only indicated in chronic recidivism and may demonstrate anatomical variants with predestination to de Quervain's tenovaginitis such as split compartment in which the adductor pollicis longus and extensor pollicis brevis are located in individual compartments or constitutional plural tendons not to be mixed up with longitudinal tendinopathic split

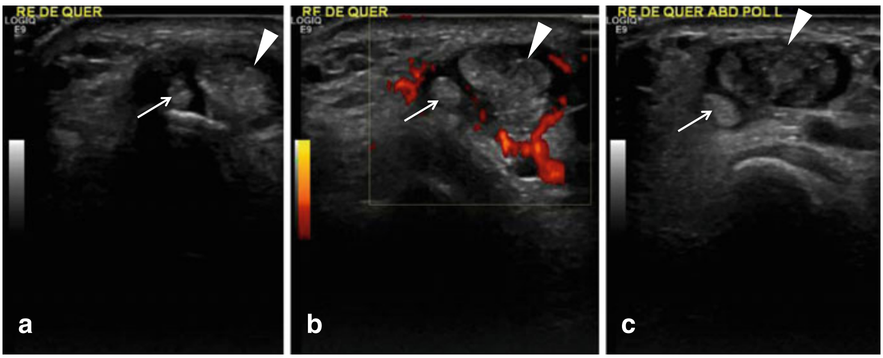

Fig. 23.26 De Quervain tenovaginitis with hypervascular thickening of the hyposonant synovium surrounding the extensor pollicis brevis (*arrow*) and abductor pollicis longus tendons (*arrow head*) in cases of unicompartmental de Quervain compartment. The abductor pollicis longus is composed of multiple tendons (**c** *arrow head*); this anatomical variant best demonstrated distal to the extensor retinaculum (**c**) is prone to recurrent disease. Axial ultrasound at the radial aspect of the wrist, at the level of the extensor retinaculum (**a**), distal adjacent to the extensor retinaculum (**b**) and at 1cm distal to the extensor retinaculum (**c**)

(de Lima et al. 2004; Kulthanan and Chareonwat 2007) (Figs. 23.26 and 23.27). Distal intersection syndrome at the level of Lister's tubercle at the crossing of the third and second extensor compartments is less frequent in sports and may be related to overuse or blunt trauma at the dorsum of the wrist. Clinical diagnosis due to its rarity is not always straightforward; diagnosis is then made on US or MRI (Parellada et al. 2007). Releasing an object with a sudden twist-and-snap action will trigger tenovaginitis of the flexor compartments of finger 2, 3, or 4, e.g., in bowling, weightlifting, and rowing. Extensor carpi ulnaris tenovaginitis and/or tendon dislocation is the second most common type of sports-related closed tendon injury. Extensor carpi ulnaris lesions are most commonly seen in basketball players and those playing racquet sports, specifically tennis with double-handed backhand play. MRI easily detects permanently dislocated ECU tendons; dynamic US in pronated position with elbow flexion or dorso-ulnar position to force the tendon to the ulnar side of its fibro-osseous groove may also demonstrate intermittent tendon dislocation (Fig. 23.28). Those closed tendon injuries that are undiagnosed and untreated may result in permanent instability (Aronowitz and Leddy 1998). Tendon rupture and its severity can also be detected on US. Tendon rupture in non-tendinopathic tendons is most often related to open – perforating – trauma. The interest of diagnostic ultrasound is the preoperative location of the retracted tendon fragments. Spontaneous distal flexor digitorum profundus ruptures are described in football and other contact sports with characteristic clinical presentation of flexion deficit at the DIP. The interest of US in this condition is the location of the proximal retracted tendon: in type I the tendon is retracted up to the level of the hand palm, in type II the tendon is retracted up to the level of the PIP joint, and in type III the tendon is distally located at the level of the A4 pulley covering the phalanx media related to an avulsed bone fragment continuous with the flexor digitorum profundus tendon.

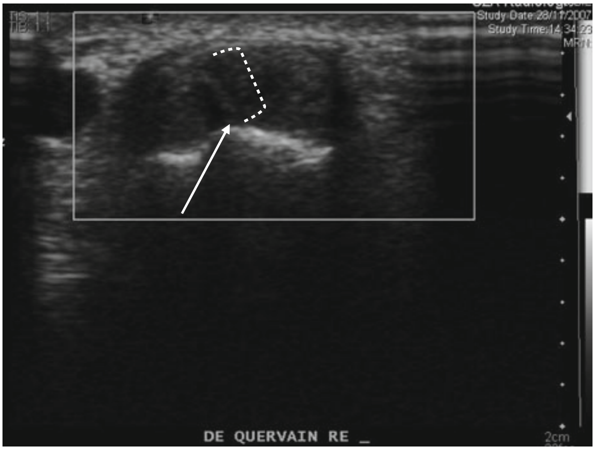

Fig. 23.27 Anatomical variant: de Quervain split compartment demonstrated by bony protuberance at the floor of the fibro-osseous groove (*arrow*) and septum (*accolade*); in this condition one of both compartments may show signs of tenovaginitis

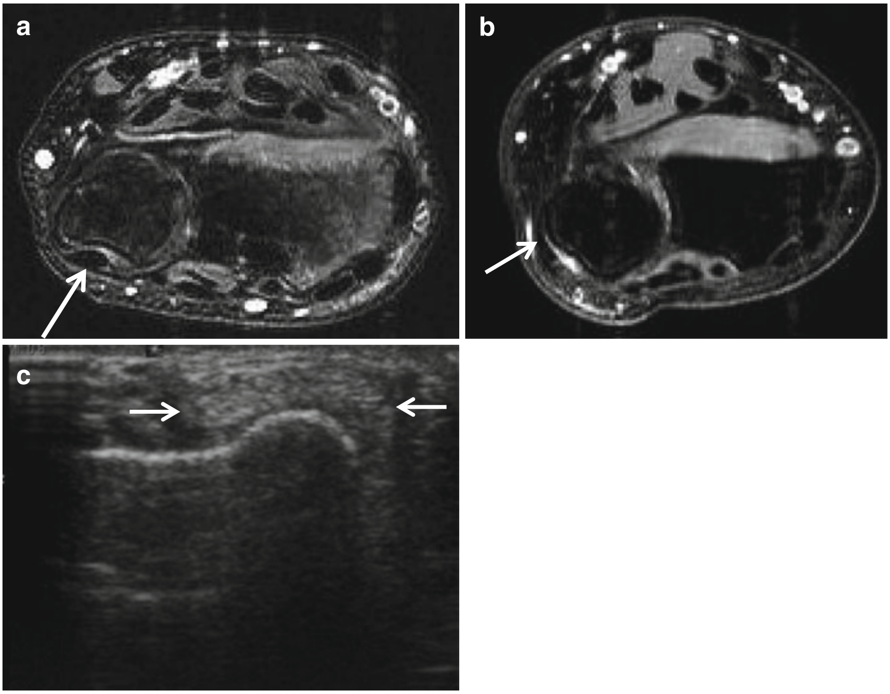

Fig. 23.28 ECU dislocation MRI and US. Normal patient with ECU tendon centered at the dorso-ulnar groove of the ulna (**b** *arrow*). Ulnar-sided subluxation of the ECU tendon (**a** *arrow*) in tennis player with chronic ulnar-sided wrist pain during tennis play. Similar findings on US axial imaging plane at the dorso-ulnar aspect of the wrist during forearm pronation, ECU tendon with subluxated position (**c** *arrows*) at the ulnar rim of the fibro-osseous groove

23.9 Neurovascular Injuries

Peripheral nerve injuries of the upper extremity in sports are rarely reported; however, they can be most debilitating to an athlete. Peripheral nerves are prone to various types of injury in sport owing to their superficial location. Most commonly, direct blows or repetitive microtrauma is implicated as a mechanism of injury. Sports, such as gymnastics, mountain climbing, and baseball, were most commonly involved (Nuber et al. 1998). Hypothenar hammer syndrome (HHS) is related to repetitive trauma of the ulnar-volar aspect of the wrist with characteristic cross-sectional imaging features which include a “corkscrew” appearance of the diseased ulnar artery segment (resulting from alternating stenosis and ectasia), thrombosis with or without aneurysm, and embolic occlusions of the digital arteries. Imaging accurately determines location, morphology, and extent of vascular injury, as well as presence of collaterals (Fig. 23.29). Conventional angiography is considered the reference standard in distinguishing HHS from other vascular pathologies; IV gadolinium-enhanced MRI of MR angiography, gray scale with color (power)

Doppler ultrasound along Guyon's canal with high-frequency transducers, is an accurate noninvasive test to determine the presence, size, and extent of HHS and identify collateral vessels (Fig. 23.29) (Dreizin and Jose 2012). Bicyclists develop ulnar nerve impingement at Guyon's canal related to local compression by drop down handle bars. Prevention by bicycle handkerchiefs is common practice.

23.10 Specific Types of Wrist Sports Injuries

The complex anatomy and function make the wrist and hand joints vulnerable to injury in sports. Sports-specific biomechanical injury depends on the unique characteristics that place a particular structure at risk for injury during a sporting activity.

23.10.1 Golf, Baseball, and Racquet Sports

Higher handicap golf players typically experience injuries that result from swing mechanics, whereas lower handicap and professional players have overuse as the major cause of their injuries. Tendon injury is the most common problem seen in the wrist and forearm of the golfer (Bayes and Wadsworth 2009; Guerini et al. 2007). The chronic use and movements in racquet sports, golf, and baseball require the carpus to resist torque stress. Depending on the strength of the weakest link, the hyperpronation-supination activity in the modern golf swing can result in either an acute or chronic injury. Overuse injuries are common in racquet sports, netball, and volleyball (Howse 1994). They are the result of

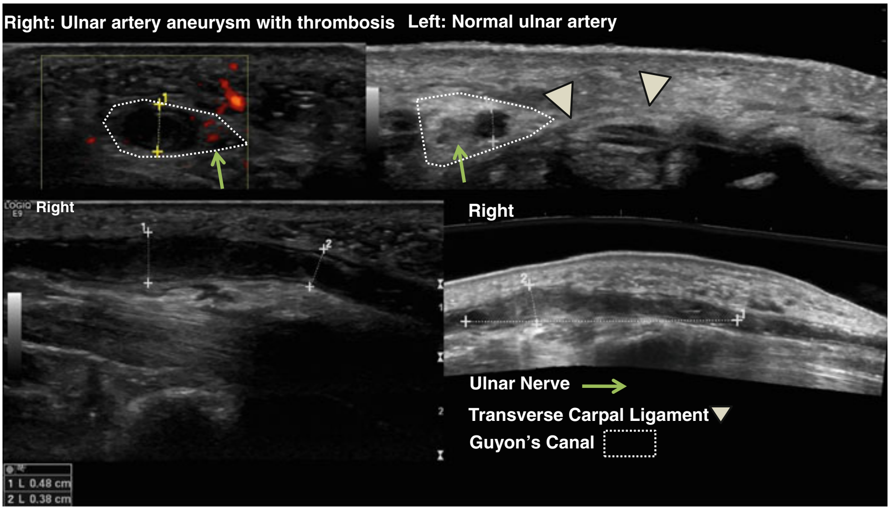

Fig. 23.29 Hypothenar hammer syndrome (HHS) US and power Doppler demonstration. *Thickened right* ulnar artery with thrombosis at Guyon's canal (*transverse left upper*, *longitudinal left lower* and *right lower*), normal left ulnar artery (*transverse US right upper*)

repetitive application of stresses to otherwise normal tissues that overcome the tissue's adaptive ability. This causes sufficient structural disruption and thus produces injuries without necessarily causing complete loss of function. The common pathway is most likely to be microdamage to tissue collagen, combined with a direct or indirect effect on the microvasculature, with subsequent oxygen deprivation (Pitner 1990).

23.10.2 Gymnastics

Wrist injury, for example, FOOSH during a gymnastic move, may directly result in a fracture; only if radiographs exclude a fracture the condition is referred to as wrist sprain with contusion of soft tissue or joint capsule injury. Overuse in gymnasts may lead to dorsal radiocarpal impingement syndrome (gymnast's wrist) with thickening of the dorsal radiocarpal capsule that demonstrated on US.

23.10.3 Roller Skating/Rollerblading/Skateboarding and American Football

23.10.3.1 Rollerblading and Roller Skating and Skateboarding

Wrist injury, for example, FOOSH during rollerblading or skating or skateboarding, may directly result in a fracture; only if radiographs exclude a fracture, the condition is referred to as wrist sprain with contusion of soft tissue or joint capsule injury.

23.10.3.2 American Football

Flexor digitorum profundus lesions (Jersey finger) are common in American football. US may be indicated to stage the tendon retraction.

23.11 Finger Injuries

23.11.1 Extensor Tendon Rupture

Extensor tendon lesion may be the result of penetrating trauma along the course of the tendon at the wrist and hand. Direct trauma to dorsal aspect of the PIP joint or proximal phalanx may result in insufficiency of the central slip. These lesions are best demonstrated on US; skin markings are drawn on the site of tendon retraction.

23.11.2 Dorsal Hood Rupture

Lesions of the sagittal bands are caused by direct trauma to the dorsum of the MCP joints or related to overuse and responsible for extension deficit and deviation of the central slip during MCP flexion. Dorsal hood lesions are well depicted on ultrasound (Fig. 23.30).

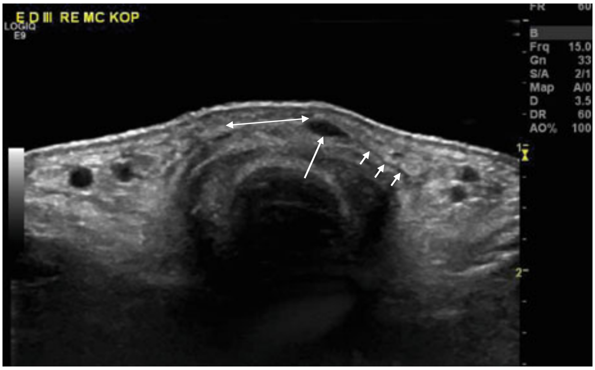

Fig. 23.30 Dorsal hood lesion MC III. Ultrasound axial image at MC-head III. Discontinuity of dorsal hood at the radial side of the metacarpal head with shift of the common extensor tendon (*arrow*) to the ulnar side. Normal continuity of the sagittal bands of extensor hood (*small arrows*) at the ulnar aspect

23.11.3 Flexor Tendon Rupture

Traumatic rupture of the flexor digitorum superficialis is rare; a typical flexor tendon lesion at the fingers is located at the distal insertion of the flexor digitorum profundus (Jersey finger or mallet finger) with flexion deficit at the DIP joint. MRI and US are able to demonstrate these tendon ruptures and the site of proximal retraction of the tendon. Minor retraction distal to the level of A4 pulley is noted if a piece of phalangeal bone remains attached to the tendon.

23.11.4 Annular Pulley Rupture

Rupture of the pulleys may be the result of penetrating trauma or overuse in (rock) climbing sports in which the ring or middle finger is most frequently involved or in baseball pitchers with lesions typically at the middle finger. The pulley lesion is initially partially severed and starts proximally at the A2 level (Fig. 23.6c); in more extensive overuse, the complete A2 pulley may be involved with extension up to the A3 or A4 pulley. The result is bowstringing of the tendons between the joints with extension deficit of the phalanx.

23.11.5 Volar Plate and Collateral Ligament Injury

The volar plate is stronger than its bony attachments; hyperextension trauma, often related to axial ball trauma, results in an avulsion fracture at the distal insertion of the volar plate; this fracture is demonstrated on lateral finger radiographs and US (Fig. 23.31). Lesions of the collateral ligaments of the long fingers are related to varus or valgus trauma often with dislocation at IP joints.


P Med
Res
a
Courtesy of Collins James
2.0
b
c

23.11.6 Ulnar Collateral Ligament of the Thumb

The ulnar collateral ligament of the thumb is elongated in gamekeeper's thumb; in grade III strain (complete rupture), the ligament may dislocate superficially to the adductor pollicis aponeurosis; this condition is called Stener's lesion and may be recognized on MRI or (dynamic) US (Figs. 23.32 and 23.33) (Creteur and Peetrons 2000; Lohman et al. 2001), Stener's lesion is an indication for surgical reposition and suture of the ulnar collateral ligament.

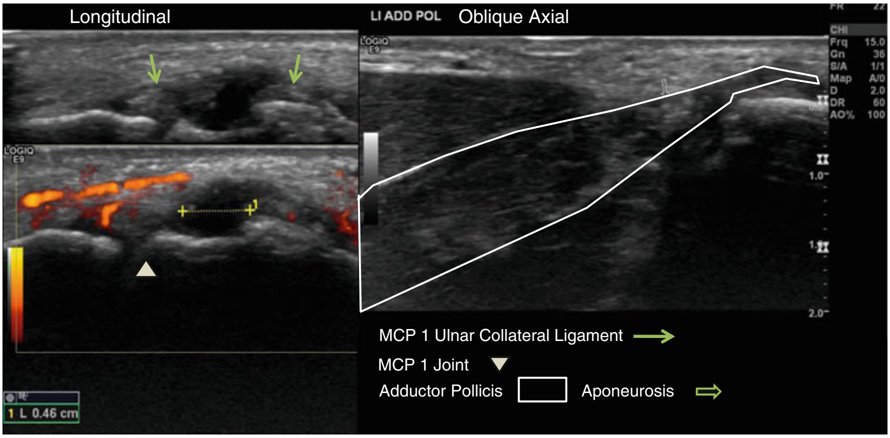

Fig. 23.32 UCL tear grade III without ligament dislocation. US demonstration of retracted fragments on coronal view (*arrows left upper*, *left lower*), sharp upper lining of the adductor pollicis and aponeurosis on oblique axial view (*thick arrow*)

Fig. 23.31 Volar plate avulsion fracture. Hyperextension trauma of the fingers may result in avulsion fracture of the distal phalangeal insertion of the volar plate of the PIP joint, easily depicted on lateral radiograph (**b** *arrow*); also documented on US (**a** *arrow*), minor bone marrow edema is present on MRI without demonstration of the fracture (**c** *arrow*, sagittal intermediate TE FS)

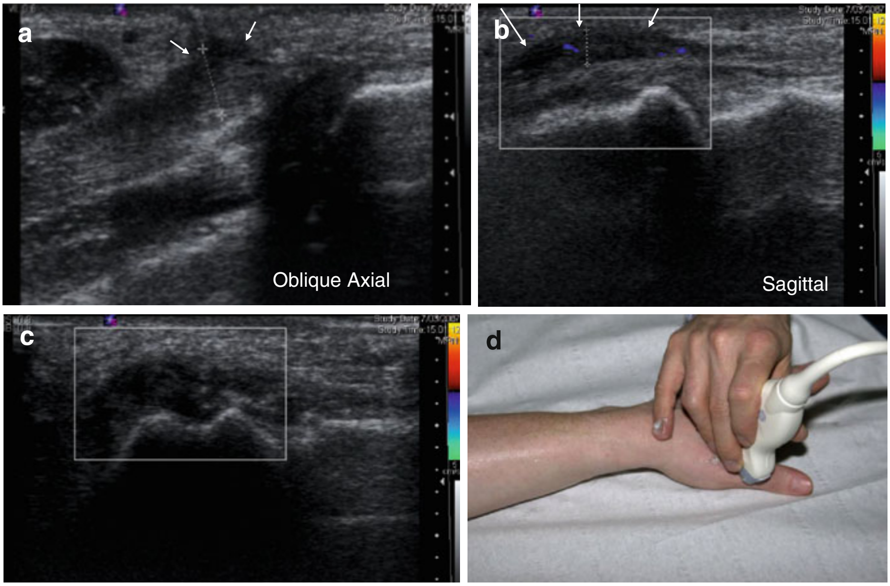

Fig. 23.33 UCL tear grade III with ligament dislocation superficial to adductor pollicis aponeurosis. US demonstration. Blurred upper lining of the adductor pollicis aponeurosis on oblique axial view (**a** and **d** probe positioning) due to dislocation of the ulnar collateral ligament distal retracted part (**a** *arrows*, **b** *arrows*) superficial to the adductor aponeurosis

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Nuclear Medicine Imaging of Sport Injuries of the Wrist, Hand and Fingers

24

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Abstract

The hand is a complex arrangement of small bones, joints and soft tissue that are at risk of injury in a wide range of sporting activities. Many bone and soft tissue injuries occur in characteristic patterns, and a simple classification for these injuries is determined by the location and the structure injured. In most of these injuries, nuclear medicine imaging has proven to be extremely useful, with bone scintigraphy and SPECT/CT depicting a characteristic pattern of increased tracer uptake in the region of interest.

Furthermore, missed diagnosis and inadequate treatment of wrist, hand and finger injuries frequently lead to serious disability. Providing a correct diagnosis in the early posttraumatic period is essential. Radiological (plain radiographs, ultrasound, CT, MRI) and nuclear medicine (bone scintigraphy with SPECT/CT) imaging techniques are useful in providing the correct diagnosis, in shortening the duration of immobilisation and in decreasing the complication rate.

Abbreviations

APL	Abductor pollicis longus
CRPS	Chronic regional pain syndrome
CTS	Carpal tunnel syndrome
DIP	Distal interphalangeal
DRUJ	Distal radioulnar joint
ECP	Extensor pollicis brevis
ECRB	Extensor carpi radialis brevis
ECRL	Extensor carpi radialis longus

ECU	Extensor carpi ulnaris
FCR	Flexor carpi radialis
FCU	Flexor carpi ulnaris
FDP	Flexor digitorum profundus
PIP	Proximal interphalangeal
RSD	Reflex sympathetic dystrophy
SLL	Scapholunate ligament
TFCC	Triangular fibrocartilage complex
UCL	Ulnar collateral ligament

24.1 Introduction

The wrist, hand and fingers are particularly susceptible to injury due to their exposed position and their key role in many activities. Frequently, the most debilitating complications of these conditions are the result of misdiagnosis or delayed diagnosis (Foreman and Gieck 1992). Hence imaging plays an important role in the evaluation of wrist, hand and finger injuries. In determining which imaging technique might be useful, the sport physician, radiologist and nuclear medicine physician must, as always, be guided by a thorough history and physical examination. In particular, the history often holds the key to understand the precise mechanism of the injury, and this information alone will usually assist the radiologist/nuclear medicine physician in the selection of the most appropriate imaging protocol and direct the search for relevant imaging findings, which can sometimes be remarkably subtle or overlooked (Fig. 24.1). Many bone and soft tissue injuries occur in characteristic patterns. Generally, the mechanisms of injury can be divided into four main categories: throwing, twisting, weight bearing and impact.

A simple classification for these injuries would be determined by the location and the structure injured:

- Tendon
- Nerve
- Ligament
- Bone/joint
- Combinations of the above

Wrist, Hand and Fingers Algorithm

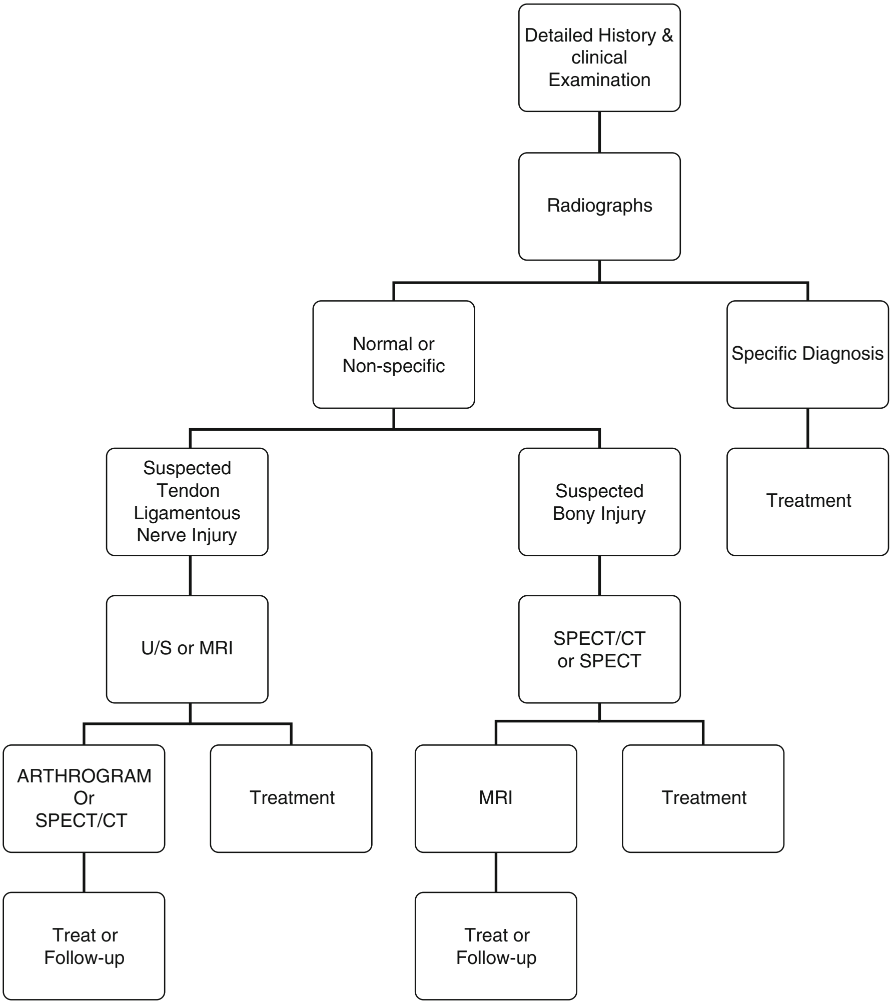

Fig. 24.1 A diagram of imaging approach to diagnose sport injuries of the wrist, hand and fingers

24.2 Tendons

24.2.1 Tendinopathies

Tendons in the wrist pass through the retinacular tunnels which are lined by the synovium. In tendinopathies the synovium is the primary tissue involved in the inflammation which is caused by repetitive motion and trauma usually experienced in racquet sports, baseball and golf (Kiefhaber and Stern 1992).

24.2.1.1 De Quervain's Tenosynovitis

De Quervain's tenosynovitis is inflammation of the tenosynovium of the first dorsal compartment tendons, the abductor pollicis longus (APL) and extensor pollicis brevis (EPB), and it is the most common tendinopathy of the wrist (Rettig 2001). Tenderness to palpation will be elicited along the radial aspect of the distal radius. The pain is evoked with Finkelstein's test which is the classic diagnostic test for de Quervain's tenosynovitis, elicited by the patient placing the thumb into the palm, wrapping fingers around the thumb, and then the wrist is passively ulnar deviated (Finkelstein 1930).

The diagnosis is usually clinical but imaging techniques may be used when the diagnosis is uncertain, to identify anatomical variants leading to recidivistic tendovaginitis (split compartment, supernumerary tendons) or to exclude other possible pathologies. The scintigraphic appearance of de Quervain's tenosynovitis can help to confirm the diagnosis while excluding other causes of wrist pain (Vande Streek et al. 1998; Leslie 2006).

Generally, tendon and ligament lesions are poorly visible on planar imaging, SPECT and SPECT/CT. In particular, superficial lesions do not show any osseous changes. This is very likely the reason for the low sensitivity of SPECT or SPECT/CT for these lesions (Leslie 2006; Huellner et al. 2012; Pin et al. 1988; Akdemir et al. 2004).

The scintigraphic appearance of de Quervain's tenosynovitis is noted by hyperaemia on the blood pool phase and focal linear skeletal uptake along the radial aspect of the wrist on the late static views (Fig. 24.2) (Leslie 2006).

24.2.1.2 Proximal Intersection Syndrome

This is an overuse-related inflammatory condition where the tendons of the first dorsal compartment tendons, the abductor pollicis longus (APL) and extensor pollicis brevis (EPB), pass over the tendons of the second dorsal compartment, the extensor carpi radialis longus (ECRL) and extensor carpi radialis brevis (ECRB). Intersection syndrome affects individuals involved in activities requiring repetitive

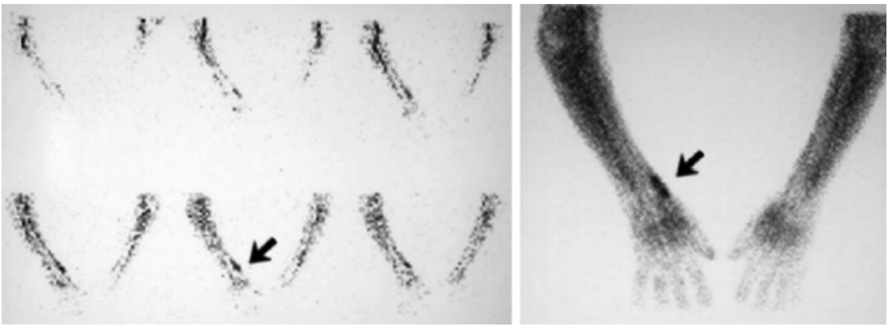

Fig. 24.2 De Quervain's tenosynovitis, blood flow hyperaemia (*arrow*) and focal linear uptake (*arrow*) along the radial aspects of the wrist on the late images (Courtesy: Leslie (2006))

flexion and extension of the wrist and therefore tends to affect sportsmen such as weightlifters, rowers, canoeists, skiers and racket sport players. There is tenderness to palpation and crepitus along the radial aspect of the dorsal distal radius (Dobyns et al. 1978).

In most cases, the clinical presentation is specific; in rare cases it may lead to misdiagnosis or a wide differential diagnosis necessitating imaging for further management.

The scintigraphic pattern is usually mild tracer uptake in the region of the tendon sheaths at the intersection between the extensor compartments (Huellner et al. 2012; Pin et al. 1988).

24.2.1.3 Extensor Carpi Ulnaris Tendinopathy

Extensor carpi ulnaris (ECU) tenovaginitis is the second most common tendinopathy of the wrist (Wood and Dobyns 1986). The extensor carpi ulnaris tendon passes through the sixth dorsal extensor compartment. The tendon may, under appropriate conditions, subluxate or dislocate. ECU tenovaginitis with or without dislocation produces pain and swelling along the dorsal ulnar aspect of athletes who participate in racquet sports, rowing and squash (Kiefhaber and Stern 1992).

Nuclear medicine imaging may prove extremely useful, with the scintigraphic pattern of ECU tenovaginitis which is elongated increased uptake in the blood flow and blood pool phase along the anatomical course of the ECU tendon. Late static images demonstrate increased focal abnormal uptake along the anatomical course.

24.2.1.4 Flexor Carpi Ulnaris Tendinopathy

The flexor carpi ulnaris is a type I tendon; it lacks a synovial tendon sheath; therefore pain associated with this tendon often points to a tendinopathy including a calcific tendinopathy. The condition is associated with repetitive ulnar deviation. Flexor carpi ulnaris (FCU) tendinopathy presents with palmar-ulnar-sided wrist pain and is seen in racquet sport athletes. Examination reveals tenderness along the FCU and pain with wrist flexion (Rettig 2001; Dobyns et al. 1978).

Bone scintigraphy with ^{99m}Tc-labelled diphosphonates may demonstrate mild nonspecific uptake, which may help to confirm the clinical suspicion.

24.2.1.5 Flexor Carpi Radialis Tendinopathy

Flexor carpi radialis (FCR) tendinopathy presents with pain in the palmar radial wrist with repetitive wrist flexion. The tendon passes through a narrow fibro-osseous canal at the level of the carpal bones, and it is at greatest risk at this point (Rettig 2001; Dobyns et al. 1978). Tenderness is located over the FCR at its insertion, where it first slips to the trapezium tuberosity then slips to the base of the second and third metacarpals, and pain is reproducible with resisted wrist flexion.

Imaging findings are the same as for tendinopathies of the other tendons around the wrist (Watanabe et al. 2010; Parellada et al. 2006).

24.2.2 Tendon Tears

Tendon tears may be open, due to lacerations, or closed. Tendon tears more commonly involve the extensor tendons and extensor mechanism of the fingers than the flexor tendons (Clavero et al. 2002). Most open tendon tears are diagnosed and managed clinically and thus not discussed in this chapter. Closed tendon injuries are usually the result of blunt impaction or indirect trauma causing sudden forced stretching of a tendon. Such injuries may also be due to repetitive direct trauma.

24.2.2.1 Mallet Finger

Extensor tendon injury at the distal interphalangeal (DIP) joint is called a mallet finger. It is the most common closed extensor tendon injury in athletes. Sudden, acute, forceful flexion of the extended finger at the DIP joint most frequently accounts for this injury. A classic example is being struck on the fingertip with a ball. Four types of extensor tendon injuries have been described. Type 1, the most common, is extensor tendon avulsion from the distal phalanx with loss of tendon continuity and possibly a small chip avulsion fracture. Type 2 is a tendon and skin laceration at or proximal to the DIP joint. Type 3 is a deep abrasion with skin and tendon loss. Type 4 encompasses fractures of the distal phalanx other than small chip avulsions (Stern and Kastrup 1988). Clinical symptoms are tenderness at the dorsal part of the DIP joint with flexion at the DIP joint and lack of possible active extension of the DIP joint.

Imaging may have added value if an avulsion fracture is present, with bone scintigraphy depicting focal increased accumulation in the area of the extensor tendon at the distal interphalangeal joint. This technique may be useful for detection of avulsion fractures (Huellner et al. 2012; Pin et al. 1988; Akdemir et al. 2004).

24.2.2.2 Jersey Finger

Jersey finger is the most common closed flexor tendon injury which is avulsion of the flexor digitorum profundus (FDP). It most commonly involves the ring finger and occurs in rugby players as the result of grasping an opponent's clothing (Clavero et al. 2002). Jersey finger results from forceful hyperextension of the DIP joint with the FDP in maximal contraction. Flexor digitorum profundus avulsion is classified into four types, depending on bony involvement and retraction (Leddy and Packer 1977): Type1 is a tendon avulsion without bone fragment with retraction of the flexor digitorum profundus tendon into the palm. Type 2 is a tendon tear without bone fragment with retraction to the proximal interphalangeal (PIP) joint. Type 3 is when an avulsed bone fragment connected to the tendon that is held in place distally by the A4 pulley. Type 4 is type 3 bone avulsion with simultaneous avulsion of the tendon from the bone fragment. Symptoms are tenderness at the volar part of the DIP joint, extension position at the DIP joint and inability to actively flex the DIP joint.

Bone scintigraphy with SPECT/CT and MRI may add new information in patients with clinically nonspecific pain of the ring finger. Bone scintigraphy depicts a characteristic pattern of increased tracer uptake in the region of the flexor digitorum profundus and at the location of the avulsion fracture (Huellner et al. 2012; Pin et al. 1988; Akdemir et al. 2004).

24.2.2.3 Pulley Lesions (Climbers)

The flexor tendons and flexor pulleys are prone to sprains and ruptures. Pulley injuries occur in rock climbers (Peterson and Bancroft 2006). Pulley ruptures related to rock climbing most commonly involve the ring and middle fingers (Klauser et al. 2002). The pulley system refers to a number of retinacular structures that span from side to side across the volar aspect of the fingers. Two types of pulleys, annular pulleys (A1–A5) and cruciform pulleys (C1–C3), are usually identified in the fingers. The annular pulleys are formed by thick arciform fibres, whereas the cruciform pulleys are formed by thin crisscrossing fibres (Peterson and Bancroft 2006; Klauser et al. 2002). Annular and cruciform pulleys extend from the metacarpal heads to the base of the distal phalanges at 8 specific points along the flexor tendon sheath. The A1, A3 and A5 annular pulleys are located over the metacarpophalangeal joint (A1), proximal interphalangeal joint (A3) and distal interphalangeal joint (A5). The A2 and A4 annular pulleys are located over the proximal phalanx (A2) and middle phalanx (A4) (Peterson and Bancroft 2006; Klauser et al. 2002). Injuries typically begin at the A2 pulley, followed by the A3 and A4 pulleys. Pulley injuries can be divided into 3 grades. Grade 1 is sprain of the finger ligaments (collateral ligaments). Grade 2 is partial rupture of the A2 pulley. Grade 3 is complete rupture of the A2 pulley causing bowstringing of the tendon. Climbers present with pain locally at the pulley, pain when squeezing or climbing, active extension deficit and sometimes pain while extending the finger.

Mild nonspecific uptake may be noted on bone scintigraphy, which may help in confirming the clinical suspicion.

24.2.2.4 Boutonnière Injury

Central slip extensor tendon injury may cause a boutonnière injury over time. The boutonnière injury is the least common and perhaps most difficult of the tendon injuries to diagnose. The injury is the result of jamming the finger causing a tear of the extensor tendon attached to the middle phalanx (Aronowitz and Leddy 1998). Patients present with tenderness at the dorsal part of the proximal interphalangeal (PIP) joint (middle phalanx), flexion at the PIP joint and inability to actively extend the PIP joint.

At bone scintigraphy, there are no typical findings. Abnormal (hyperperfusion) blood pool and slightly elevated uptake at the late images in the area of the extensor tendon attached to the middle phalanx can be found; however, this is rather unspecific.

24.3 Nerves

Neuropathies in the upper extremities commonly include acute compression by direct or indirect trauma, chronic irritation related to overuse, pressure related to extreme positions of flexion and extension and repetitive stretching.

24.3.1 Carpal Tunnel Syndrome

Carpal tunnel syndrome (CTS) results from compression of the median nerve, and it is the most common entrapment neuropathy. CTS is common in cyclists, gymnasts, throwers, wheelchair athletes and racquet sport players (Izzi et al. 2001). It is commonly caused by fractures and dislocations or by overuse tenosynovitis of flexor tendons (Bencardino and Rosenberg 2006). The median nerve is entrapped as it passes through the nonyielding carpal tunnel. The athlete has a positive Tinel's test which is performed by lightly percussing over the nerve to elicit a sensation of tingling, indicating nerve pathology, and a positive Phalen's test which is elicited by allowing a wrist to fall freely into maximum flexion and maintain the position for 60 seconds or more.

The diagnosis may be made clinically and with the use of nerve conduction studies. Imaging studies may be used to confirm the diagnosis in equivocal cases but, more importantly, may be useful in detecting the underlying cause of median nerve compression.

Levinsohn suggests that a combination of the clinical and appropriate imaging modalities will offer the referring clinician an adequate assessment of the bones and soft tissues of the hands and wrists (Levinsohn 1990). The three-phase bone scan is particularly useful to assess the chronicity of the abnormality. To optimise the value of bone scans of the wrist, the images should be recorded for an extended interval of time. The low concentration of labelled diphosphonate uptake in the wrists of adults, coupled with the complex anatomy, requires high-resolution data and preferable SPECT/CT for definitive diagnosis. The use of three-phase bone scintigraphy assists the referring physician in identifying osseous abnormalities or synovitis as a cause for pain.

24.3.2 Ulnar Neuropathy

Cycling is a particularly common cause of ulnar neuropathy, because the ulnar nerve at the wrist passes through the Guyon's canal/ulnar canal. The term handlebar palsy refers to a compression syndrome of the deep motor branch of the ulnar nerve and is particularly common in downhill mountain biking (Capitani and Beer 2002). Ulnar neuropathy presents with pain and paraesthesias of the small finger and the ulnar half of the ring finger. Symptoms depend on the location of compression relative to Guyon's canal.

Bowler's thumb is a neuropathy of the digital nerve on the ulnar side of the thumb. As the name implies, it is a condition in bowlers who develop compression of the nerve due to keeping their thumbs in the hole of the bowling ball. Imaging is not necessary but MRI may demonstrate perineural fibrosis. No specific scintigraphic pattern can be found; only diffuse uptake may be noted on the blood pool images.

24.3.3 Radial Sensory Neuropathy

The radial nerve is frequently compressed in the distal forearm in its subcutaneous area. The nerve runs subcutaneous between the brachioradialis and extensor carpi radialis longus and is subject to irritation by wristbands and gloves (Izzi et al. 2001). Patients present with pain and decreased sensation over the dorsoradial part of the hand, dorsal thumb and index finger. There is no motor loss. A positive Tinel's sign may be present with percussion of the nerve. No specific scintigraphic pattern can be found; only diffuse uptake may be noted on the blood pool images.

24.4 Ligaments

Wrist stability is maintained by a series of intrinsic and extrinsic ligamentous structures. The most important intrinsic structures are the scapholunate ligament (SLL), the lunotriquetral ligament (LTL) and the triangular fibrocartilage complex (TFCC) (Lisle et al. 2009). Carpal instability is a continuum of disorders that can result from an acute trauma or from repetitive injury.

Ligament tears are easily visible on CT arthrography or MR (arthrography) due to the leakage of intra-articular contrast medium into the ligaments. Only longstanding ligament lesions are usually associated with changes in the osseous surfaces, i.e. secondary degenerative changes due to advancing instability (Cerezal et al. 2002).

For triangular fibrocartilage complex injuries, MR or CT arthrography is recommended (Zinberg et al. 1988) followed by bone scan if the arthrogram is normal. In the case of suspected bone abnormality, the order of imaging is spot radiographs, tangential radiographs or special radiograph views. This series of studies can then be followed by bone scintigraphy.

In the case of ligamentous injuries, the patient is radiographically evaluated for ligamentous instability. If this exam is normal, then an arthrogram with fluoroscopy is recommended. When the arthrogram with fluoroscopy is unrevealing, bone scintigraphy should be employed.

24.4.1 Scapholunate Injuries

Scapholunate injuries result from a fall on a hand in which the wrist is extended with ulnar deviation. Typical signs are swelling, decreased range of motion and dorsal wrist tenderness in the area of the scaphoid and lunate. A positive scaphoid shift test or Watson's sign which is done by placing a thumb over the patient's scaphoid tubercle and applying dorsal pressure indicates a scapholunate tear (Parmelee-Peters and Eathorne 2005). Traumatic tears of the SLL may be partial or full thickness and may involve the central ligament or either one of the bony attachments, more commonly the scaphoid attachment (Connell et al. 2001). Chronic scapholunate ligament tears may result in the presence of ganglion.

The scintigraphic evaluation using three phases will mostly be negative in a partial-thickness tear. The full-thickness tear will demonstrate focal increased activity in the area of the scaphoid and lunate bone.

24.4.2 Lunotriquetral Ligament Tear

Lunotriquetral ligament tears also result from a fall on a dorsiflexed wrist that forces the forearm into pronation (Connell et al. 2001). It is much less common than scapholunate tears. Lunotriquetral tears present with ulnar-sided wrist pain, weakness and possibly clicking. There is tenderness over the area of the lunotriquetral ligament. Dorsal pressure over the pisiform and palmar force on the lunate may produce a painful click.

Bone scintigraphy is less requested for lunotriquetral tears as some of the cases irrespective of whether they have complete or incomplete tear may be normal. In almost half of the cases, there will be focally increased uptake in the first two phases than the 3rd phase. Occasionally diffusely increased uptake at the late phase may be seen throughout the carpus (Huellner et al. 2012; Pin et al. 1988; Akdemir et al. 2004).

24.4.3 Triangular Fibrocartilage Complex Injury

The triangular fibrocartilage complex (TFCC) is composed of the semicircular biconcave fibrocartilage or articular disc called the TFCC, the palmar and dorsal distal radioulnar ligaments, a meniscus homolog and the ulnalunate and ulnatriquetral ligaments (Palmer 1989).

The main function of the TFCC is to act as a strut, which stabilises the distal radioulnar joint while conducting functional pronation and supination activities (Palmer 1989). It acts as a shock absorber when conducting the radial and ulnar deviation activities. The TFCC can sustain injuries in both the medial meniscus disc area and the outer lateral disc areas. This structure is commonly injured with distal radius fractures and wrist sprains. TFCC injuries are more commonly seen in gymnastics, hockey, racquet sports, boxing and pole vaulting (Palmer and Werner 1981).

Palmar's classification divides TFCC injuries into two types: (1) traumatic (type 1) and (2) degenerative (type 2) (Palmer 1987). Type 1 is further classified into four subtypes based upon the location of the insult. Type 1A is the most common lesion, a horizontal tear in the articular disc adjacent to the sigmoid notch of the distal radius. Type 1B is an avulsion of the TFCC from the ulna. Type 1C is an avulsion of the ulnocarpal ligaments from the carpus. Type 1D is an avulsion from the sigmoid notch of the radius.

Degenerative type 2 tears are believed to result from ulnocarpal impaction. They are divided into five stages: (a) thinning of the TFCC without perforation,

(b) thinning of the disc with chondromalacia of the ulnar head or lunate, (c) disc perforation with chondromalacia, (d) disc perforation with chondromalacia and lunotriquetral ligament tear and (e) disc perforation with chondromalacia, lunotriquetral tear and ulnocarpal arthritis. Central perforations are usually attributed to degenerative processes (Palmer 1989).Triangular fibrocartilage complex perforations increase with age. Ulnar-sided wrist pain with tenderness on palpation of the TFCC, with or without distal radioulnar joint instability, is indicative of TFCC injury.

The presence or absence of focal scintigraphic abnormality correlates with the presence or absence of TFCC injury. SPECT/CT improves the specificity of detecting TFCC and correlates well with MRI (Huellner et al. 2012; Pin et al. 1988; Akdemir et al. 2004).

24.4.4 Distal Radioulnar Joint Instability

The distal radioulnar joint (DRUJ) is located between the distal radius and the head of the ulnar. Five structures are important in ensuring the stability of the DRUJ: (1) the TFCC, (2) the ulnocarpal ligament complex, (3) the infratendinous extensor retinaculum (i.e. the ECU tendon sheath), (4) the pronator quadratus muscle and (5) the interosseous membrane (Garcia-Elias and Dobyns 1998). The DRUJ has intimate and overlapping structures with TFCC; hence, injury is caused by similar mechanisms. Like TFCC, it presents with ulnar-sided wrist pain. The most common cause of DRUJ instability is a result of TFCC injury since TFCC is significant to DRUJ stability. Other causes of instability are distal radius fractures or disruption of any of the distal radioulnar ligaments or interosseous membrane (Parmelee-Peters and Eathorne 2005).

Currently there is no evidence on the role of bone scintigraphy in DRUJ. An indirect role of scintigraphy is that of being sensitive in severe/complete TFCC.

24.4.5 Skier's (Gamekeeper's) Thumb

A tear of the ulnar collateral ligament (UCL) at the MCP joint of the thumb on the side of the webspace is called a skier's thumb (Spaeth et al. 1993). This injury is caused by violent abduction of the thumb. This injury was historically named gamekeeper's thumb because of its frequency in the gamekeepers of the large hunting estates in England. The injury is most commonly seen in football players and skiers. The two classifications of this injury are (1) incomplete, or proper collateral ligament injury with accessory collateral preserved, and (2) complete, in which the ligament rupture is complete and the distal end may displace superficial and proximal to the adductor aponeurosis. This condition is referred to as a Stener's lesion (Stener 1962). In patients with complete ruptures, the incidence of adductor aponeurosis interposition and ligament displacement is controversial but has been reported in as many as 80 % of cases (Bowers and Hurst 1977).

At bone scintigraphy, hyperaemia at the blood pool phase and moderate increased osseous uptake at the late phase will be seen on the UCL at the MCP joint of the thumb on the side of the webspace. These findings are better seen on SPECT/CT (Huellner et al. 2012).

24.5 Fractures

Bone scintigraphic evaluation of wrist and hand injuries is often a very helpful procedure when fractures are suspected, especially with nondiagnostic radiographs. These may include fractures of the distal radius and ulna and the carpal or metacarpal and phalangeal regions. SPECT/CT may help to improve the sensitivity and specificity by better resolution and exact localisation of the increased uptake.

In a study to evaluate the role of bone scintigraphy in patients with suspected carpal fracture and normal or suspicious radiographs following carpal injury, a three-phase ^{99m}Tc-MDP scan was performed on 32 patients with negative radiographs but clinically suspected fracture two weeks after the trauma. Twelve (38 %) patients had a normal scan excluding fracture. Twelve patients had a single fracture. Multifocal fracture was present in 8 (25 %) patients. Eight patients showed scaphoid fractures: three showed single scaphoid fracture, and the other five patients revealed accompanying fractures (Weber 2011). Distal radius fractures and carpal bone fractures other than scaphoid were both observed in 12 patients. These were eleven fractures of distal radius; three fractures of pisiform; two fractures of hamate; and single fractures of lunate, trapezium and triquetrum. In one patient there was a fracture of a first metacarpal bone. In patients with suspected carpal bone fracture and normal or suspicious radiographs, bone scintigraphy can be used as a reliable method to confirm or exclude the presence of a scaphoid fracture and to detect clinically unsuspected fractures of distal radius and other carpal bones (Akdemir et al. 2004). In another study involving 87 patients, the sensitivity and negative predictive value for carpal fractures were 97 and 98 %, respectively, highlighting the benefit of nuclear medicine imaging techniques in the detection of occult carpal fractures, thereby reducing the risks of complications such as pseudoarthritis (Querellou et al. 2009).

24.5.1 Distal Radius Fracture

A fracture of the distal radius is the most common forearm fracture. It is usually caused by a fall onto an outstretched hand (FOOSH). It can also result from direct impact or axial forces. The classification of these fractures can be based on distal radial angulation and displacement, intra-articular or extra-articular involvement and associated anomalies of the ulnar or carpal bones (Rettig and Trusler 1999).

A Colles' fracture, the most common distal radius fracture, is a closed fracture of the distal radial metaphysis in which the apex of the distal fragment points in the palmar direction and the hand and wrist are dorsally displaced. This fracture usually occurs within 2 cm of the articular surface (Cooney 1998). Colles' fractures are common in adults and rare in children, because children tend to sustain injuries through the distal radial physis. Common distal radius fractures in children include torus, greenstick and physeal fractures. A torus fracture occurs when the tough periosteum, while remaining intact, buckles circumferentially at the fracture site. If one side of the periosteum buckles but the other side breaks, it is called a "greenstick" fracture. Physeal injuries are typically classified radiographically using the Salter-Harris classification (Morgan and Slowman 2001). Type I fracture is a disruption of the physis. Type II is a fracture through the physis extending obliquely through the metaphysis. Type III is an intra-articular fracture through the epiphysis that extends across the physis to the periphery. Type IV fractures cross the epiphysis, physis and metaphysis. Type V fractures are compression injuries of the physis, typically diagnosed retrospectively due to growth disturbance (Morgan and Slowman 2001).

Bone scintigraphy, especially with the advent of SPECT/CT, is used as a diagnostic tool in patients with suspected fracture and normal radiographs. ^{99m}Tc-MDP scintigraphy is a sensitive and noninvasive technique for the diagnosis of such fractures. A negative scan 72 hours after an injury virtually excludes a fracture (Huellner et al. 2012; Pin et al. 1988; Akdemir et al. 2004). Focal hyperaemia on early phase and focal intense activity on late-phase scintigraphic images in the distal radius are diagnostic of the fracture.

24.5.2 Scaphoid Fracture

The scaphoid is the most commonly fractured bone of the carpus. The injury normally occurs when an athlete falls on the outstretched hand. Scaphoid fractures are considered to be a very serious injury due to the poor blood supply (Rettig et al. 1989).

Most simply, fractures are divided into anatomical location: distal pole, middle third and proximal pole. There are several more complex classifications of scaphoid fractures based on location and stability for healing. There are three classic fracture sites associated with the scaphoid bone. Fractures of the middle third are the most common (60 %), and those of the distal third the least common (10 %), with proximal pole accounting for the remaining 30 % (Manusov 2002). Adults most commonly sustain middle-third fractures, and children most commonly fracture the distal pole or middle third (Manusov 2002). Another useful classification in terms of healing is the Herbert classification (Herbert and Fisher 1984): Type A: stable acute fractures; A1 is fracture of tubercle and A2 is incomplete fracture of the waist (middle third). Type B: unstable acute fractures; B1 is distal oblique, B2 is complete or displaced waist fracture, B3 is proximal pole fracture, B4 is trans-scaphoid perilunate dislocation fracture and B5 is comminuted fracture. Type C: delayed union. Type D: established union; D1 is fibrous nonunion (stable) and D2 is displaced nonunion (unstable). The evaluation and treatment of scaphoid fractures is controversial and continues to evolve.

Several reports conclude that the three-phase bone scintigraphy is a sensitive and specific diagnostic modality in the diagnosis of scaphoid fracture (Tiel-van Buul et al. 1997; Murphy and Eisenhauer 1994; Roolker et al. 1997).

Fig. 24.3 ^{99m}Tc-MDP demonstrates occult scaphoid fracture on a delayed static image with intense uptake in the carpal scaphoid

Three-phase scintigraphy can be used to make the diagnosis of occult scaphoid fracture demonstrating increased blood flow and blood pool and increased uptake at the late static image in the carpal scaphoid (Figs. 24.3 and 24.4) (Tiel-van Buul et al. 1995). The bone scan may also identify additional or alternative sites of occult injury. Missed diagnosis and inadequate treatment of a scaphoid fracture frequently leads to nonunion and may cause pain and serious disability. With prompt diagnosis and subsequent treatment, bony union will be obtained in 94–98.5 % of such fractures (Barton 1992).

24.5.3 Triquetrum Fracture

The triquetrum is reported as the second most common carpal fracture representing all carpal bone injuries (Geissler 2001; Höcker and Menschik 1994; Marchessault et al. 2009). Triquetral fractures typically occur from a hyperextension injury with the wrist in ulnar deviation (Papp 2007). Shearing forces exerted by the proximal hamate, distal ulna or both may play a role. Injury can also occur with hyperflexion. In addition, either the dorsal or volar radiotriquetral ligaments may avulse triquetral

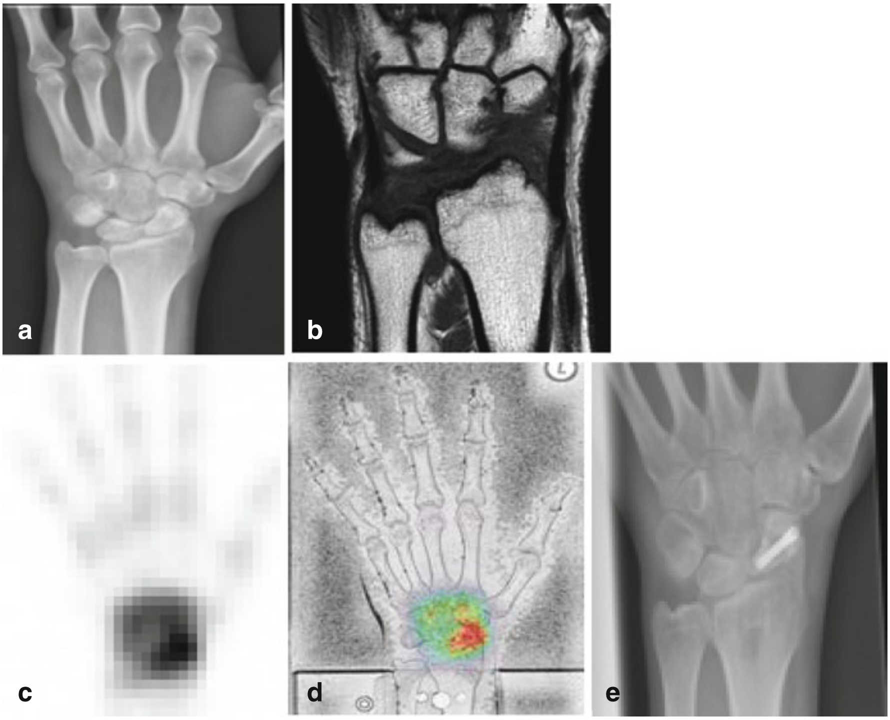

Fig. 24.4 A 36-year-old male presenting with left-sided wrist pain 4 years after left hand injury. Plain radiographs of the left hand and wrist showed sclerotic changes and presumed avascular necrosis of the radial scaphoid (**a**, plain radiograph, PA view in neutral position). MRI showed old scaphoid fracture with nonunion, avascular necrosis and scaphoid collapse (**b**). Bone scintigraphy showed marked focal uptake in the radial part of the scaphoid and generalised increased uptake in the wrist joint and surrounding region thought to be due to synovitis and RSD (**c**, **d**). The scaphoid was subsequently fixated internally, and a bone graft was completed to build up the collapsed bone (**e**)

fragments at their attachments (Geissler 2001). Triquetral fractures may be divided into two types: The first type is chip fractures which usually tear off at the dorsal radial surface and typically occurs with a wrist hyperextension injury (Höcker and Menschik 1994). Such fractures account for up to 93 % of triquetral fractures (Marchessault et al. 2009). Tear-off dorsal chip fractures can also occur with the hyperflexion mechanism mentioned previously. The second type, the midbody fracture, is less common than chip fractures. This type of fracture is usually the result of a direct blow with high energy. They may occur in conjunction with a (peri)lunate dislocation in 12–25 % of triquetral injuries. The patient typically presents with a history of injury and pain on the ulnar aspect of the wrist.

Fractures of the triquetrum are not always identified at the initial radiographic examination. At bone scintigraphy, increased activity on the triquetrum on the dynamic flow images in parallel with the increased uptake observed on blood pool and late-phase images is diagnostic of a fracture (Querellou et al. 2009; Roolker et al. 1997).

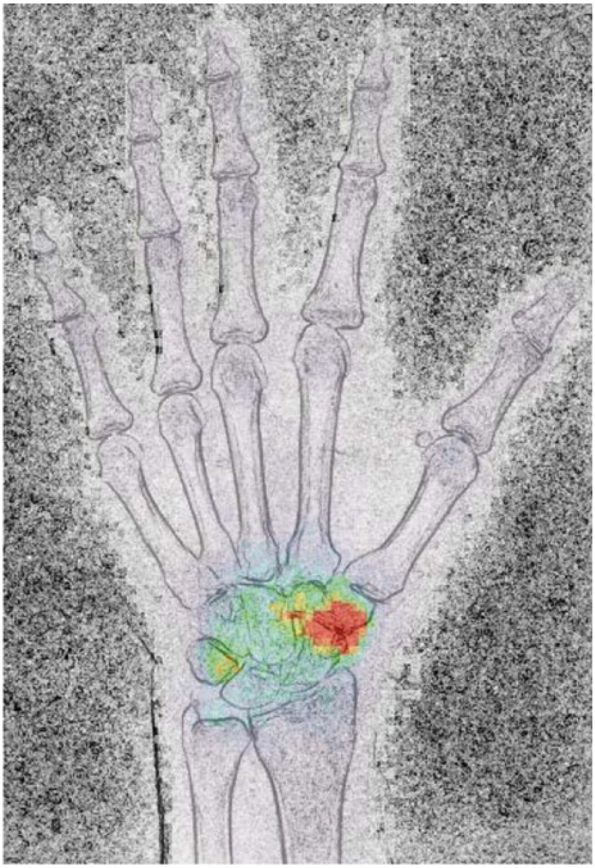

Fig. 24.5 High focal tracer concentration is noted in the radial aspect of the left wrist in the joint between the trapezium and scaphoid bone. Slightly increased tracer concentration is also noted between the trapezoid bone and the scaphoid bone of the left wrist and in the joint between the lunate bone and the triquetrum. Compatible with fractures of the scaphoid bone and the trapezium

24.5.4 Trapezium Fractures

Trapezium fractures often occur in association with other injuries, such as fracture-dislocations of the first metacarpal (Rolando and Bennett injuries), first metacarpophalangeal dislocations, scaphoid fractures and distal radius fractures (Geissler 2001). Isolated trapezium fractures are uncommon. Axial loading of the 1st (thumb) metacarpal bone in the adducted position typically causes vertical fractures through the articular surface of the trapezium. Dorsiflexion of the wrist (i.e. falling on an outstretched hand) rotates the radius and scaphoid and can make the trapezium more prone to injury (Giannikas et al. 2008). The patient with a trapezium fracture typically presents with minimal swelling but may have significant discomfort (more than expected from other carpal bone fractures).

Radiographic or computerised tomographic findings are commonly positive, but when normal, bone scintigraphic evaluation is recommended (Fig. 24.5). Although isolated trapezium fractures are rare, bone scintigraphy could be used to confirm a fracture when increased uptake is found or exclude a fracture when no focal increase in osteoblastic activity accumulation is noted.

24.5.5 Hook of Hamate Fractures

Fractures of the body of the hamate may occur from trauma and usually occur in combination with fractures of the base of the fourth and fifth metacarpals (Rettig 2003). Fractures of the hook of the hamate are more common in sports that use a racquet, bat or club, because of the impact on the hypothenar eminence at the hook of the hamate. Fractures of the hook of the hamate bone have also been described by sudden contracture of the hypothenar intrinsic muscles or by a shearing force applied to the flexor tendon of the small and ring fingers (Mirabello et al. 1992; Stark et al. 1977; Weber and Chao 1978). Patients present with tenderness over the hook of the hamate, which lies on a line between the pisiform and second metacarpal head.

Bone scintigraphy with SPECT/CT is very important to diagnose and localise hamate fractures, especially if it occurs in combination with fractures of the base of the fourth and fifth metacarpals. The scintigraphic findings are that of focal hyperaemia, increased blood pool activity and increased tracer accumulation at the late-phase images (Huellner et al. 2012; Querellou et al. 2009; Roolker et al. 1997).

24.5.6 Pisiform Fracture

Fractures of the pisiform bone are extremely rare and frequently associated with other carpal or distal radial injuries. The pisiform bone may be injured from a direct blow, and it may undergo chondral changes from overuse, leading to pisotriquetral arthrosis. This is frequently seen in athletes who participate in racquet sports (Palmieri 1982). Early diagnosis of a pisiform fracture is important, because missed diagnosis or delayed treatment may result in malunion or nonunion.

Increased ^{99m}Tc-MDP uptake will be observed in the flow and blood pool phase, and together with increased tracer uptake at the fracture site in the pisiform bone (with SPECT/CT) at the late-phase images is diagnostic. However in some of these patients, there may be normal flow images (Huellner et al. 2012; Querellou et al. 2009; Roolker et al. 1997).

24.5.7 Lunate Fracture

An acute fracture of the lunate bone is uncommon, and many of these fractures are unrecognised until avascular necrosis occurs, a condition known as Kienböck's disease (osteonecrosis of the lunate). Associated risk factors include occupations or sports with repetitive pressure to the base of the hand with the wrist in extension (e.g. gymnast, jackhammer operator) and those with ulnar shortening relative to the length of the radius, a condition referred to as "ulna minus variance" (Geissler 2001). Acute lunate fractures most often occur as the result of a fall on an extended wrist or some other wrist hyperextension injury (Geissler and Slade 2011). Patients may not recall the specific incident but typically present with pain in the wrist area that is aggravated by wrist motion or gripping. Because of the intracapsular location of the lunate, swelling may be minimal.

At bone scintigraphy, increased activity at the lunate bone on the dynamic flow images in parallel with increased uptake observed on blood pool and late-phase images is diagnostic of a fracture. SPECT/CT is essential for exact localisation due to the overlap of the carpal bones (Huellner et al. 2012; Querellou et al. 2009; Roolker et al. 1997).

24.6 Kienböck's Disease

Kienböck's disease or lunatomalacia is an aseptic osteonecrosis of the lunate bone initiating a progressive collapse of the lunate bone, followed by total carpal collapse (De Smet and Degreef 2009). Although the aetiology remains unknown, it is believed to result from devascularisation of the lunate owing to either repetitive trauma or single trauma causing a fracture (Almquist 1986). Morphological variations, such as negative ulnar variance, high uncovering of the lunate, abnormal radial inclination and/or a trapezoidal shape of the lunate and the particular pattern of its vascularity, may be predisposing factors (Schuind et al. 2008). Kienböck's disease usually affects adults between 20 and 40 years of age, who are predominantly male manual workers. The symptoms of dorsal wrist pain and diminished grip strength usually occur at the time of carpal collapse, probably related to the progressive alteration in carpal architecture and function rather than to bone necrosis (Bochud and Büchler 1994; Beckenbaugh et al. 1980). Carpal tunnel syndrome may complicate the course of the disease (Tiel-van Buul et al. 1997).

The uptake of the ^{99m}Tc-MDP in the lunate is variable. Generally there is focal accumulation of the tracer at the lunate bone; however, no abnormality may be present on bone scintigraphy if the examination is performed during the time of impaired vascular supply, before reactive changes and increased metabolism result in increased tracer uptake (Huellner et al. 2012; Querellou et al. 2009; Roolker et al. 1997).

24.7 Complex Regional Pain Syndrome (Reflex Sympathetic Dystrophy, Sudeck's Dystrophy)

Complex regional pain syndrome (CRPS) is one of the most challenging chronic pain conditions of the limbs. Historically, CRPS has been described by a number of terms that include causalgia, Sudeck's atrophy, reflex sympathetic dystrophy (RSD), algodystrophy, posttraumatic dystrophy and shoulder-hand syndrome. In order to bring some uniformity to this problem, the International Association for the Study of Pain (IASP) in 1994 introduced the term CRPS to describe a wide variety of posttraumatic neuropathic pain conditions of the limbs (Merskey and Bogduk 1994). The use of the term CRPS has also been questioned, and perhaps another more appropriate term will be developed in the future (Complex 2007). CRPS or RSD often presents with pain, swelling, vasomotor disturbance, dystrophic skin changes and motor abnormalities. Many diseases, precipitating events or drugs have been associated with RSD. Although trauma (especially fractures or peripheral nerve injuries) is accepted as the most common precipitant of RSD, it can also appear after myocardial infarction or related to Pancoast tumour and use of barbiturates/antituberculous drugs, or it can be idiopathic (Kozin 1997; Derbekyan et al. 1993; Scwartman and McLellan 1987). For patients with these classical findings of RSD, the diagnosis can be made with reasonable confidence. However, not all patients have all these typical findings of CRPS. Furthermore, the condition progresses through stages – from acute to dystrophic and atrophic –and many patients experience a change in the quality of their pain while, unfortunately, the affected limb develops contractures. Stage 1 (acute, first three months) consists of pain, oedema, hyperthermia and increased nail and hair growth. Stage 2 (dystrophic, three to nine months) consists of pain, induration, oedema, cool skin and hyperhidrosis with a livedo reticularis appearance or cyanosis. Stage 3 (atrophic, symptoms in excess of nine months) is characterised by pain spreading proximally, shiny skin, flexion contractures, bony demineralisation and ankylosis (Merskey and Bogduk 1994; Scwartman and McLellan 1987; Driessens et al. 1999).

Hence the findings of CRPS may be confused with several other conditions such as arthritis, radiculopathy, plexopathy, neuropathy and other less commonly encountered pathologies. Some patients may suffer from two or more of the conditions. The diagnosis of CRPS may be problematic in the patient who also suffers from diabetic neuropathy. The three-phase bone scintigraphy is particularly useful (Genant et al. 1975; Kozin et al. 1976, 1981a, b; MacKinnon and Holder 1984; Holder and MacKinnon 1984; Davidoff et al. 1989) and has been widely utilised in both the diagnosis and monitoring of treatment (Genant et al. 1975; Kozin et al. 1976, 1981a, b; MacKinnon and Holder 1984; Holder and MacKinnon 1984; Davidoff et al. 1989). Several reports have shown that the bone scan has a sensitivity of up to 100 % and a specificity of up to 98 % for the diagnosis of RSD (Kozin et al. 1981b; MacKinnon and Holder 1984; Holder and MacKinnon 1984; Davidoff et al. 1989; Holder et al. 1992). Scintigraphic imaging shows increased perfusion during the first two phases and widespread increase in radiophosphonate bone uptake in the late phase (Genant et al. 1975; Kozin et al. 1976, 1981a, b; MacKinnon and Holder 1984; Holder and MacKinnon 1984; Davidoff et al. 1989; Holder et al. 1992; Colamussi et al. 2004). The highest diagnostic accuracy is provided by the combination of three signs: increase activity ratio in the blood pool phase performed at 5–15 min, diffuse uptake in the carpal and periarticular uptake in all the small joints (Fig. 24.6) (Genant et al. 1975; Kozin et al. 1976, 1981a, b; MacKinnon and Holder 1984). Decreased radiotracer accumulation has also been described, especially in children and adolescents (Leslie 2006; MacKinnon and Holder 1984). Bone scintigraphy is of major importance for the diagnosis in order to clearly differentiate from other conditions which are incorrectly diagnosed and treated as RSD.

Bone scintigraphy is a valuable and objective method for diagnosis and for the evaluation of response to therapy and may also be useful for staging of patients and predicting the response to therapy (MacKinnon and Holder 1984; Demangeat et al. 1988; Oztürk et al. 2004; Zyluk and Birkenfeld 1999).

Fig. 24.6 Late-phase bone scintigraphy showing intense ^{99m}Tc-MDP periarticular uptake in the wrist joint and in all the small joints

Conclusion

Missed diagnosis and inadequate treatment of wrist, hand and fingers injuries frequently lead to serious disability. Providing a correct diagnosis in the early posttraumatic period is essential. Radiological (radiographs, CT, MRI) and nuclear medicine imaging techniques (bone scintigraphy with SPECT/CT) are useful in providing the correct diagnosis, in shortening the duration of immobilisation and in decreasing the complication rate.

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Part VIII

The Musculoskeletal System Topographically: Pelvis, Groin, Hip and Thigh

Injuries in the Pelvis, Groin, Hip and Thigh

25

Per Hölmich and Kristian Thorborg

Contents

Abstract

Pelvis, groin, hip and thigh injuries in sports include multiple, complex and long-standing conditions, causing great frustration among athletes and sports practitioners. Pain in these regions may originate from many anatomical structures such as the muscle, tendon, ligament, cartilage or bone. Acute groin and hamstring injuries are the most frequent injuries in the different football codes, where especially hip and groin injuries are very prevalent problems. Moreover, the recurrence rates of these acute injuries are very high and a major problem during the rehabilitation and return-to-sport phase. Basic understanding of the anatomy and biomechanics and its relation to specific injuries in this complex region is important to make relevant clinical choices concerning clinical examination and diagnostic imaging. Hip, pelvis and trunk muscles are all constantly involved in

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most sports activities contributing to a considerable amount of both eccentric and concentric work, including fast changes between these work forms. These muscles are highly important but also at risk of sustaining an injury. Acute muscle-tendinous injuries in the hip and groin region occur in the adductor muscles (usually the adductor longus), the hamstring muscles (often biceps femoris) and the quadriceps muscle (often the rectus femoris), often during forceful eccentric contractions such as accelerating and decelerating movements, kicking and extreme positions. In the athlete with long-standing hip and groin pain symptoms often seem to be contradictory and confusing. In up to 1/3 of patients with long-standing hip and groin pain, multiple causes can be found. The symptoms associated with an intra-articular hip problem can include pain, catching, locking, clicking, feeling of instability and giving way. A labral/cartilage injury in the hip commonly refers pain to the anterior groin. However, anterior groin pain is not specific for this injury but can be due to other intra-articular pathologies and/or extra-articular pathologies. Important differential diagnoses including stress fractures, referred pain or nerve entrapment and abdominal or gynaecological disorders are other possible causes of pain in these regions and should therefore also be considered.

25.1 Introduction

Pelvis, hip and groin injuries in sports include multiple, complex and long-standing conditions (Bennell and Crossley 1996; Bradshaw et al. 2008; Holmich 2007; Lovell 1995). Pain in these regions may originate from many anatomical structures such as the muscle, tendon, ligament, cartilage or bone. Abdominal or gynaecological disorders, referred pain and nerve entrapment are possible causes of pain in this region and should always be considered. Acute muscle injuries in the hamstrings, quadriceps and adductor muscles are some of the most frequent injuries in sports including high-speed running and cutting movements, which involve the lower extremity (Hägglund et al. 2009; Orchard and Best 2002; Orchard and Seward 2002; Petersen et al. 2010; Pettersson and Lorentzon 1993). Overuse problems originating from muscle-tendinous structures and their insertion (enthesis) are common and represent long-standing conditions that can be difficult to recover from. Groin and hamstring injuries are especially frequent in the different football codes, with an incidence of approximately one injury per 1,000 h of play, involving 10–20 % of all players each year (Hägglund et al. 2009; Orchard and Best 2002; Orchard and Seward 2002; Petersen et al. 2010). Moreover, the prevalence of hip and groin pain seems to be much higher, involving more than 50 % of the players each year (Hanna et al. 2010; Thorborg et al. 2011). Previous injury seems to be the most prominent risk factor, and recurrence is a major problem, including 20–30 % of football players with a previous injury (Hägglund et al. 2009; Orchard and Best 2002; Orchard and Seward 2002; Petersen et al. 2010). Injuries in the pelvis, hip and groin are therefore often troublesome causing great frustration among athletes and sports practitioners. Basic understanding of the anatomy and biomechanics and its relation to specific injuries in this complex region is important to make relevant clinical choices concerning clinical examination and diagnostic imaging and to optimise clinical pathways and treatment solutions.

25.2 Functional Anatomy and Biomechanics

The hip joints are part of the pelvis from a functional point of view (Dalstra and Huiskes 1995; Oatis 1990). Numerous muscles and ligaments originating from and/or inserting into the pelvis all contribute to this function (Dalstra and Huiskes 1995; Oatis 1990). The trunk and the pelvis are joined at the sacroiliac joints, and the pelvis and the lower extremities are joined at the hip joints (Oatis 1990). The synergies between the muscles acting across the pelvis, sacroiliac joints and hip joints are important for achieving optimal function in movements that involve the extremities (Dalstra and Huiskes 1995; Snijders et al. 1993a, b). The pelvis is the centre of load transfer from the upper extremities and the trunk to the lower extremities and vice versa (Snijders et al. 1993a, b). The pelvis is dependent of both skeletal and articular stability as well as sufficient neuromuscular coordination controlling large synergistic actions and forces transmitted through the hip and pelvic ring (Hungerford et al. 2003; Snijders et al. 1993a, b). A number of muscle groups interact on the pelvis and hip, and the quadriceps, hamstrings, adductors, iliopsoas and abdominals are the primary muscle-tendinous structures at risk of being injured (Hölmich 2007). The adductor muscle group have been shown to be very important as stabiliser of the hip joint, and the interaction of the abdominal muscles (in particular the transverse abdominis muscle), the multifidus muscles deep in the low back and the pelvic floor muscles has been shown to be important for the integrity and stability of the trunk, lumbar spine and pelvis (Hodges et al. 1997; Hungerford et al. 2003; O'Sullivan et al. 2002). The precise functions of the iliopsoas are not fully understood, but this muscle group seems to work both as an important hip flexor and as a pelvic stabiliser, as well as a stabiliser for the lumbar spine (Andersson et al. 1995; Bogduk et al. 1992). The hamstring and quadriceps muscles (rectus femoris) are important prime movers developing large forces during lengthening contractions especially during high-speed running but also during accelerating and decelerating events, and therefore these muscle groups are highly stressed in most sporting movements.

These hip, pelvis, and trunk muscles are all constantly involved in most sports activities contributing to a considerable amount of eccentric and concentric work, including fast changes between these work forms (Barfield 1998; Brophy et al. 2010; Charnock et al. 2009; Dorge et al. 1999). This makes them highly important but also at risk of sustaining an injury (Hölmich 2007; Ekstrand and Hilding 1999; Nielsen and Yde 1989). Muscles are often defined and even named from the concentric action they have on the non-weight-bearing leg (Oatis 1990). However, these muscles also have a primarily eccentric function as stabilisers of the pelvis including the hip joints and the trunk (Morrenhof 1989). The abdominal muscles, including the external oblique, internal oblique, rectus abdominis and transversus abdominis, are also stabilisers of the pelvis, and in synergy with the muscles of the back, they control the movements of the trunk in relation to the pelvis and the legs (Snijders et al. 1993a, b). The tendons of the internal oblique and the transversus abdominis muscles insert into the pubic bone as they blend to create the conjoint tendon (the falx inguinalis) (Gibbon et al. 1999; Gibbon 1999). A close anatomical relationship exists between the conjoint tendon, the rectus abdominis sheath and the common adductor origin (Gibbon et al. 1999; Gibbon 1999). These structures undergo large eccentric forces and strains in sports where kicking, acceleration/deceleration, sudden change of direction, extreme positions and rotational movements of the hip and pelvis are included (Barfield 1998; Brophy et al. 2010; Charnock et al. 2009; Dorge et al. 1999).

25.3 Aetiology and Injury Mechanisms

The acute strain usually involves one or more muscle-tendinous structures. In most cases, the lesion is close to the muscle-tendinous junction, but in some cases, the tendon itself or the enthesis where the tendon inserts into the bone is the site of the injury. These injuries usually happen during forceful actions such as in kicking and skating and with other sporting movements where the muscle is being stretched during forceful contraction. The athletes are usually not in doubt that something happened: it hurts, the function of the limb is affected and sometimes a discoloration of the skin occurs in 24 h. In most cases, the athlete will have to stop the activity. In some cases, the athlete describes a snapping feeling in the groin, sometimes even accompanied by a sound. If not attended to appropriately, these injuries might develop into a more long-standing and sometimes chronic injury. In other cases, the hip and groin injuries have the characteristics of an overuse injury, and an exact moment of injury (the inciting event) can be hard to establish. In the beginning, there is only pain after activity with stiffness of the joint or the muscle group and decreased range of motion of the hip joint, developing to pain in the hip and/or groin at the commencement of sports activity. The pain will often disappear as the athlete warms up but will recur during the activity. If the athlete does not get appropriate treatment and instead continues to participate in the sport, the pain-free periods often become shorter, and finally all sports activities start to cause pain. At this point, even activities of daily living might be a problem. A similar behaviour and injury pattern can also be seen in athletes returning to sports too early after an initial acute hip and/or groin injury without receiving appropriate and/or sufficient treatment and rehabilitation. Athletes will often try to compensate for symptoms of hip and groin pain, and although they might succeed for a while, gradually, the pain and loss of function will take over, and the athlete will not be able to continue sports participation. Typically, athletes will seek treatment when their ability to produce fast movements such as in sudden changes of direction, sprinting and kicking is impaired and painful. At this point, specific structures are often already severely stressed. Therefore, early detection and load management are extremely important for these athletes to avoid some of the long-standing problems that may arise if acute or overuse hip and groin problems are initially ignored.

25.4 Injuries

25.4.1 Acute Injuries in the Pelvis, Hip, Groin and Thigh

The three most common acute muscle-tendinous injuries in the hip and groin region occur in the adductor muscles (usually the adductor longus), the hamstring muscles (most often biceps femoris) and the quadriceps muscle (most often the rectus femoris). When the muscles are acutely strained, it is often during eccentric contractions. This often occurs in specific situations during forceful eccentric contractions, such as in accelerations, cutting movements, kicking and/or while stretching the injured extremity to an extreme (Charnock et al. 2009). Traditionally, muscle injuries are divided into three grades (O'Donaghue 1970):

1. Grade I: A mild strain with only a minimal tear of the muscle.
2. Grade II: Damage of several muscle fibres but not a complete disruption. There is a definite loss of strength.
3. Grade III: A total tear of the muscle-tendon unit, with a total lack of function of the muscle.

Grade I and II lesions are painful and often disabling. In cases where the fascia is ruptured as well, discoloration and swelling can be found representing local hematoma and oedema. Usually, a "pull" has been felt in the muscle with a sudden sharp pain, and in most cases, the patient is unable to continue the activity. Complete muscle tear (grade III) is rare and is in most instances located to the insertion (Peterson and Stener 1976; Symeonides 1972).

Other muscle groups such as the iliopsoas muscle, being a very important and strong hip flexor, can be acutely strained during actions including forceful hip flexion contraction and/or stretching (Hölmich 2007; Hölmich et al. 2014; Werner et al. 2009). This could happen in forceful hip flexion during sprinting, skating, jumping or kicking. An acute strain of the lower abdominal muscles usually involves either the conjoint tendon (falx inguinalis) where the tendons of the transverse abdominal muscle and the internal oblique muscle join and insert into the pubic tubercle or the rectus abdominis muscle usually in the enthesis at the pubic bone or close to the distal muscle-tendinous junction. The typical mechanism is a traumatic episode where the athlete overstretches the front of the groin and lower abdomen as in a forceful kicking or other situations where the hip is fully extended and the pelvis rotated, as the abdominal muscles are working hard to oppose these movements and forces, often by forceful eccentric contractions. The more rotation involved in the fall either in the hip joint or in the trunk, the more likely it is that the conjoint tendon will sustain the lesion. In this situation, the hip flexors (iliopsoas, rectus femoris and tensor fasciae latae) are also at risk of sustaining an injury. Lesions to the lower abdominal muscles and other structures associated to the inguinal canal can lead to a condition with some similarities of a hernia (i.e. often called "sports hernia" or "incipient hernia"). A predisposition for hernia development might be present, but the primary mechanism of injury is probably an acute trauma as described above or a period of overuse. The overuse can be a result of misbalance of the muscles acting on the pelvis and intense strenuous activity often involving exercises with many fast reactions including sprinting, kicking and sudden changes of direction. The nature of the lesion is not always clear. It may be a strain or a tear, inflammation or degeneration at certain points of excessive stress, an avulsion, haemorrhage or oedema. It is probably the result of a structural lesion to the muscles and/or tendons (i.e. rectus abdominis muscle or insertion, the external oblique, internal oblique and/or transversalis muscle or aponeurosis and the conjoint tendon) involving a weakness of the posterior inguinal wall without a clinically obvious hernia.

During clinical examination, acute muscle injuries will usually be painful at palpation and during stretching and isometric contraction. Discoloration and haematomas from bleeding structures may sometimes be present but will tend to run down the leg alongside fasciae and muscle fibres due to the gravitational forces. Specific anatomical location of acute muscle injuries can therefore be difficult to locate, and diagnostic imaging can here be an important aid, when trying to decide what structures are involved. Specific knowledge on structural involvements will often have implications for the prognosis, as size of the structural injury and the insertional proximity seem to be factors related to a longer and thereby poorer prognosis.

25.4.2 Long-Standing Muscle-Tendinous Injuries in the Hip and Groin

Symptoms often seem to be contradictory and confusing in the athlete with long-standing groin pain. In about 25–35 % of the patients, multiple causes for the chronic groin pain can be found (Bradshaw et al. 2008; Hölmich 2007; Lovell 1995). Characteristic activities causing pain include sprinting, making cutting movements, kicking the ball and making a sliding tackle. Complaints of pain when coughing and sneezing and pain when standing on one leg to pull on socks or pants are also frequent. Acute overload, fatigue or overuse of the adductor muscles during sports activities may lead to injuries. The adductor muscles are important stabilisers of the pelvis and the hip joint. If the loads on the hip joints and the pelvis are no longer balanced, the adductor muscles are among the muscle groups most likely to be recruited to increase work and thereby risking an overuse situation that might lead to an injury. Adductor-related pain is located medially in the groin and may radiate down along the adductor group on the medial side of the thigh. The clinical signs of the diagnostic entity "adductor-related groin pain" are defined as (1) tenderness of the origin of the adductor longus and/or the gracilis at the inferior pubic ramus and (2) groin pain on resisted adduction (Hölmich 2007; Hölmich et al. 2004).

Iliopsoas-related pain is another common cause of long-standing groin pain and a very important differential diagnosis to hip joint problems. The precise functions of the iliopsoas muscle are not yet fully understood, but the muscle seems to work as pelvic stabiliser as well as a stabiliser for the lumbar spine as well as being an important flexor of the hip joint (Andersson et al. 1995; Bogduk et al. 1992). The workload on the muscle includes a considerable amount of both eccentric and concentric work, and fast changes between these work forms. Both strains and overuse injuries in the iliopsoas muscle might develop into a chronic problem. The pain is located in the anterior part of the proximal thigh more laterally than adductor-related groin pain. It sometimes radiates down the anterior thigh and sometimes involves an element of lower abdominal pain lateral to the rectus abdominis muscle. In differentiating between the intra- and the extra-articular problems, it is very important to know that the impingement test will give rise to pain in the psoas in case of iliopsoas-related groin pain, because of the sore muscle being folded (flexion), twisted (adduction) and pulled (internal rotation).

The clinical signs of "iliopsoas-related groin pain" are defined as (1) pain when palpating the muscle through the lower abdominal wall and (2) pain at passive stretching of the muscle using the Thomas test position (Hölmich 2007; Hölmich et al. 2004).

Inguinal-related groin pain can probably be attributed to a number of anatomical structures (Hölmich 2007; Hölmich et al. 2014). The problem has been given numerous names in the literature such as sports hernia, sportsman's hernia, incipient hernia, Gilmore's groin, pubic pain, athletic pubalgia and others. The lesions as they are noted in the literature are described as non-specific and with large variations in the pathoanatomy. The primary lesion can be in the rectus abdominis, the external oblique, internal oblique and/or transversalis muscles/tendons or in the conjoint tendon. The nature of the lesion is not clear, since it may be a strain or tear, an inflammation or degeneration of certain points of excessive stress, or it may be an avulsion, a haemorrhage or an oedema. These strains/lesions can be precipitated by a traumatic episode including overstretching the front of the groin and/or lower abdomen, also often involving lengthening contractions. Dilation of the external ring and tenderness of the posterior wall are often found. Sometimes, a bulge can be felt with increased intra-abdominal pressure from, for example, coughing. The pain may be exacerbated during coughing (Ekstrand and Ringborg 2001; Muschaweck and Berger 2010; Paajanen et al. 2011).

The clinical signs of "inguinal-related groin pain" are defined as (1) tenderness at the conjoint tendon towards the pubic tubercle and (2) tenderness of the external ring of the inguinal canal (Hölmich 2007; Hölmich et al. 2004).

Chronic injuries related to the rectus femoris or the sartorius are more rare. They are usually located at the proximal end of the muscle and tendon close to the insertion at the anterior iliac spine.

The snapping hip is a condition where a snap is felt in the hip/groin region, sometimes concomitant with a sound and sometimes painful (Flanum et al. 2007; Ilizaliturri et al. 2006, 2008; Wettstein et al. 2006; Yoon et al. 2009). When snapping is not associated with discomfort or pain, the condition can usually be neglected and considered without any pathologic importance. The snapping can be located externally on the lateral side of the hip (Ilizaliturri et al. 2006, 2008; Yoon et al. 2009) or internally on the medial side (Flanum et al. 2007; Wettstein et al. 2006). The external snapping hip is on the lateral side of the hip often in the area of the greater trochanter. The thickened border of the iliotibial band or the anterior border of the gluteus maximus is tight in the relationship to the bone prominence, and the tensile and compressive forces can produce tendinopathy. The snapping can often be felt in the area of the greater trochanter when the hip is flexed from an extended position (Ilizaliturri et al. 2006, 2008; Yoon et al. 2009).

The internal snapping hip can either be an intra-articular problem in the hip joint or much more commonly an extra-articular problem caused by a snapping iliopsoas tendon (Bureau 2013). In the hip joint loose bodies, a cartilage lesion or a labral tear might result in a painful clicking (snapping) internal hip in most cases associated with internal and external rotation of the hip. The iliopsoas tendon is snapping over the iliopectineal eminence or over the femoral joint. The tendon lies in a groove between the iliopectineal eminence and the anterior inferior iliac spine; it crosses over the femoral head and capsule and inserts into the lesser trochanter. If the tendon is tight or fibrotic, it can result in an audible and sometimes painful snap when the hip is extended from the flexed and externally rotated position. Palpation over the hip joint can often reveal a snapping sensation against the fingers. The same examination techniques used to diagnose iliopsoas-related groin pain are relevant in this case and will often reveal a painful and tight iliopsoas muscle.

25.4.3 Hip Joint Pathology

Pathologies in the hip joint include labral tears, osteoarthritis, chondral lesions, loose bodies, synovial deceases, ligamentum teres (ligamentum capitis femoris) lesions, osteochondritis dissecans, ligamentous instability, avascular necrosis and others. The patient's complaints and the injury mechanism can be helpful in narrowing the field of possible intra-articular diagnosis. The main goal is to decide whether an intra-articular problem is present and the cause of the patient's complaints in order to decide whether further imaging or hip arthroscopy is indicated. At present, the evidence level is not sufficient to definitely diagnose the various intra-articular injuries specifically with clinical examination alone (Martin and Sekiya 2008; Tijssen et al. 2012). The symptoms associated with an intra-articular problem in the central compartment can include pain, catching, locking, clicking, feeling of instability and giving way. A labral tear most commonly refers the pain to the anterior groin. However, anterior groin pain is not specific for labral tears but can be due to a number of other intra-articular pathologies as well and to several extra-articular pathologies. The mechanical symptoms such as instability feeling, giving way, clicking, locking and catching are also quite common with labral tears (Keeney et al. 2004; McCarthy and Busconi 1995; Narvani et al. 2003). The kind of clicking that most often seems to be related to the central compartment is the one associated with internal and external rotation of the hip. Clicking that occurs when the hip is flexed from an extended position seems to be more associated with lateral snapping hip caused by the iliotibial band and gluteus tendon snapping over the greater trochanter, and the click occurring when the hip is extended from the flexed position is most commonly caused by the iliopsoas tendon snapping over the iliopectineal eminence or femoral head.

25.4.4 Other Differential Diagnoses

Stress fracture is an important differential diagnosis including stress fracture of the femoral neck, the sacrum, the pubis and the ischium (Kiuru et al. 2003). When there is a sudden onset of pain without an adequate trauma, when weight bearing is painful and when the pain is persistent sometimes without a corresponding precise tenderness, a stress fracture should be considered. The fracture is usually the result of changes with increased weight-bearing activity such as running. As the stress continues, pain occurs during training and becomes more intense. Unless the form of the activity is modified, the pain gradually worsens over a few weeks to the point where the patient is unable to walk without pain. The fracture site is painful, but it is not always possible to locate or pinpoint by palpation. Especially the quite serious stress fracture of the femoral neck can be difficult to diagnose clinically since it is not possible to palpate the neck. Avulsion fractures about the pelvis should be considered in the adolescent patient.

The apophyses are prone to overuse or a traumatic overload causing a painful lesion especially in young patients without bony fusion of the apophyses. The most frequent locations in the groin are anterior superior iliac spine (ASIS) caused by the sartorius muscle especially during jumping activities, anterior inferior iliac spine (AIIS) caused by the rectus femoris muscle during kicking and the ischial tuberosity caused by the hamstring muscles during sprinting. The history, tenderness of the suspected area and a radiograph will usually reveal the diagnosis.

Some authors use the term "osteitis pubis" as a vaguely defined differential diagnosis to the soft tissue-related groin problems. Osteitis pubis is a term originally used to describe an infection in the pubic bone around the symphysis joint. The characteristic radiological findings – bone resorption, widening of the symphysis and sclerosis along the rami – can often be found in both athletes with or without groin problems.

Bursitis either traumatic or inflammatory should also be considered. The bursae are usually localised between tendons and muscles and over bony prominences. A common example is the superficial trochanteric bursa over the greater trochanter that often is subject to direct trauma and to inflammation due to an external snapping hip. The iliopectineal bursa was earlier considered a major contributor to groin pain in athletes. But recent imaging techniques as ultrasound and MRI have shown that this is not the case.

Nerve entrapment can occur when a peripheral nerve becomes entrapped after direct trauma or due to an overuse condition of the neighbouring fascia, tendons or muscles leading to an inflammatory condition. Nerves most commonly affected are the ilioinguinal, genitofemoral and lateral cutaneous femoral nerves. The diagnosis can be difficult, but localised tenderness at the site of penetration through the fascia is common. The pain is usually experienced with hyperesthesia or hypoesthesia of the skin along the specific nerves' innervation area. The characteristics of the pain may vary considerably.

Neoplasms may exist in seemingly healthy athletes and should be kept in mind as a possible cause of hip and groin pain. Osteosarcomas, chondrosarcomas and other tumours have been diagnosed often at a late stage, due to both patient's and doctor's delay. Persistent pain or an unexplained "mass" in the hip and groin region should be carefully examined to exclude a neoplasm. Imaging techniques should always be included at an early stage in patients with diffuse and unclear hip and groin pain.

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Radiologic Imaging of Pelvis, Groin, Hip, and Thigh Injuries

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Abstract

Radiography, CT(A), and MRI(A) are the major radiological techniques to evaluate pelvic and hip sports injury. Intra-articular pathology of the hip is ideally assessed with magnetic resonance arthrography (MRA). Typical diagnoses are labral lesions in femoroacetabular impingement. Hyaline articular cartilage abnormalities are identified with lower sensitivity. Intra-articular loose bodies are well demonstrated on MRA (direct or indirect) (D-MRA or I-MRA). Avascular necrosis (AVN) may occur in athletes especially after subcapital fracture or hip dislocation. MRI is very sensitive and specific in the diagnosis of AVN of the hip. Based on the shape of the lesion, AVN can be differentiated from subchondral insufficiency fractures (SIF) in osteoporotic women. Subchondral fatigue fractures in young athletes show identical imaging findings as the insufficiency fractures and may be located either in the femoral head or in the acetabulum.

MRI and CT detect a reduced distance between the ischial tuberosity and lesser trochanter in ischiofemoral impingement syndrome, on fluid-sensitive sequences on MRI increased signal intensity of the quadratus femoris muscle is detected.

Iliopsoas impingement is a recently described entity in the orthopedic literature. The only reliable MR feature seems to be the visualization of a labral tear at the 3-o'clock position on MR arthrography.

A specific but not sensitive examination to evaluate snapping iliopsoas tendon is dynamic ultrasound performed by an experienced ultrasonographist. Lateral snapping hip is caused by snapping of the iliotibial tract or gluteus maximus relative to the greater trochanter. Intra-articular processes may produce a snapping hip sensation, such as intra-articular bodies.

US is sensitive to demonstrate the superficially located iliopsoas bursa. MRI is the modality of choice for deeper located bursitis like obturator externus bursitis and ischiogluteal bursitis. Trochanteric bursitis can be found in case of trochanteric pain syndrome, especially in case of tendinopathy of the gluteus medius and minimus. Fluid in the bursae is often not prominent and secondary to tendinopathy. The gluteal tendons may be evaluated with MRI and ultrasound. US-guided treatment is performed in therapy-resistant tendinopathy.

Morel-Lavallée lesion at the hip region is typically located at the level of the greater trochanter and can well be evaluated with US because of its superficial localization.

Muscle contusions are very frequent around the hip and thigh in sports. The damage with contusion usually occurs in the layer closest to the bone (intermediate vastus muscle of the quadriceps) or tendon. MR images reveal edema at the injured site, frequently due to interstitial hemorrhage as well as edema. In more severe contusions, hematomas can be seen as mass-like lesions surrounded by edema. The signal intensity of a hematoma on T1W and T2W images depends on the degradation of hemoglobin. The major complications of muscle contusion are myositis ossificans and seroma.

Myositis ossificans (MO) or focal myositis is a noninfectious myositis often with heterotopic ossification. Imaging plays an important role in identifying myositis ossificans and focal myositis to prevent biopsy with misleading

histology and wide resection. CT and ultrasound are more sensitive than radiography for detecting ossification. MRI may show the so-called zone phenomenon before ossification appears. US may be the most sensitive imaging modality to early depict the calcified area at the peripheral zone in MO. The aspect of adult bone in the later stages characterized by central spongious bone containing fat and at the periphery cortical bone, that is easily recognized on radiographs, CT, or MRI.

Muscle strains in adults at the level of the quadriceps (rectus femoris) are typically located at the level of the proximal or distal musculotendinous junction (MTJ).

In superficial and low-grade MTJ lesions even at the hamstrings, ultrasound has the advantage to better differentiate grade II lesions with elongation or grade I lesions. Generally in acute lesions US is as useful as MRI in depicting hamstring MTJ injuries. Strains at the hamstring enthesis are examined with MRI.

On MRI ruptures of the rectus abdominis–common adductor origin (RA-CAO) will show the shearing of the RA-CAO aponeurosis with surrounding soft tissue edema, widening the distance between the aponeurosis and the pubis; arcuate ligament tear is only demonstrated on MRI. RA-CAO lesions may predispose to a direct inguinal hernia or a "sportsman's hernia" that is demonstrated on dynamic US.

MRI is the imaging modality of choice to evaluate osteitis pubis; radiographs and CT only demonstrate chronic advanced disease.

In patients with bone marrow edema (BME) on MRI at the SI joints, the major differential with sacroiliitis is stress reaction. Specific radiological diagnosis is not possible in early cases of sacroiliitis without demonstration of erosions. A specific diagnosis of sacroiliitis is made in bilateral and symmetrical presentations in SpA and is typical asymmetric in psoriasis and reactive arthritis.

Nerve lesions around the hip involve especially the ischial nerve, the femoral nerve, and the lateral femoral cutaneous nerve. Entrapment of the lateral femoral cutaneous nerve can best be evaluated with high-frequency US. US-guided treatment with injection of corticoids in the perineurium shows promising results.

Because of its deeper location, the best modality to evaluate the sciatic nerve is MRI.

US is particularly well suited to examine the pediatric musculoskeletal system, especially of the hip and pelvis. It is a well-tolerated and noninvasive way without using ionizing radiation or sedation. In transient synovitis, fluid is seen between the 2 layers of the hip capsule.

In recurrent stress on the apophysis with apophysitis in children, apparent physeal widening, apophyseal edema, and adjacent muscle and bone edema can be seen on MRI. On ultrasound the physeal widening and the apophyseal hypertrophy and angiogenesis can be depicted.

More severe acute trauma may result in an avulsion of the apophysis or apophysiolysis. In these a distraction of the apophysis is demonstrated without signs of inflammation and angiogenesis in the acute phase on US. There can be a hematoma and bone marrow edema in the apophysis and adjacent bone.

Fractures of the hip and the pelvis are initially evaluated with radiographs. In the second stage CT with three-dimensional reconstruction is used.

Abbreviations

ARCO	Association Research Circulation Osseous
AVN	Avascular necrosis
AS	Ankylosing spondylitis
BME	Bone marrow edema
CEa	Center-edge angle
CT	Computed tomography
CTA	Computed tomographic arthrography
DHD	Developmental hip dysplasia
D-MRA	Direct magnetic resonance imaging arthrography
DTPA	Diethylene triamine pentaacetic acid
FADDIR	Flexion, adduction, and internal rotation of the hip: impingement test
FAI	Femoroacetabular impingement
FHAVN	Femoral head avascular necrosis
FS	Fat saturation
GTPS	Greater trochanter pain syndrome
IV	Intravenous
I-MRA	Indirect magnetic resonance imaging arthrography
HF	US high-frequency ultrasound
LCP	Legg–Calve–Perthes disease
MO	Myositis ossificans
MRI	Magnetic resonance imaging
MRA	Magnetic resonance imaging arthrography
MRI	Magnetic resonance imaging
MTJ	Musculotendinous junction
NCFL	Nervus cutaneus femoris lateralis
PET	Positron emission tomography
PM	Piriformis muscle
PWD	Power Doppler ultrasound
RA	Rectus abdominis
RA-CAO	Rectus abdominis and the common adductor origin
SCFE	Slipped capital femoral epiphysis
SE	Spin echo
SI	Signal intensity
SIF	Subchondral insufficiency fracture
SpA	Spondyloarthropathy
T	Tesla
US	Ultrasound

26.1 Introduction

Radiography, CT(A), and MRI(A) are the major radiological techniques to evaluate pelvic and hip sports injury. Superficial soft tissues are demonstrated on US with the use of high-frequency probes at a much higher spatial resolution compared to MRI. Ultrasound is used in the initial assessment of evaluation of joint fluid and for diagnostic evaluation of tendons and muscle abnormalities including tendon snapping and superficial-located peripheral nerves and to guide injections. US is preferred for the examination of the pediatric hip and pelvis.

26.2 Imaging Modalities

Osseous abnormalities can be characterized with radiography, CT, or MRI. Soft tissue pathology is best evaluated with MRI or US. MRA and CT arthrography (CTA) are especially useful for intra-articular pathology of the hip. CT is superior to demonstrate the bone itself. It does not evaluate BME and is poor in the evaluation of soft tissues. MRI is superior to evaluate soft tissues and is very sensitive in finding edema, BME, and inflammation. The hip joint can well be evaluated on plain MRI examinations. Accuracy for intra-articular pathology is higher on MRA. Indirect MR arthrography (I-MRA) is performed after IV administration of gadolinium DTPA. After the IV gadolinium administration and before the MRI examination, the patient is asked to exercise the joint for 20 min in order to achieve enhancement of the synovial membrane and excretion of gadolinium in the synovial fluid. In direct MR arthrography (D-MRA), gadolinium DTPA contrast (1/200 diluted solution) is administered directly in the joint under fluoroscopic or US guidance. Recent prospective studies demonstrate comparable accuracy of I-MRA compared to D-MRA at 3 T (Petchprapa et al. 2015) (Figs. 26.1, 26.2, and 26.3).

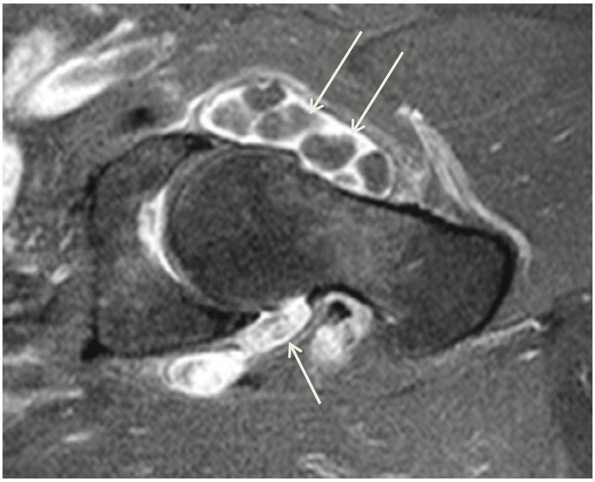


Fig. 26.1 I-MRA of the left hip. Synovial osteochondromatosis with loose bodies (*arrow*) and hydrops

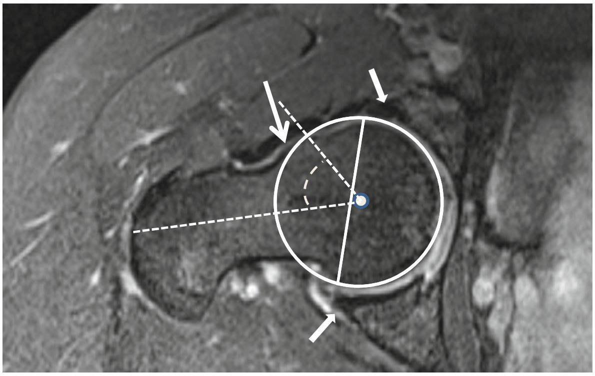


Fig. 26.2 I-MRA of the right hip. Mixed cam and pincer configuration in a 34-year-old female. There is an obvious bump (cam) on the anterior femoral neck (*big arrow*) with alpha angle over 50° (*striped curved line*). The acetabulum is overcovering the femoral head (*small arrows*); the straight line connecting the anterior and posterior margin of the labrum at the midsection of the femur head is located latero-anterior to the center of the femur head (pincer)

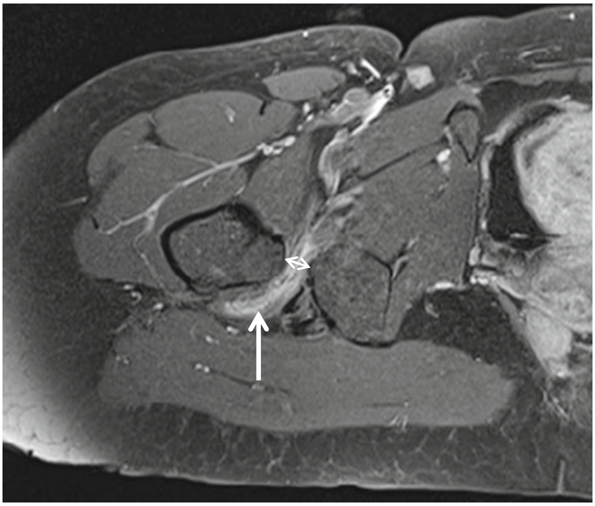


Fig. 26.3 I-MRA of the right hip. Reduced distance between the ischial tuberosity on the left and lesser trochanter on the right to 1 cm (normally 2 cm) (*double arrow*) with edema in the quadratus femoris muscle (*arrow*). I-MRA T1 FS axial image, with high SI in the muscle: edema with contrast enhancement

Superficial soft tissues are demonstrated on US with the use of high-frequency probes at a much higher spatial resolution compared to MRI. The deeper the structures are located, the lower the ultrasound frequency and the lower the spatial resolution. Ultrasound is used in the initial assessment of evaluation of joint fluid and for diagnostic evaluation of tendons and muscles abnormalities including tendon snapping (Dawes and Seidenberg 2014). The use of US can be the most appropriate way to examine the postoperative hip as it has little artifacts from metal in hip prosthesis. It can be used in the evaluation of the superficial-located peripheral nerves (NCFL, femoral nerve, and sciatic nerve) with high resolution using high-frequency probes.

Ultrasound can also be used to guide injections: injection for MR or CT arthrography, diagnostic or therapeutic aspiration, diagnostic injection with anesthetics, or therapeutic injection (Jacobson et al. 2012). US is preferred for the examination of the pediatric hip and pelvis, because of the lack of radiation.

26.3 Pathology

26.3.1 Intra-articular Hip Pathology

Bony morphology of the hip joint is primary examined radiographically. Intra-articular pathology of the hip is ideally assessed after administration of intra-articular diluted gadolinium (1/200 solution). D-MRA has an accuracy as high as 90 % in the diagnosis of labral tear (Perdikakis et al. 2011). D-MRA allows to recognize anatomic variants like intra-articular synovial plicae and sublabral sulci. Causes of labral lesions are femoroacetabular impingement (FAI), trauma, hip dysplasia, capsular laxity, degenerative joint disease, and recently described iliopsoas impingement. Paralabral cysts are a hallmark of a labral tear; they are easily identified because of their liquid content, often in multilobular cysts that may fill with intra-articular contrast material (Magee and Hinson 2000). The cysts are best depicted on the fluid-sensitive sequences and can be missed on the T1 FS sequences as they often do not fill with gadolinium contrast.

Hyaline articular cartilage abnormalities also may be identified but with lower sensitivity compared with labral tears (Perdikakis et al. 2011). Recent prospective studies demonstrate comparable accuracy of I-MRA compared to D-MRA at 3 T (Petchprapa et al. 2015).

Features of osteoarthritis are joint space narrowing, osteophyte formation, variable reactive BME, and subchondral cysts.

Hydrops can be present and is well evaluated on US or MRI (MRI or I-MRA, not on D-MRA since the joint is injected). Intra-articular loose bodies are well demonstrated on MRA (direct or indirect) (Fig. 26.1). Intra-articular loose bodies may give a snapping sensation in the hip with movement (snapping hip).

AVN of the hip affects mostly middle-aged patients in their active phase of living. It may occur in athletes especially after subcapital fracture or hip dislocation leading to vascular disruption of the femoral head. D-MRA is an accurate method to detect tears of the ligamentum teres as a cause of vascular disruption of the femoral head (Chang et al. 2015). Early diagnosis of AVN plays a crucial role with respect to therapeutic success and prognosis. MRI is very sensitive and specific in the diagnosis of AVN of the hip. Although bone scintigraphy and CT and more recently PET have been used for diagnosing AVN, currently the most important imaging methods included in the most used classification systems for AVN of the hip (Steinberg, Ficat and ARCO) are radiographs and MRI (Karantanas 2013). Radiographs are normal in the early non-symptomatic stages of AVN. Specific crescent sign on radiographs, representing subchondral parallel bone fracture, is an early sign of collapse and found in symptomatic more advanced AVN stages (Fig. 26.4). MRI is superior to

Fig. 26.4 Radiograph of the left hip in a patient with AVN. Crescent line (*arrows*) is demonstrated at the latero-superior subchondral area. No obvious collapse of the femur head is demonstrated

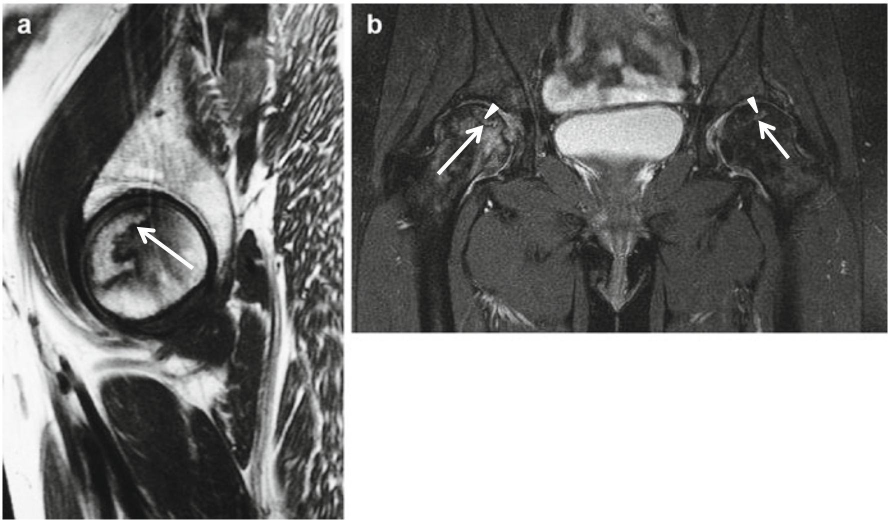


Fig. 26.5 MRI of AVN of the hip. (**a**) Sagittal T1WI of the left hip and (**b**) coronal T2WI with FS of both hips with bilateral AVN in another patient. Incidental finding in **a**, pain in the right hip region was reported in patient **b**. Demarcation (*arrows*) zone circumscribing the necrotic portion on T1- and T2WI. Pathognomonic double-line sign on T2WI (**b** *arrowheads* pointing at the high SI line representing reparative tissue). Normal subchondral bone lamella is present in **a**. On T2WI perilesional BME is detected in patients with loss of spherical surface of the femoral head related to collapse of the subchondral lamella (**b** right hip); no perilesional BME is present on the left side

plain radiographs in depicting the early stages, in staging accurately the lesions that result in early articular collapse, and in monitoring vascularized fibular grafts. A specific and very early (pre-collapse) MRI sign of AVN, found in 100 % of cases, is a low SI demarcation zone on T1- and T2WI extending from subchondral bone to subchondral bone circumscribing the necrotic portion (Fig. 26.5a, b). Pathognomonic for AVN is the double line at the interface between necrotic and healthy bone on

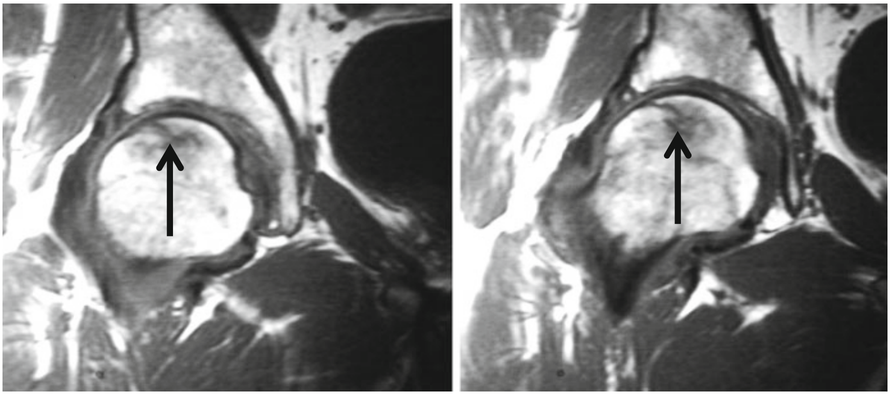


Fig. 26.6 MRI of subchondral fatigue fracture of the right hip. Coronal T1WI with irregular fracture line *arrows* at the subchondral area without complete circumscription to the subchondral lamella. Area of reduced signal surrounds the fracture line and represents BME

T2WI with high signal on the necrotic side representing reparative tissue and low SI line at the vital part representing sclerosis and fibrosis (Fig. 26.5b). The double-line sign is present in 65–80 % of AVN (Mitchell et al. 1987). The reported sensitivity of MRI for early diagnosis of osteonecrosis ranges between 88 and 100 % compared with 81 % of bone scintigraphy (Karantanas 2013). The necrosis is most often located in the anterosuperior weightbearing region. The treatment of FHAVN is determined in large part by the stage of the disease and by the location and size of the necrotic fragment. The capital point of all the classification systems is the loss of the spherical surface of the femoral head representing a point of no return. The diagnosis of a non-spherical articular surface is based only on plain radiographs in all classification systems currently used. MRI is used only at the early pre-collapse stages. Especially in the pre-collapse stage, calculation of size in percentage of FH involved and the location of the lesion are the most significant factors predicting the possibility of collapse and thus the prognosis.

Based on the shape and subchondral location of the lesion, AVN can be differentiated from subchondral insufficiency fractures (SIF) in osteoporotic women. The AVN lesion has a smooth delineation, is concave to the articular surface, and circumscribes the entire necrotic segment. In insufficiency fractures the delineation of the fracture is irregular, discontinuous, and convex or parallel to the articular surface. Subchondral fatigue fractures in young athletes are rare but show identical imaging findings as the insufficiency fractures and may be located either in the femoral head or in the acetabulum (Fig. 26.6) (Yoon et al. 2012). Joint effusion and bone marrow edema (BME) are found and precede the fracture line in fatigue fractures.

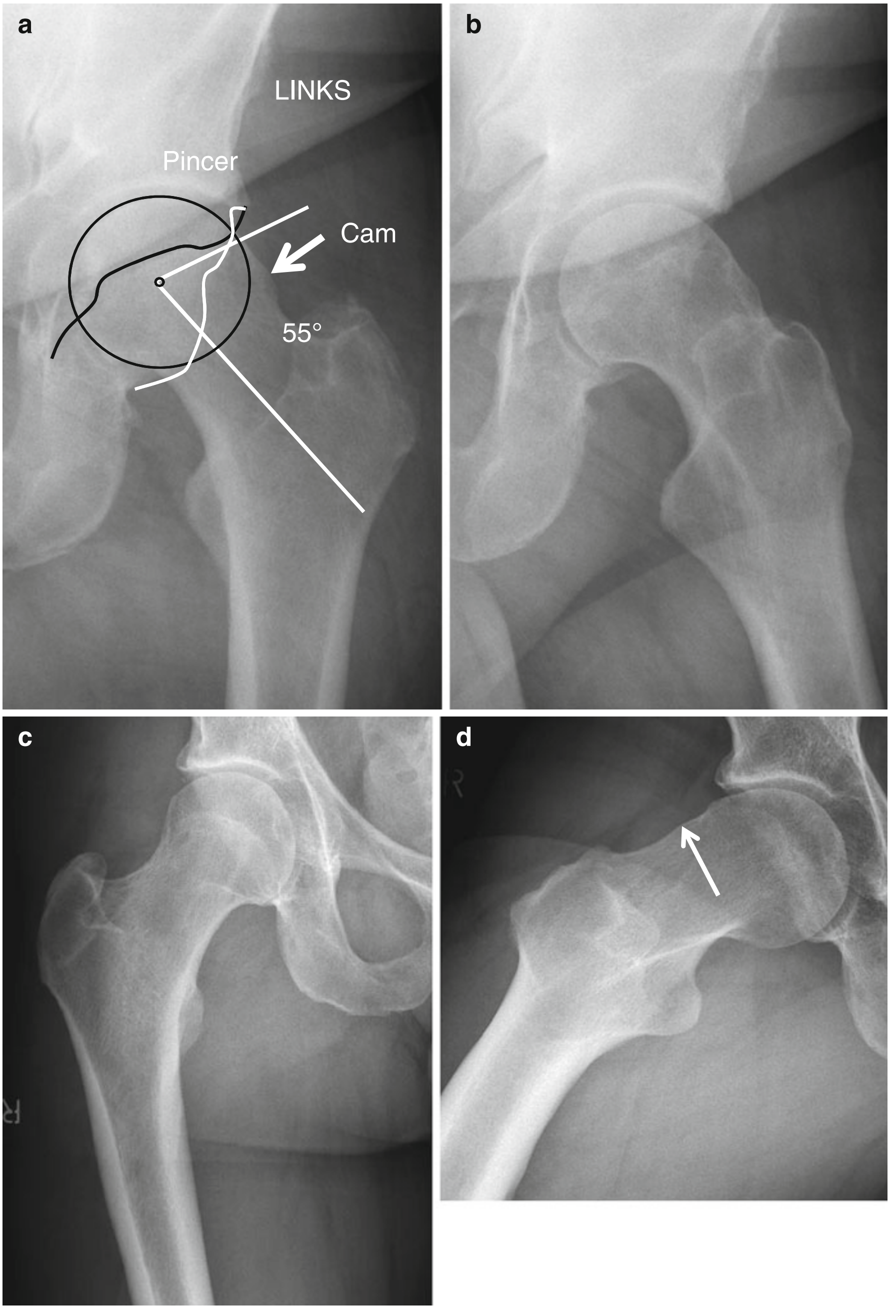
As stated before only radiographs are employed routinely for the evaluation of collapse. It has been shown that plain radiographs overestimate stage II (pre-collapse) and underestimate stage III (collapse before flattening) lesions and are inaccurate in estimating the collapse size, which is an important parameter in therapeutic decisions. Therefore, it has been suggested that the wider use of MRI findings in staging AVN may be necessary (Karantanas 2013).

26.3.2 Femoroacetabular Impingement

Femoroacetabular impingement (FAI) was first described in 1999. FAI is the abutment of the femur with the acetabular rim causing degeneration of the labrum and cartilage. Two types of FAI are described. Cam impingement is caused by a non-spherical head resulting in an osseous bump lateral or anterosuperior on the femoral neck. With flexion and internal rotation at the hip, abutment may proceed with damage to the anterosuperior cartilage and tearing off of the labrum. It is more frequent in males. The second type is pincer impingement, caused by acetabular overcoverage. Osseous impaction along the anterosuperior or superior femoral neck with compression may proceed with damage of the anterosuperior labrum and a small rim of chondromalacia. Posteroinferior cartilage lesions are caused by "contrecoup" forces in pincer-type impingement. Pincer type is more frequent in females. Most of the FAI are mixed cam and pincer impingement (Fig. 26.2). FAI has been shown to be responsible for a large proportion of tears of the acetabular labrum, a major cause of hip pain in young adults. It is now established that FAI is a major factor in the development of early osteoarthritis of the hip in athletes (soccer players) but also in the general population.

A number of conditions are associated with FAI. Developmental hip dysplasia (DHD), Legg–Calve–Perthes disease (LCP), slipped capital femoral epiphysis (SCFE), and malunited fractures of the femoral neck are all anatomical abnormalities related to FAI. Variant anatomy of the femoral head and acetabulum responsible for FAI is depicted on radiographs (Figs. 26.7a–c and 26.9b) (Scheidt et al. 2014) or MRI–MRA in paracoronal series parallel to the femur neck

Fig. 26.7 Radiographic evaluation of FAI-related osseous anomalies. (**a**, **b**) AP view (**a**) and Lequesne false profile (**b**) of the left hip in a patient with combined cam (*arrow*) and pincer morphology demonstrated on AP view (**a**). (**c**, **d**) AP view (**c**) and Dunn view (**d**) in a 44-year-old patient with positive impingement test at the right hip with demonstration of small cam (*arrow*) on Dunn view (**d**) that is not demonstrated on AP view (**c**). Generally three views, AP pelvis (**a**, image cutout on the right hip), Lequesne false profile (**b**), and Dunn view (**d** different patient), are convenient to define femur and acetabular anatomy. The most convenient technique to obtain a digital Dunn view (**d**) is prone patient position, with hip in 45° flexion and with 20° abduction and non-inclined AP radiation bundle centered on the hip joint. Cam morphology is objectified by calculation of an alpha angle of over 50° on AP view of the pelvis (**a** *white angle*) and/or Dunn view (**d**). Related to the anterolateral location of cam, the AP view is less sensitive in the detection of cam morphology compared to Dunn view. Additional Dunn view is not needed if cam is depicted on AP view (patient **a**, **b**). Pincer morphology is depicted on AP pelvis when a crossover is depicted of the ischial spine (anterior limbus of the acetabulum) (**a** *black irregular line*) and the posterior acetabular limbus (**a** *white irregular line*). On Lequesne false profile, joint space narrowing at the posterior part of the joint is depicted


a
LINKS
Pincer
Cam
55°
b
c
d

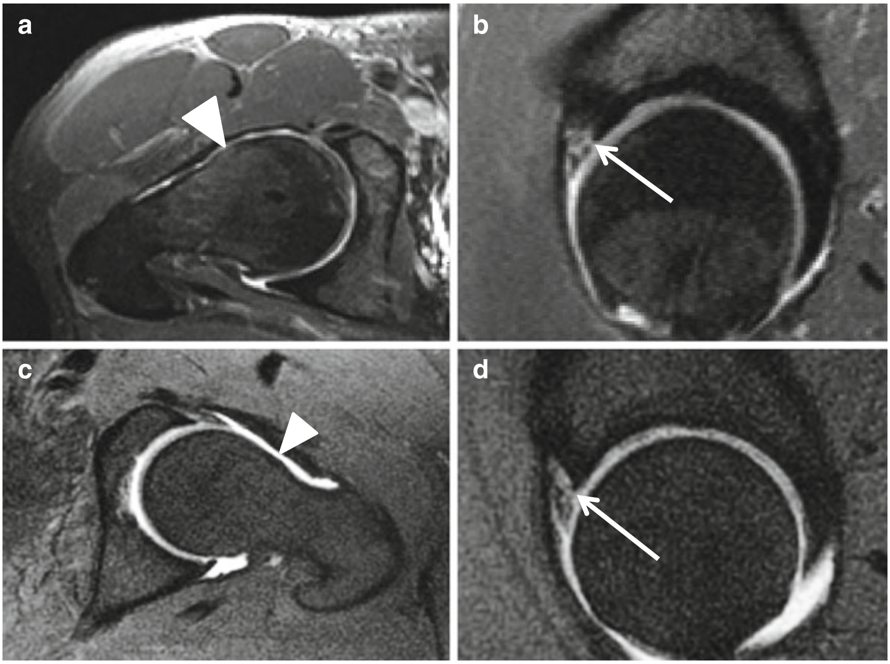


Fig. 26.8 MRA of labral dissociation, comparison of I-MRA and D-MRA in different patients. I-MRA with axial (**a**) and sagittal (**b**) series. D-MRA with axial (**c**) and sagittal (**d**) series. Cam-type femur is documented on **a** and **c** (*arrowheads*). Gadolinium interposition between limbus acetabuli and labrum at the anterolateral part is depicted on sagittal images (**b**, **d** *arrows*). Increased expansion in D-MRA (**c**, **d**) compared to I-MRA is obvious (**a**, **b**)

(Fig. 26.8a, c). In patients with cam and/or pincer morphology, repetitive adduction with flexion of the hip causes impingement of labrum and cartilage with lesions as a result. Specific clinical impingement test that may elucidate pain is done with flexion, adduction, and internal rotation of the hip (FADDIR). These labrum and cartilage lesions are evaluated with MRA or CTA (Fig. 26.8a–d); high-magnetic-field MRI at 3 Tesla (T) is capable of demonstrating lesions without gadolinium administration. In pincer-type impingement, the labrum is crushed and torn at the free lateral margin; calcifications and ossifications at the labrum may develop; a narrow strip of chondromalacia is found at the level of the labral lesion; a broader area of chondromalacia may be found at the posterior part of the hip joint related to lever action of the femur metaphysis at the anterior acetabulum. Cam femur morphology typically leads to push-off lesions of the labrum relative to the limbus acetabula with dissociation of the labro-cartilaginous area and development of cystic expansion through the dissociation (paralabral cyst). Labral lesions are not accurately depicted on US; paralabral cyst may be the only US sign of labral dissociation.

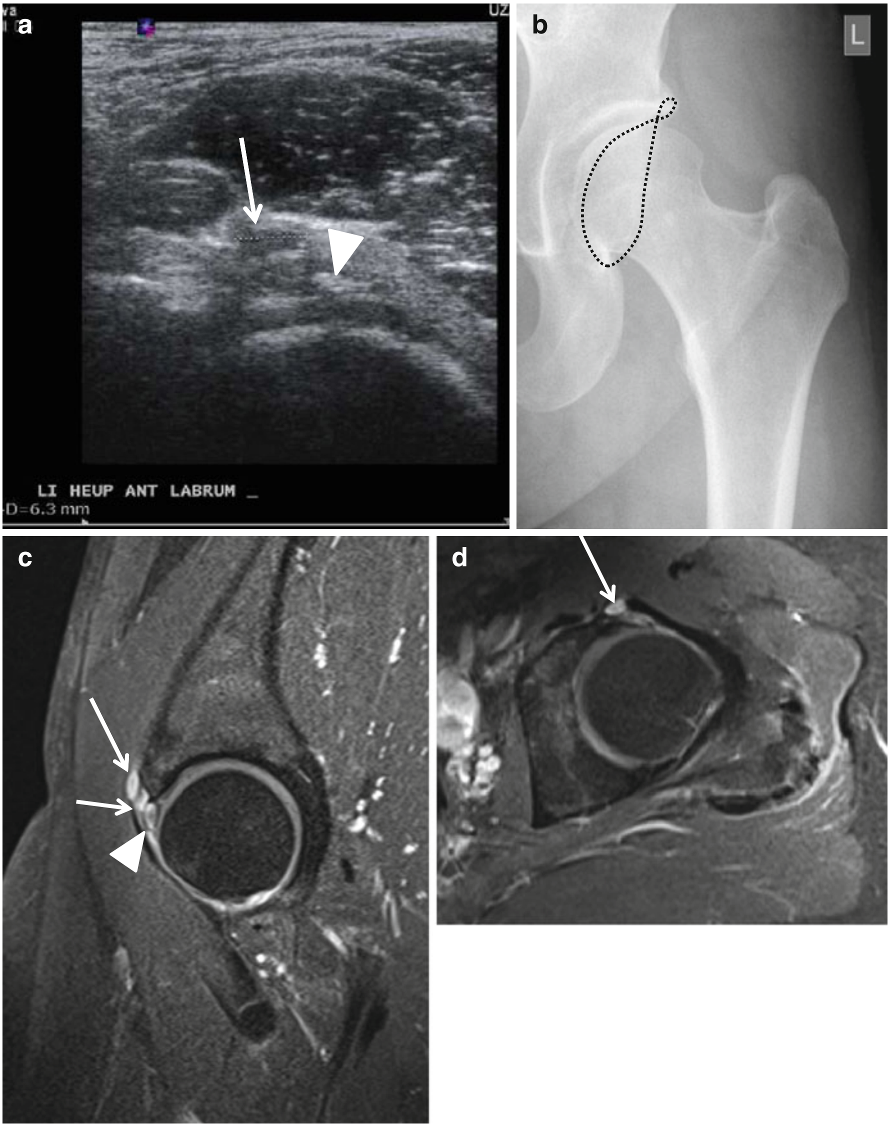


Fig. 26.9 Radiograph, US, and MRI of labral degeneration and paralabral cyst. Twenty-eight-year-old female with chronic pain at the left hip. US sagittal view (**a**) demonstrating paralabral cyst (*arrow*) and calcifications at the labrum (*arrowhead*). Radiographic AP view with demonstration of limbus acetabuli lining with crossover related to pincer type (**b**). I-MRA (**c** sagittal section and **d** axial section) confirmed the paralabral cyst (*arrows*) and also demonstrated cystic degeneration of the labrum (*arrowhead*)

26.3.3 Other Impingement Syndromes Around the Hip

Ischiofemoral impingement syndrome (Fig. 26.3) can be the cause of hip pain due to impingement of the quadratus femoris muscle between the ischium and femur. It is usually associated with previous trauma, mass lesions, or surgery. MRI and CT detect a reduced distance between the ischial tuberosity and lesser trochanter (normal $\geq$ 2 cm), and on fluid-sensitive sequences on MRI, increased signal intensity of the quadratus femoris muscle is detected; positioning with MRI in full range of motion improves detection (Torriani 2009; Singer et al. 2014).

Iliopsoas impingement is a recently described entity in the orthopedic literature. It can be the cause of labral tears, especially those located in the 3-o'clock position. This type of impingement is an arthroscopic diagnosis and treated with arthroscopic iliopsoas tenotomy at labral level. The only reliable MR feature seems to be the visualization of a labral tear at the 3-o'clock position on MR arthrography (Blankenbaker 2012).

26.3.4 Snapping Hip

The prevalence of snapping hip or coxa saltans is estimated to occur in up to 10 % of the general population, but it is especially seen in athletes such as dancers, soccer players, weight lifters, and runners. The cause of snapping hip can be intra- or extra-articular.

Two types of extra-articular snapping hip are known: anterior located snapping iliopsoas tendon and lateral located snapping iliotibial band. Lateral snapping hip is attributed to the abrupt movement of the iliotibial band across the greater trochanter. Anterior snapping hip or snapping of the iliopsoas tendon usually requires contraction of the hip flexors and may be difficult to differentiate from intra-articular causes of snapping (Lewis 2010). A specific but not sensitive examination to evaluate snapping iliopsoas tendon is dynamic ultrasound performed by an experienced ultrasonographist. With regard to snapping iliopsoas, the transducer is placed parallel to the inguinal ligament over the iliopsoas at the level of the bony pelvis. Dynamic US examination is performed, the patient is asked to flex and externally rotate the hip in a frog-leg position, and then US examination is performed during slow straightening of the leg. In the abnormal situation, medial fibers of the iliacus muscle are interposed between the psoas major tendon and the ilium. Lateral snapping hip is caused by snapping of the iliotibial tract or gluteus maximus relative to the greater trochanter. Intra-articular processes may produce a snapping hip sensation, such as intra-articular bodies (Magee and Hinson 2000; Lee et al. 2013).

26.3.5 Bursae/Bursitis

A distended iliopsoas bursa is located anterior to the femoral head and medial to the iliopsoas tendon; a communication with the joint can be depicted in 15 % of the normal population and is increasingly found in cases of hip disease or hip prosthesis. It can extend deep or superficial to the iliopsoas muscle and extend far

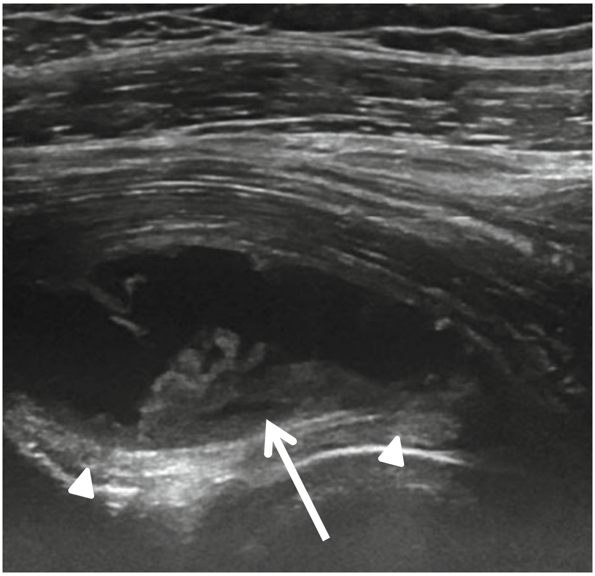


Fig. 26.10 Iliopsoas bursitis. US sagittal plane at the level of the iliofemoral ligament (*arrowhead*) shows an iliopsoas bursitis with synovial proliferation (*arrow*)

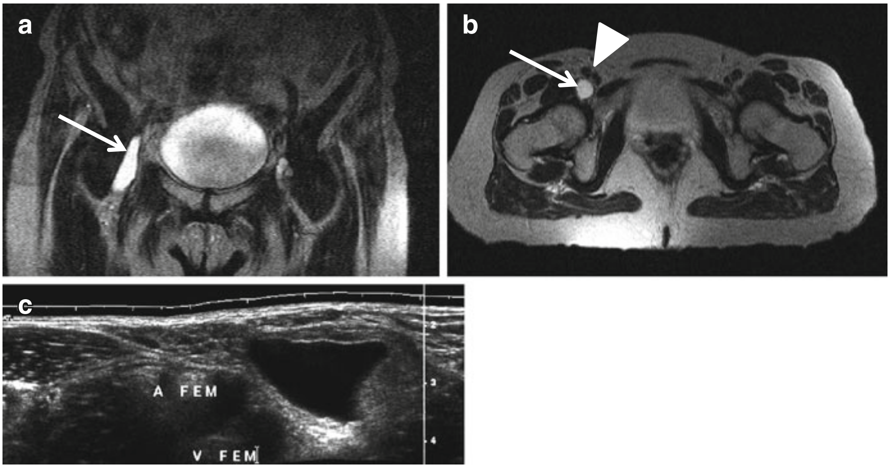


Fig. 26.11 Iliopsoas bursitis MRI and US in two different patients. Coronal (**a**) and axial (**b**) T2WI with high-intensity elongated bursa (*arrow*) along the course of the psoas MTJ lateral to the femoral artery and vein (*arrowhead*). Axial US (**c**) demonstration of assonant bursa in between the iliopsoas and femoral artery and vein

intra-abdominally (Blankenbaker 2008). US is sensitive to demonstrate the superficially located iliopsoas bursa (Figs. 26.10 and 26.11a–c).

MRI is the modality of choice for deeper located bursitis like obturator externus bursitis and ischiogluteal bursitis. Obturator externus bursitis may cause groin pain. MRI demonstrates the bursa between the obturator externus muscle and the ischium.

Ischiogluteal bursitis is also best documented on MRI since it is located deep to the gluteus muscles and posteroinferior to the ischial tuberosity. The superior end of the bursal sac abuts the inferomedial aspect of the ischial tuberosity (Kil-Ho Cho et al. 2004).

Trochanteric bursitis can be found in case of trochanteric pain syndrome, especially in case of tendinopathy of the gluteus tendons as described below in Sect. 26.3.6.

26.3.6 Greater Trochanter Pain Syndrome

Greater trochanteric pain syndrome (GTPS) is mostly caused by the gluteus medius and minimus pathology: tendinosis, tendinous calcification, partial tendon tears, or complete tendon rupture. Fluid in the bursae is often not prominent and secondary to tendinopathy. Histologically no inflammation is found in the distended trochanteric bursae (Silva et al. 2008), and the distended bursae itself are not associated with pain (Blankenbaker 2008).

The gluteal tendons may be evaluated with MRI and ultrasound (in thin patients).

Patients with GTPS have peritrochanteric increased fluid signal abnormalities. However, although the absence of peritrochanteric T2 MR abnormalities makes trochanteric pain syndrome unlikely, detection of these abnormalities on MRI is a poor predictor of trochanteric pain syndrome as these findings are present in a high percentage of patients without trochanteric pain (Blankenbaker 2008). About half of the patients with GTPS present with peritrochanteric edema, and about 20 % of them (34/174) display real bursitis. The vast majority (78/91) of the patients with edema present with gluteus medius tendon degeneration, and only rarely a tear is documented (1/91). A relationship between gluteus tendinopathy and increased acetabular coverage is suggested by Klontzas and Karantanas; they calculated a significantly mean increased center edge angle (CEa) of 6° in symptomatic compared to non-symptomatic patients.

US of the greater trochanter is not easy to perform because of aliasing artifact with hypoechoic aspect of the tendons if they are not examined properly. They must be examined in both the axial and coronal planes with correct probe position (Fig. 26.12).

Tendinopathy appears ultrasonographically typically as a hypoechoic and swollen tendon. Partial tears can be seen as hypoechoic clefts (Fig. 26.13). Fiber discontinuity is demonstrated in case of tendon rupture (Fig. 26.14). US-guided treatment (infiltration of the bursae or percutaneous needle tenotomy with or without bursal infiltration) is performed in therapy-resistant tendinopathy (Klauser et al. 2013).

26.3.7 Morel-Lavallée Lesion

Morel-Lavallée lesion is a shearing injury in which the skin and the subcutaneous fatty tissue are abruptly separated from the underlying fascia (also called “closed degloving injury”).

At the hip region it is typically located at the level of the greater trochanter and is typically seen after a fall with a bike or motorcycle or skiing with shear

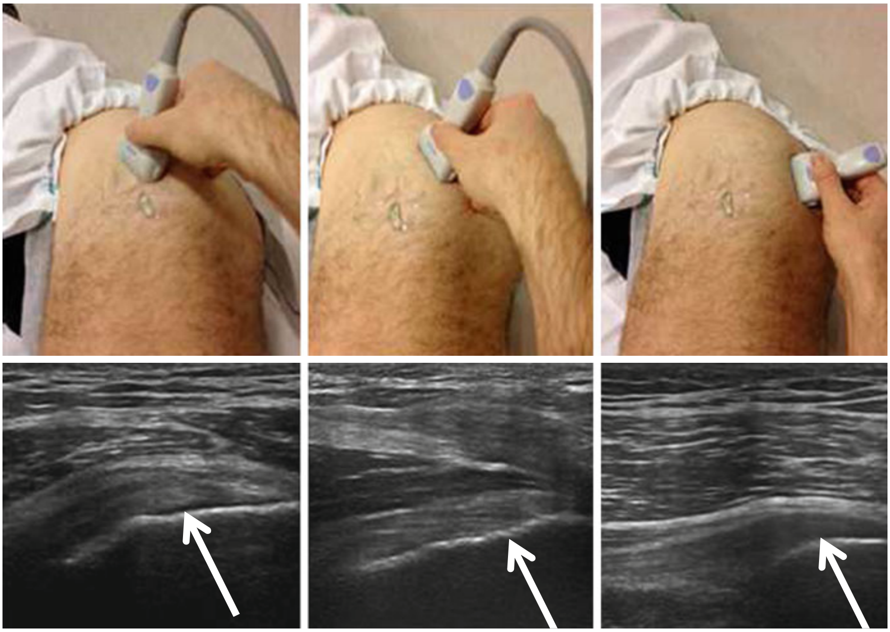


Fig. 26.12 US evaluation of the gluteal insertions on the greater trochanter. The correct probe positions are shown together with the obtained US images in the correct paracoronal planes. The image on the *left* shows the insertion of the gluteus minimus on the anterior facet. The image in the *middle* shows the insertion of the gluteus medius on the lateral facet and the image on the *right* the gluteus medius insertion on the posterosuperior facet. Posteroinferior facet is naked (without tendon insertion); the trochanteric bursa is located in this area deep to the gluteus maximus and distal MTJ

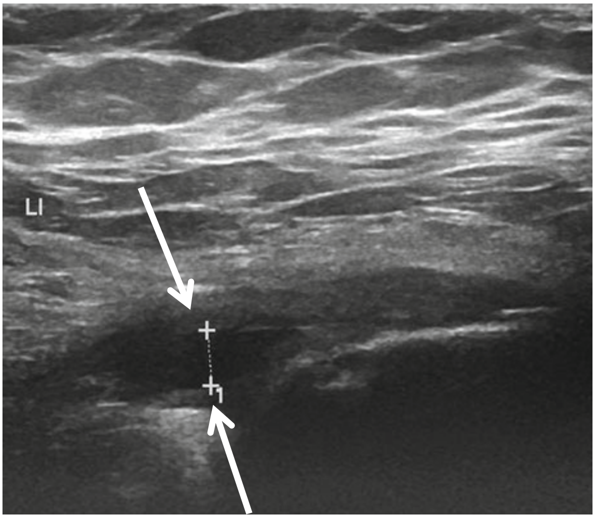


Fig. 26.13 Tear of the gluteus medius. US shows a partial tear in the insertion of the gluteus medius on the lateral facet of the greater trochanter. The tendon (*arrows*) is swollen and has a hypoechoic appearance and signs of tendinopathy with tendinosis. The tear is seen as the hypoechoic cleft (+ marks)

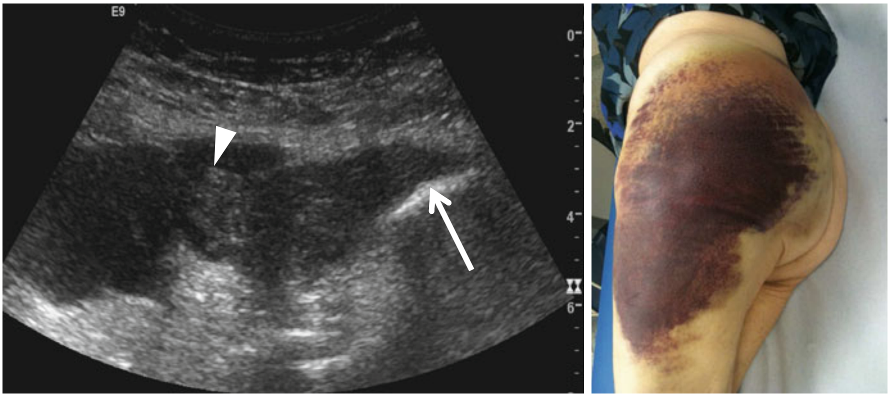


Fig. 26.14 Tear of gluteus medius and minimus. US shows rupture (*arrowhead*) of the gluteus medius and minimus tendons at the greater trochanter (*arrow*). Low-frequency abdominal probe is used to better visualize the deep structures

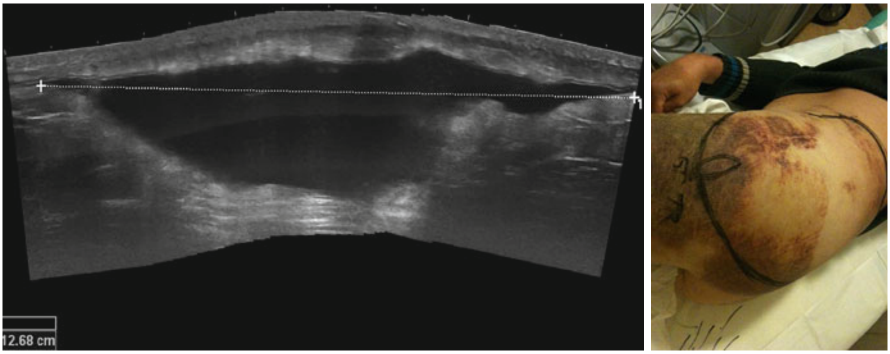


Fig. 26.15 Morel-Lavallée lesion. US shows a huge subcutaneous serosanguinous fluid collection caused by disruption of the lymph and venous plexus below the subcutaneous fat tissue after shearing injury. Image on the *right* shows the extension of the degloving lesion, marked with the *black line* and evaluated with US

force application on the skins. It has recently been described around the knee and can be seen on the back as well. Deglovement of subcutaneous tissues from the underlying fascia disrupts the subcutaneous vascular plexus (lymphatic and venous) at the level of the superficial fascia with leakage of serosanguinous fluid that because of the low hydrostatic pressure at the subcutaneous tissue easily persists and may result in huge soft collections. In severe cases surgery with aspiration and compression is needed. Morel-Lavallée lesion can well be evaluated with US because of its superficial localization (Choudhary and Methratta 2010; Neal et al. 2008). US can easily show the extension of the lesion (Fig. 26.15). Ultrasound-guided aspiration of the collection followed with elastic compression may be performed.

26.3.8 Muscle Contusion

Next to muscle strains, traumatic muscle contusions have been reported as the most frequent type of quadriceps injury in sports. Contusions are very frequent around the hip and thigh in contact sports. Muscle contusions are a result of direct trauma, usually by a blunt object, frequently the fellow sports man's knee in contact sports (rugby)/soccer. This causes edema, hemorrhage, and/or hematoma resulting in muscle swelling and spontaneous pain. Muscle strength typically is not reduced.

The anterior thigh is a commonly injured part of the body.

The damage with contusion usually occurs in the layer closest to the bone (intermediate vastus muscle of the quadriceps) or tendon in soccer players or pectoralis major muscle in rugby players (Hayashi et al. 2014).

Muscle contusions and strains are differentiated by the history of high stress use in the latter as opposed to the history of a direct trauma with a contusion in the former. In the case of muscle strain with incomplete tear, only minor pain is present at rest but characteristically increases with muscle contraction. Muscle ruptures are usually straightforward: sudden intense pain, tightness, and loss of function occur. The patient usually describes a popping sensation. Strain lesions usually involve the rectus femoris muscle.

Contusions are usually larger in size than strain injuries, but the recovery time tends to be significantly shorter.

On imaging there is no typical myotendinous junction localization seen like in muscle strain.

In elite athletes imaging (US and/or MRI) is used to assess correctly the severity of the injury and to exclude important complications as these two elements influence treatment decisions, prognosis, and time to return to unrestricted physical activity. US is regarded less sensitive compared to MRI (Draghi et al. 2013; Hayashi et al. 2012).

MR images reveal edema at the injured site, frequently due to interstitial hemorrhage as well as edema. Typically, there are also skin edema and sometimes bone contusion. In more severe contusions, hematomas can be seen as mass-like lesions surrounded by edema. The signal intensity of a hematoma on T1W and T2W images depends on the degradation of hemoglobin. Hematomas can look like tumors and vice versa. Hematomas can show some enhancement but only at the edge. The major complications of muscle contusion are myositis ossificans and seroma.

Usual complication of muscle contusion is myositis ossificans (myositis ossificans traumatica).

26.3.9 Myositis Ossificans and Focal Myositis

Myositis ossificans (MO) or focal myositis is a noninfectious myositis often with heterotopic ossification. It is usually located within large muscles of the thigh and upper leg.

The etiology and potential predisposing factors of MO remain unclear. In many cases no causative factor can be identified. Well-established predisposing factors are direct traumatic insults (contusion, surgery, burns), neurological insults (paraplegia), or bleeding dyscrasias (hemophilia). Myositis ossificans has been reported in 9–20 % of all cases of quadriceps contusions.

It is a benign "don't touch" lesion; unfortunately on histology it can appear similar to sarcoma (Colman et al. 2014). Imaging plays an important role in identifying myositis ossificans and focal myositis to prevent biopsy with misleading histology and wide resection.

Histopathology and radiological imaging (radiographs, CT, ultrasound, and MRI) of MO is thoroughly studied (Peck and Metreweli 1988; Diaine et al. 1993; De Smet et al. 1992; Kransdorf et al. 1991). The acute phase (lasting 1 week) is characterized by proliferation of mesenchymal cells secreting a myxoid matrix as well as fibroblasts exhibiting abundant mitoses, which gives it a pseudo-fibrosarcomatous appearance. In the first week to 10 days, fibroblasts differentiate into osteoblasts and produce an osteoid matrix at the periphery of the myxoid zone. In the maturation phase or late phase (second to fifth week), the osteoid matrix mineralizes to produce bone; this mineralization starts at the periphery of the lesion. At this stage the three characteristic zones of MO are present. In the end the osteoid matrix will fill up the whole lesion producing the aspect of mature bone exhibiting a cortical and spongious architecture.

Radiographs do not show any anomaly in the early, noncalcified stages of MO. The pathognomonic ossification surrounding a clear central area and separated from the adjacent bony structures with a radiolucent cleft is only seen in the later phases, starting in the second to third week.

CT and ultrasound are more sensitive than radiography for detecting ossification and may also show a central amorphous metaplastic area (Fig. 26.16a). The peripheral rim of mineralization is highly specific for focal myositis or myositis ossificans and usually visible within 4–6 weeks.

MRI may show the so-called zone phenomenon before ossification appears. On MRI scans, an iso- or slight hyperintensity can be observed within the intramuscular mass on T1W and T2W images respectively (Fig. 26.16b). MRI shows the inflammatory edema extending beyond the MO (Fig. 26.16b). On gadolinium-enhanced T1W images, a hyperintense rim is suggestive of the zone phenomenon and may correspond to active hypervascularized osteoid matrix. This annular enhancement is distinct from the heterogeneous enhancement seen in sarcomatous tumors. Although rim enhancement is common in the acute phase of MO, diffuse enhancement may also be seen. The rim becomes hypointense on all sequences within the subacute phase of MO, indicating mineralization. Other important imaging characteristics of MO include the lack of invasion of adjacent tissues and the presence of viable muscle fibers, which are often involved in case of tumor.

US may be the most sensitive imaging modality to early depict the calcified area at the peripheral zone in MO. Three concentric zones have been described on US (Thomas et al 1991), corresponding to the characteristic MO zones. The first peripheral zone is hypoechoic and encircles the lesion. Contiguous hyperemia can be observed on PWD. The second zone is thinner and hyperechoic. It corresponds to the ossifications (Fig. 26.16a). The third central zone is hypoechoic and corresponds to the central stromal fibroblastic component. The aspect of adult bone in the later

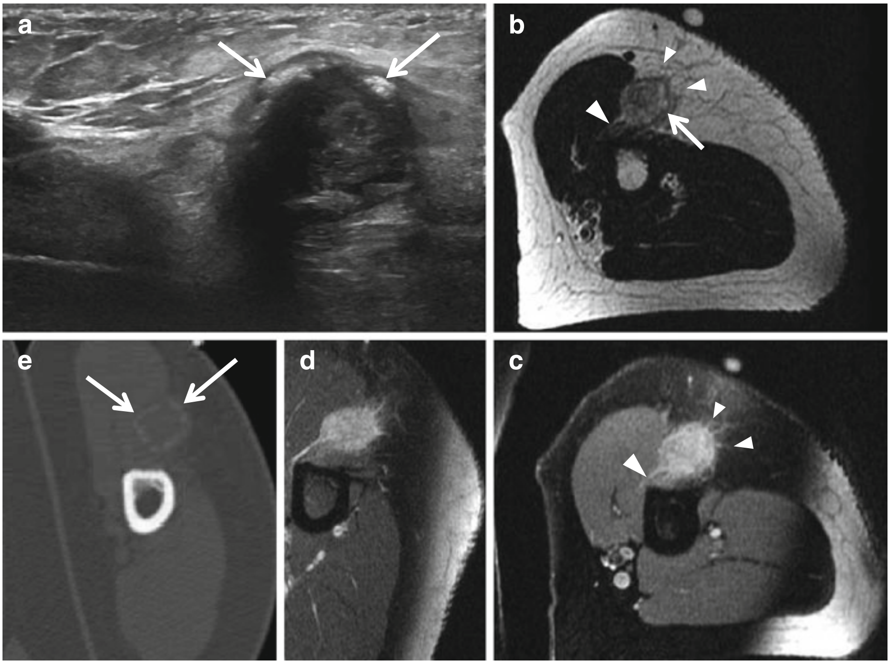


Fig. 26.16 Focal myositis. Thirty-year-old sports physician with lump at the left shoulder, no history of trauma is reported. (**a**) Ultrasound examination demonstrating a rounded lesion with reflective parts with acoustic shadowing at the periphery (*arrows*) located at the subfascial aspect of the deltoid muscle. Demonstration of peripheral mineralization is a specific sign of myositis ossificans/focal myositis. In the absence of peripheral mineralization, a specific diagnosis is not possible. (**b**) Axial TSE T2-weighted MR image demonstrating zonal architecture in the rounded mass lesion. Low SI at the center is surrounded by intermediate SI; at the periphery of the lesion, hypointense calcified layer (*arrow*) is recognized on all sequences. The lesion is surrounded with a hypointense infiltrative area extending into the subcutaneous tissue (*arrowheads*). The low SI peripheral zone identifies the calcified area but cannot be differentiated from other tissues with low mobile proton content (collagen, hemosiderin). (**c**) Axial TSE T2W MR image with FS, the infiltrative edematous infiltration surrounding the lesion is better demonstrated (*arrowheads*). (**d**) Axial TSE T1WI with FS and after IV gadolinium administration demonstrates the diffuse enhancement of the lesion and the infiltrative area; the enhancement is slightly less pronounced at the center. (**e**) Axial CT examination. Hyperdense peripheral calcified area is well demonstrated (*arrows*)

stages with central spongious bone containing fat and at the periphery cortical bone is easily recognized on radiographs, CT, or MRI.

26.3.10 Muscle Sprain and Tendon Tears

Hip adductor injuries are common sporting injuries following overuse or/and acute strain trauma. The adductor longus and gracilis muscle enthesis are the most affected. In partial (grade II) tears, US demonstrates an irregular, hypoechoic, and

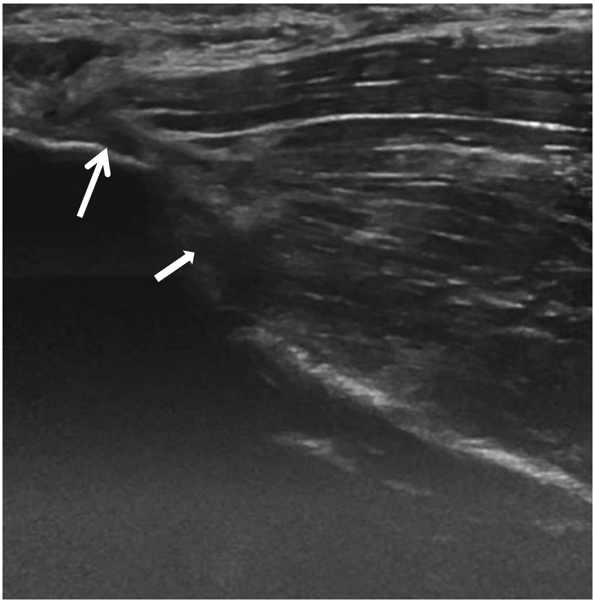


Fig. 26.17 Acute adductor longus muscle tear. US shows a rupture in the origin of the adductor longus (*arrow*) and a partial tear in the origin of the underlying adductor brevis (*small arrow*) on the symphysis

ill-defined adductor origin over the symphysis pubis, whereas a complete separation (grade III) of the adductor longus from the pubis is seen in complete rupture (Fig. 26.17); avulsed bone fragments may still be attached to the tendon.

Similar findings are seen in partial tears or rupture of the hamstring enthesis at the origin of the hamstrings; the common proximal insertion of the long head of the biceps femoris and the semitendinosus is more commonly involved compared to that of the semimembranosus.

In adults acute sprain lesions at the level of the quadriceps are typically located at the level of the proximal or distal musculotendinous junction (MTJ) of the rectus femoris; these are accurately depicted on US or MRI. Grade I lesions may present not aberrant a normal ultrasound examination with typical clinical history of muscle elongation trauma is diagnostic for grade I sprain. Early and complete recovery in 10 days is the rule in sprain grade one (Connell et al. 2004). In superficial and low-grade MTJ lesions even at the hamstrings, ultrasound has the advantage to better differentiate grade II lesions with disruption of muscle fibers in comparison with elongation or grade I lesions without fiber disruption. MRI is more sensitive in detecting and evaluating the extent of tears of the hamstrings.

In low-grade or chronic injuries of the adductor and hamstrings, US has a low sensitivity for detecting tenoperiosteal–entheseal disease. Especially the hamstrings, enthesis is difficult to assess with US because of its deep location. In these cases MR is a more reliable. Generally in acute lesions, US is as useful as MRI in depicting hamstring injuries. Because of the lower cost, US is the preferred imaging technique. MRI however is more sensitive for follow-up imaging of healing injuries (Connell et al. 2004). Fibrosis is the most frequent cause of recurrence of muscle

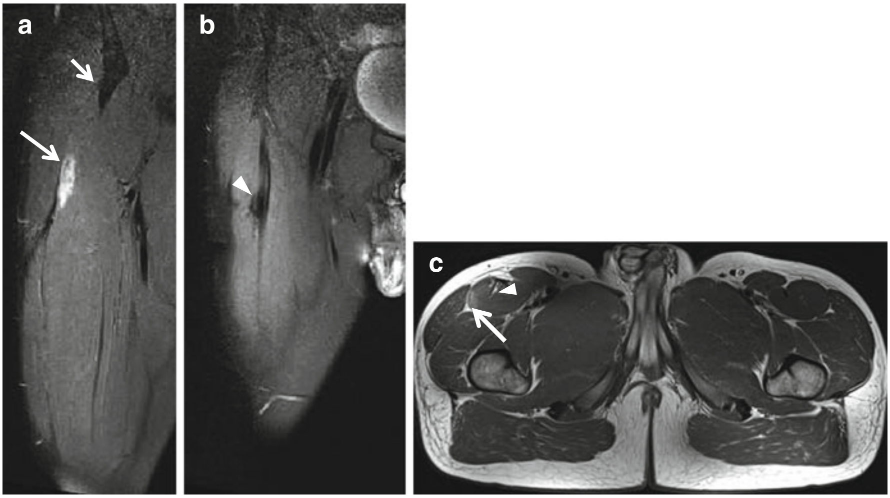


Fig. 26.18 Recidive of right rectus femoris muscle tear at the proximal musculotendinous junction of the reflected head. (**a**) Coronal TSE intermediary TE FS (*mid portion*), edematous infiltration at the proximal MTJ of the reflected head of the rectus femoris muscle (*arrow*) at the site of the acute grade II muscle tear. The retraction of muscle is not well demonstrated. The origin of the reflected head at the posterolateral hip capsule is demonstrated (*short arrow*). (**b**) Coronal TSE intermediary TE FS (anterior portion), hypointense area at the MTJ of the straight head of the rectus femoris muscle (*arrowhead*) composed of fat and/or fibrotic tissue. (**c**) Axial TSE intermediary TE at the proximal MTJ of the right rectus femoris muscle. Hyperintense edematous infiltration at the lateral fourth of the muscle (*arrow*) at the level of the acute muscle tear. Mixed hyperintense (fatty involution) and hypointense (fibrotic) area anterior in the MTJ of the straight head (*arrowheads*)

tear and thus is the sequel to be afraid of in elite athletes (Fig. 26.18). Fibrosis is to be differentiated from fatty muscle infiltration by comparison of series with and without fat suppression (Fig. 26.18b, c).

26.3.11 Sports Hernia and Groin Disruption

The major findings explaining the variant and confusing clinical presentation of overuse and acute traumatic problems at the pubis are the anatomic connections between the supra- and infrapubic structures, the interconnections between the right and left side, and the interconnections between the pubic joint capsule and the musculotendinous enthesis (Gibbon and Schilders 2007). The rectus abdominis and the common adductor origin (RA-CAO) form a conjoined aponeurosis, which adheres to the central portion of the anterior pubic surfaces and also to the anterolateral pubic margin. More particularly the rectus abdominis tendon partially inserts on the adductor longus tendon (Fig. 26.19); this is more pronounced in male patients compared to female patients. The inguinal ligament is continuous with the contralateral inguinal ligament through the superior pubic ligament that fuses with the cranially

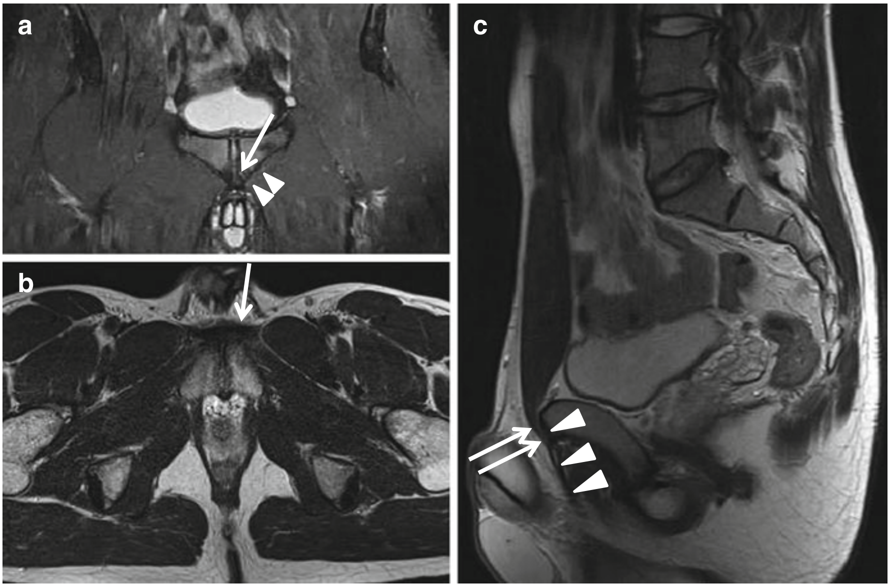


Fig. 26.19 RA-CAO anatomy. Twenty-four-year-old soccer player with chronic left groin pain while kicking the ball. MRI examination. (**a**) Coronal TSE intermediate TE FS WI at the level of the pubis. Demonstration of the disruption of the left leg of the arcuate ligament (*arrow*). Minor increased signal at the origin of the adductor longus and gracilis (*arrowheads*). (**b**) Axial TSE T2WI at the level of the pubis, origin of the adductor longus. Thickened prepuberal aponeurosis at the left side (*arrow*) compared to the right side. (**c**) Anatomical relationship of the rectus abdominis (RA) (*arrows*) with the common adductor enthesis (CAO) (*arrowheads*) demonstrating the insertion of the rectus abdominis on the enthesis of the CAO

thickened pubic joint capsule. The inferior capsular ligament of the pubis, the arcuate ligament, fuses with the proximal enthesis of the adductor longus–gracilis tendon. Thus a primary injury to the adductor longus enthesis influences the rectus abdominis distal insertion (the conjoint RA-CAO aponeurosis) where it attaches to the anterolateral pubic margin and potentially will also shear off the inguinal ligament at the pubic tubercle; also the arcuate ligament may be involved. On MRI or US ruptures of the RA-CAO will show the shearing of the RA-CAO aponeurosis with surrounding soft tissue edema, widening the distance between the aponeurosis and the pubis (Figs. 26.20a–d, 26.21a-c, and 26.22a–d); arcuate ligament tear is demonstrated on MRI only (Fig. 26.23a–d).

Therefore, an injury to the RA-CAO at its pubic insertion will potentially weaken the posterior wall of the inguinal canal at the level of the external inguinal ring, and it may predispose to a common direct inguinal hernia or a “sportsman’s hernia.”

Dynamic US with Valsalva maneuver in standing position (by an experienced examiner) may demonstrate small bowel loops or bladder appearing under the inguinal ligament at the level of the pectineus muscle origin (Fig. 26.24a, b). Bony and musculotendinous abnormalities are demonstrated on MRI and US except for

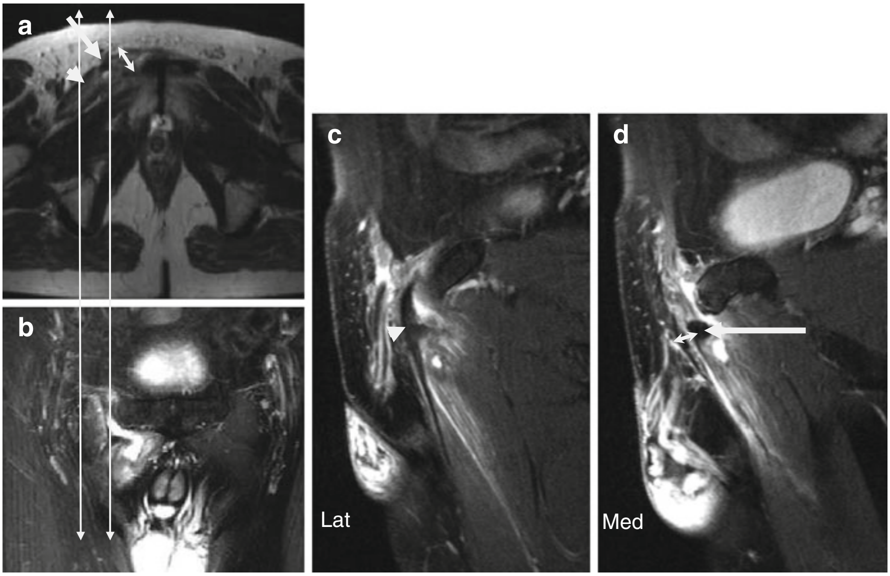


Fig. 26.20 MRI acute groin disruption related to alpine ski slip and fall with forceful hyperextended and hyperabducted right leg. Pain and swelling at the groin with increased pain with hip adduction against resistance and abdominal flexion against resistance. (**a**) Axial T2WI, (**b**) coronal intermediary TE WI FS, and (**c**, **d**) sagittal intermediary TE WI FS at lateral and (**c**) more medial (**d**) position marked on (**a**, **b**) with *double arrowed lines*. Thickening and increased signal in the aponeurotic tissue anterior to the pubis (*double arrow*) with increased signal at the pectineus muscle (*arrowhead*). Hematoma in between the pubis and the adductor longus tear with adherent bone fragment (*long arrow*)

the sportsman's hernia that specifically needs dynamic US during Valsalva maneuver (Orchard et al. 1998). The location of sportsman hernia is medial relative to the femoral canal and femoral hernia that follow the femoral vessels.

26.3.12 Osteitis Pubis

Osteitis pubis is a painful noninfectious inflammation of the pubic symphysis and surrounding muscle insertions. It can become apparent after delivery or other pelvic procedures or operations. It may occur as an inflammatory process in athletes. On radiographs late findings with sclerosis, cystic or erosive bony changes, and widening of the symphysis may be present. MRI is the imaging modality of choice to evaluate osteitis pubis.

Subchondral bone marrow edema, fluid in the symphysis pubis joint, and periarticular edema are the most reliable MRI findings of osteitis pubis that has a history of less than 6 months (Fig. 26.25). Subchondral sclerosis, subchondral resorption, bony margin irregularities, and osteophytes (or pubic beaking) are the most reliable MRI findings of chronic disease that has been present for more than 6 months (Kunduracioglu 2007).

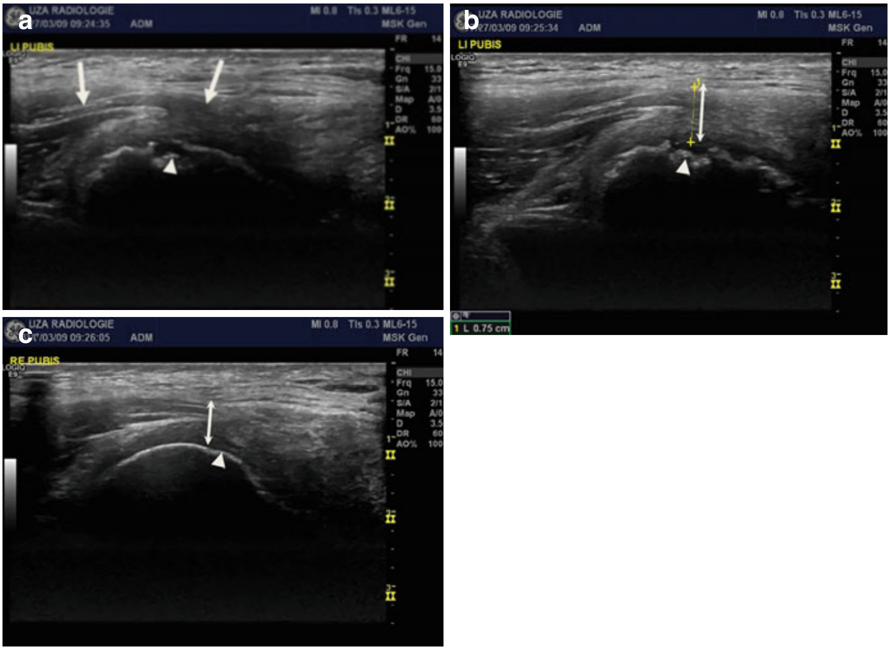


Fig. 26.21 US of chronic left groin disruption in male 27-year-old professional soccer player. (**a**) Sagittal image of the left pubis along the course of the rectus abdominis (RA) (*arrow*) demonstrating the insertion of the RA on the adductor longus (*right arrow*). (**b**) Oblique sagittal image of left pubis along the course of the adductor longus. (**c**) For comparison oblique sagittal image of the non-symptomatic right pubis along the course of the adductor. Irregular lining of the left anterior pubis (**a**, **b** *arrowhead*) with thickening of the prepubic aponeurosis at the level of the RA insertion (*double arrow*) at the left side compared to the right side (**c** *double arrow*) and regular lining of the anterior pubis at the origin of the adductor longus (**c** *arrowhead*)

26.3.13 Sacroiliitis

Related to sports in patients with BME at the SI joints on MRI, the major differential with sacroiliitis is stress reaction. Specific radiological diagnosis is not possible in early cases of sacroiliitis without demonstration of erosions. Sacroiliitis is divided in four grades on CR and CT, with CT being more sensitive (Fig. 26.26a, b). MRI can play an important role in early stages, the stage where only bone marrow edema, without erosive changes at the subchondral bone lamella, is seen. BME at the sacroiliac joint is not specific for sacroiliitis; it can be seen with overuse, stress reactions, fracture, osteomalacia, crystal arthropathies, infection, and tumor (Tuite 2008).

In a selected patient group, the sensitivity and specificity of BME on MRI can be increased up to 90 % in patients with inflammatory back pain without or with few other AS clinical features that are HLAB-27 positive. In the group with inflammatory low back pain with 1 or more clear clinical features of SpA, MRI is not needed for specific diagnosis (Rudwaleit and van der Heijde 2004).

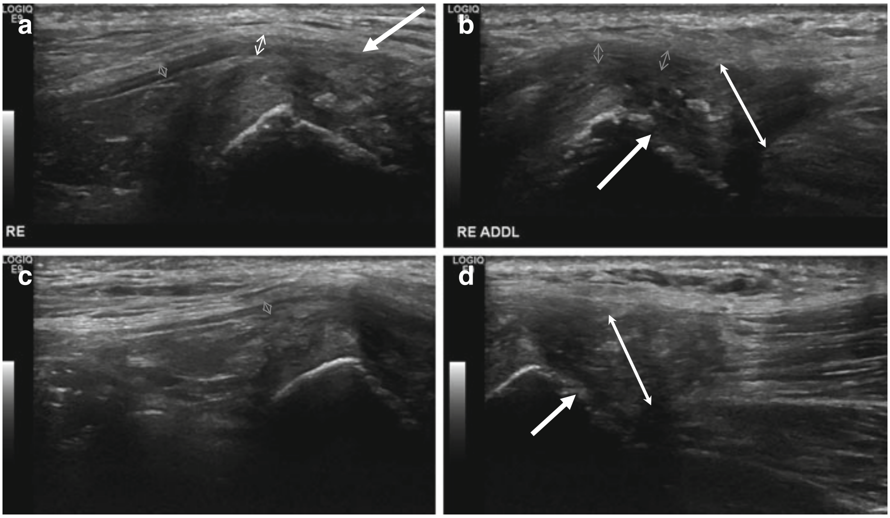


Fig. 26.22 US of chronic right groin disruption in male 43-year-old marathon runner. (**a**) Sagittal image of right pubis along the course of the RA, *double-sided arrows* marking the RA, insertion on the adductor longus (*big arrow*). (**b**) Oblique sagittal image of the right pubis along the course of the adductor longus and erosive aspect of the pubis at the enthesis of the adductor longus (*big arrow*). Thickening (*big double-sided arrow*) with structural anomaly and reflections (calcifications) at the adductor longus tendon. (**c**) For comparison sagittal image of left pubis along the course of the RA (*double-sided arrows*). (**d**) Oblique sagittal image of the right pubis along the course of the adductor longus and erosive aspect of the pubis at the enthesis of the adductor longus (*big arrow*). Thickening (*big double-sided arrow*) with structural anomaly and reflections (calcifications) at the adductor longus tendon. Prepubic location of the distal rectus abdominis tendon is demonstrated (*small double sided arrow*)

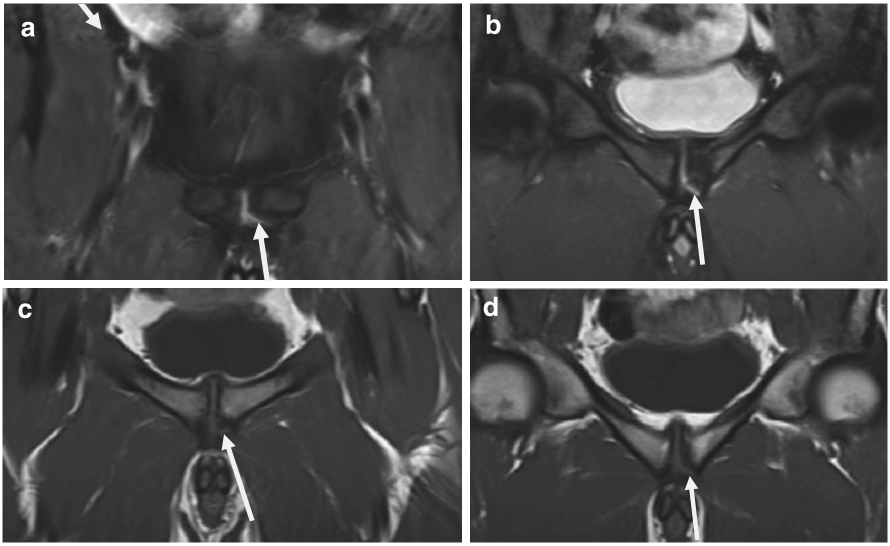


Fig. 26.23 MRI of 22-year-old male soccer player with chronic left groin pain. Coronal intermediary TE WI FS (**a**, **b**) and coronal T1WI (**c**, **d**) demonstrating the lateral extention (*arrows*) of the pubic joint at the level of the rupture of the arcuate ligament

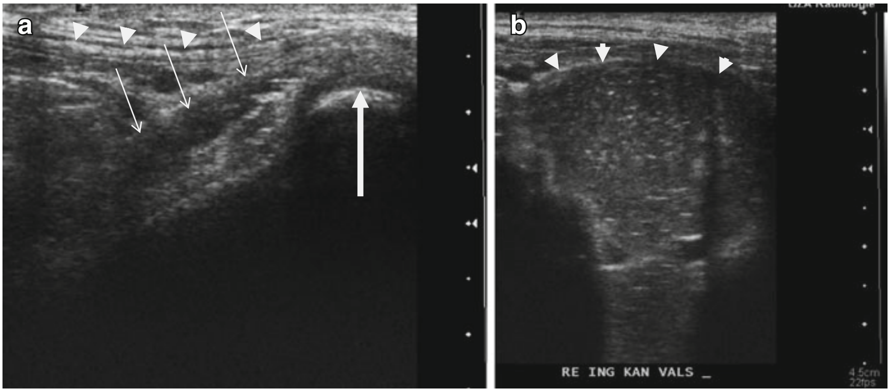


Fig. 26.24 19-year-old male soccer player with chronic pain and intermittent swelling at the right inguinal area. US with Valsalva test with demonstration of right-sided sportsman hernia. (**a**) Oblique axial US imaging plane in rest along the course of the inguinal ligament (*arrowheads*) with demonstration of the insertion at the pubis (*arrow*) and pectineus muscle (*thin arrows*) in front of the iliopubic bone. This area is located medial to the femoral canal (not demonstrated). (**b**) Oblique axial US image at the same imaging plane (along the course of the inguinal ligament) during Valsalva test demonstrating external bulging of the inguinal ligament and internal oblique aponeurosis with bowel structures (*arrowheads*) descending between the inguinal ligament and pectineus muscle

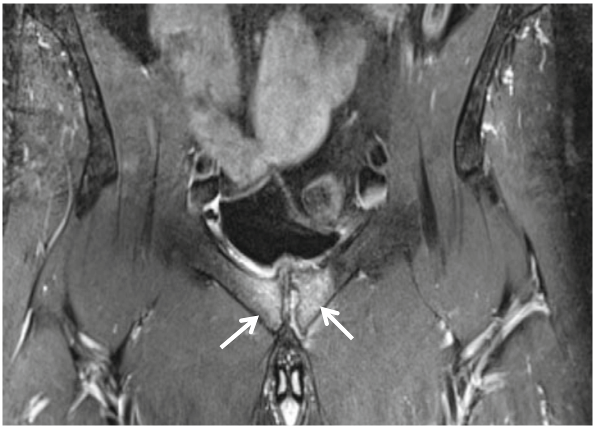


Fig. 26.25 Osteitis pubis in a 46-year-old male. Coronal PD FS coronal MR image at the level of the pubis. Bone marrow edema is demonstrated as high signal intensity adjacent to the symphysis (*arrows*). At the left side infiltration at the adductor origin and arcuate ligament rupture is present

A specific diagnosis of sacroiliitis is made in bilateral and symmetrical presentations in SpA and is typical asymmetric in psoriasis and reactive arthritis.

26.3.14 Nerve Lesions

Nerve lesions around the hip involve especially the ischial nerve, the femoral nerve, and the lateral femoral cutaneous nerve. Entrapment of the lateral femoral cutaneous nerve causes “meralgia paresthetica,” with typical symptoms of numbness,

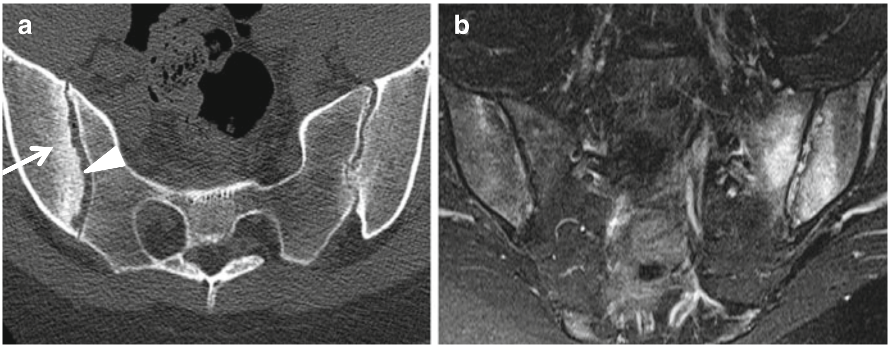


Fig. 26.26 Sacroiliitis grade 3. Demonstration of early sacroiliitis signs on MRI. (**a**) Axial CT image. Remark the "variegated pattern" of pathologic changes at the right SI joint: joint space widening, sclerosis (*arrow*), and erosions (*arrowhead*). Joint space narrowing, erosions, and bony proliferation with beginning ankylosis are demonstrated in the left SI joint. (**b**) Paracoronal TSE PD FS MR image of asymmetric sacroiliitis with marked bone marrow edema at the left side, with some erosions and synovitis. Only limited bone marrow edema is seen in the right SI joint

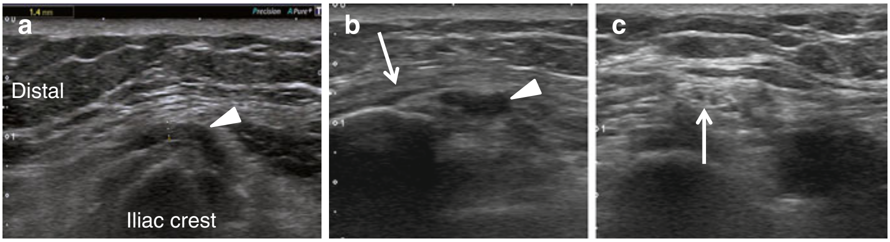


Fig. 26.27 Meralgia paresthetica. High-frequency US (18 MHz) shows a swollen and hypoechoic NCFL (arrowheads) in the sagittal plane (**a**) and axial plane (**b**) under the inguinal ligament (*arrow*) in a patient with meralgia paresthetica. Axial image (**c**) of a normal nerve on the right (*arrow*)

hypersensitivity, and paresthesia in the anterolateral region of the thigh. This nerve can best be evaluated with high-frequency US (18 mHz) (Fig. 26.27). The nerve runs from intra-abdominally deep to the lateral part of the inguinal ligament superficial to the sartorius muscle origin. Entrapment deep to the inguinal ligament causes focal swelling of the nerve with ultrasonographic hypoechoic appearance proximal to the entrapment. US-guided treatment with injection of corticoids in the perineurium shows promising results (Tagliafico 2011). Variant anatomical locations of this nerve are described demonstrating the nerve lateral to the superior iliac spine.

Entrapment of the femoral nerve is a rare condition. At the superficially located nerve segments, high-resolution US may be useful to identify the cause of nerve compression, i.e., the suprainguinal, inguinal, and infrainguinal regions. A kinking or fibrous encasement of the nerve bundles beneath the inguinal ligament can be seen. Denervation with muscle edema and gadolinium enhancement in the first 3 weeks or lipomatous involution in older cases of the quadriceps muscle is better evaluated with MRI.

Sciatic nerve lesions are not typically related to sports activity. Possible causes of sciatic nerve lesions are significant trauma (such as fracture dislocations of the hip joint) and as a complication of hip replacement. Other causes include prolonged periods of immobilization in bed, space-occupying masses, and the piriformis syndrome. The best modality to evaluate the sciatic nerve is MRI. US examination of the sciatic nerve is difficult and has a low sensitivity. In particular, the piriformis syndrome cannot be revealed with US. Piriformis syndrome refers to a rare entrapment neuropathy resulting in radicular pain radiating into the buttock and hamstrings. The entity is still controversial. The sciatic nerve typically passes immediately anterior to the piriformis muscle. This relationship is variable, however, as the nerve occasionally passes though the muscle or splits early, with part of it passing though the muscle. Additionally an accessory piriformis muscle, which arises from the medial part of the sacrum, can be implicated. Also muscle hypertrophy and muscle spasm in athletes have been postulated as cause of piriformis syndrome. On MRI increased signal (muscle edema) within the piriformis muscle may be seen. The course of the sciatic nerve can be evaluated on MRI; also an accessory piriformis muscle may be identified. However controversy exists as to the value of imaging modalities to document or confirm piriformis syndrome. Imaging is especially important to rule out other causes of sciatica.

Miller proposed criteria for the classification of piriformis syndrome (Miller et al. 2012):

1. Buttock and leg pain made worse with sitting, stair climbing, and/or leg crossing.
2. Pain and tenderness to palpation of the sciatic notch area (piriformis muscle) and pain with increased PM tension.
3. No evidence of axonal loss to the sciatic nerve on electrophysiological testing.
4. No evidence of abnormal imaging or other entity that could explain the presenting features of sciatica (e.g., radiculopathy, tumor, etc.).
5. Reduction of >60 % of buttock and leg pain with diagnostic injection into the piriformis muscle under radiographic imaging (fluoroscopic or US) and/or EMG guidance. In our opinion infiltration around the sciatic nerve is best performed under US guidance.

26.3.15 Pediatric Hip

US is particularly well suited to examine the pediatric musculoskeletal system, especially of the hip and pelvis (Cook 2014; Vanderhave et al. 2014). It is a well-tolerated and noninvasive way without using ionizing radiation or sedation.

It is very useful in evaluating developmental dysplasia and painful hip.

In transient synovitis fluid is seen between the two layers of the hip capsule (Fig. 26.28).

Differential diagnosis has to be made with septic arthritis of the infant hip, which tends to occur in a younger age group (<3 years old). The child usually appears more ill and has fever or a history of fever and pronounced pain. In cases of suspected septic arthritis, which is a medical emergency, needle aspiration of the hip effusion, ideally performed under US guidance and under sterile conditions, remains

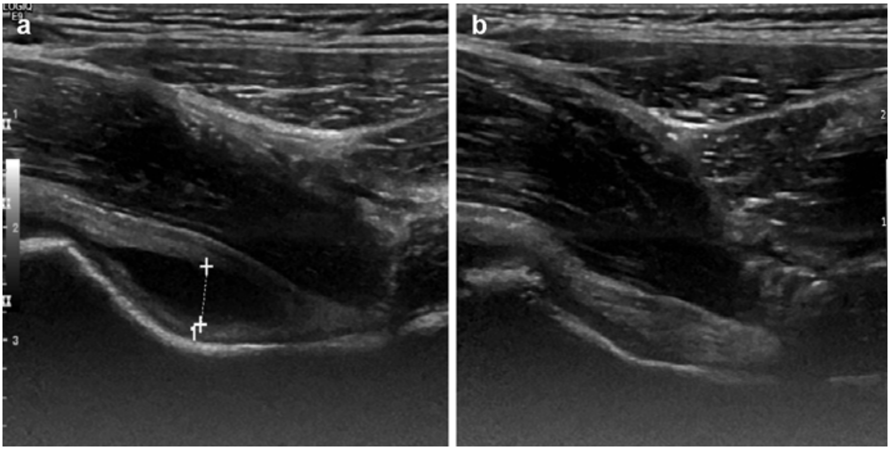


Fig. 26.28 Transient synovitis. Fluid in the hip joint is well depicted with US in the anterior recess of the hip between the 2 layers of the capsule (**a**). For comparison a normal hip joint (**b**)

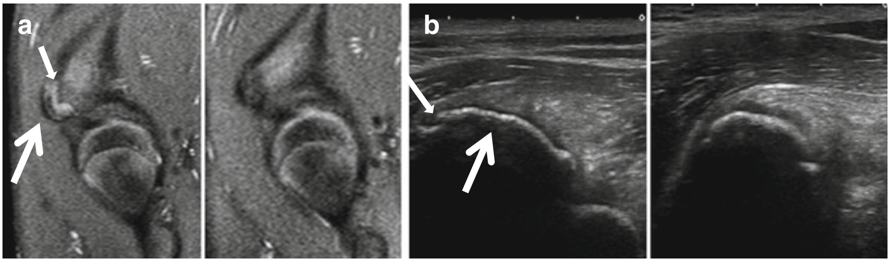


Fig. 26.29 Traction apophysitis at the spina iliaca anterior inferior. MRI and US images in the same patient. (**a**) Sagittal STIR MR with widening of the apophyseal growth plate (*small arrow*) with high SI (STIR sequence) and the hypertrophy of the apophysis (*arrow*). The *left images* demonstrate the normal contralateral side. (**b**) Sagittal US images with similar findings (*small arrow*: apophyseal growth plate and *large arrow*: apophysis)

the key for the diagnosis, even if this leads to a substantial number of children with uninfected hips undergoing joint aspiration (Vanderhave et al. 2014).

Perthes disease and slipped capital femoral epiphysis can well be evaluated with MRI.

26.3.16 Apophysitis/Avulsion Fractures

Recurrent stress on the apophysis in children causes microtrauma to the physis provoking an inflammatory response and fracture with fragmentation of the calcified parts of the apophysis. Proliferation and hypertrophy of the chondrocytes and inflammatory cells are found at the physis. Inflammation affects the apophysis itself and extends into bone marrow and adjacent structures (Arnaiz et al. 2011). Apparent physeal widening, apophyseal edema, and adjacent muscle and bone edema can be seen on MRI and US (Fig. 26.29a).

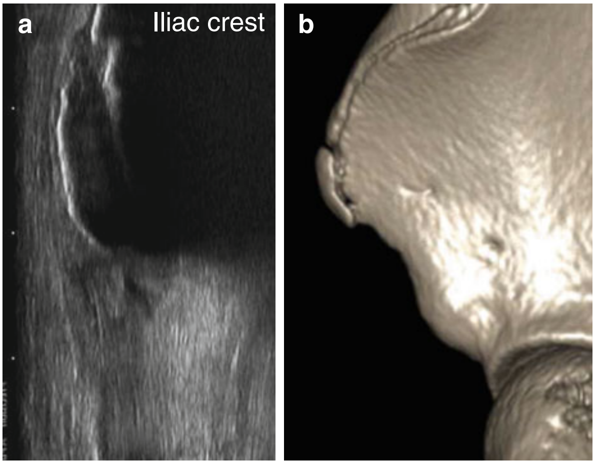


Fig. 26.30 Acute apophysiolysis of SIAI in a 14-year-old boy after acute football injury. US (**a**) and CT (**b**) image of an avulsion of the SIAI. The apophysis is separated at the level of the growth plate from the underlying bone

On ultrasound the physeal widening and the apophyseal hypertrophy can be depicted (Fig. 26.29b). With the use of PWD in the hands of an experienced ultrasonographist, the angiogenesis in the apophysis and surrounding soft tissue structures can be evaluated.

In more severe cases, acute trauma may result in an avulsion of the apophysis. In this case there are no signs of inflammation and angiogenesis in the apophysis. There can be a hematoma and bone marrow edema in the apophysis and adjacent bone. Displacement of the apophysis is demonstrated on radiography, MRI, US, or CT (Fig. 26.30a, b).

26.3.17 Fatigue Fractures/Fractures

Fatigue fractures of the hip and the pelvis are initially evaluated with radiographs; in 24 % of cases radiographs are initially normal (Fig. 26.31). In the second stage, CT or MRI is used. Typical location is the femur shaft (53 %), lesser trochanter (20 %), intertrochanteric region between the femoral neck and the greater trochanter (15 %), and the femoral neck (11 %); only a minority is located at the trochanter major (1 %). A minority of these stress fractures (2 %) present as complete fractures with displacement (Clement et al. 1993). In long-distance runners, stress fractures are described associated with iliopsoas tendon activity at the lesser trochanter (Nguyen et al. 2008).

Stress fractures can be missed easily and are well evaluated with MRI. The low-intensity fracture line is best seen on the T1-weighted images; the adjacent bone marrow edema is best demonstrated on the edema-sensitive sequences (STIR or PD and T2 FS) (Fig. 26.32a, b).

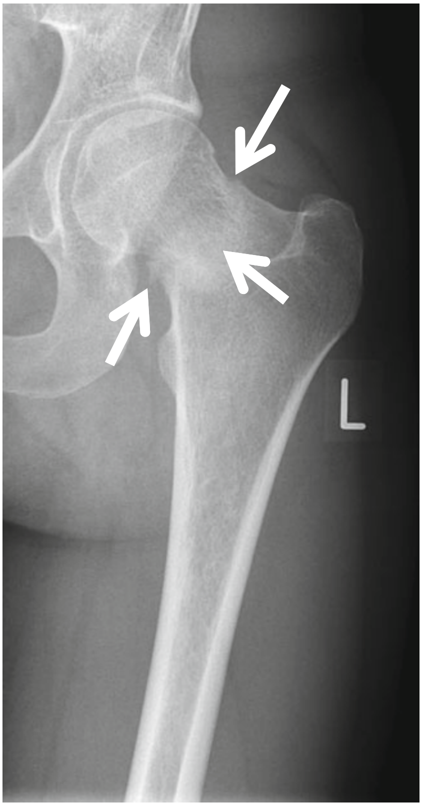


Fig. 26.31 Stress fracture at the femur neck in a 22-year-old female. AP radiograph of the left hip demonstrates slightly displaced stress fracture (*arrows*) met cortical disruption and step off at the inferior and cranial lining of the femur neck

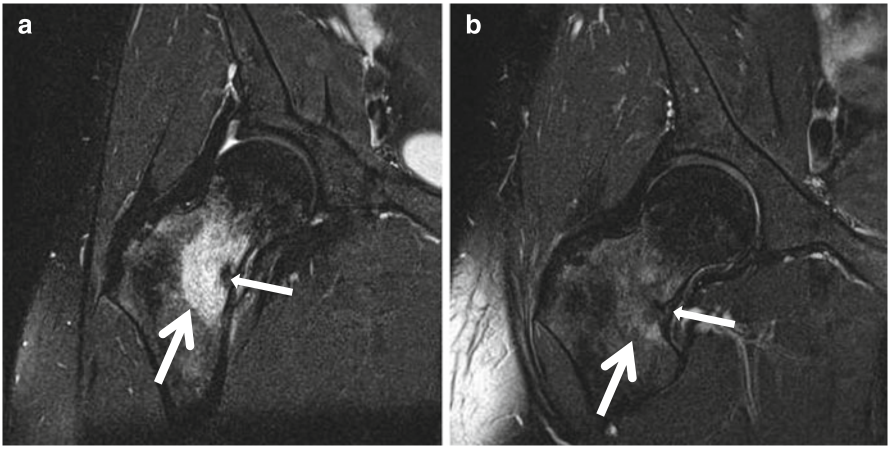


Fig. 26.32 Stress fracture at the femur neck in a 35-year-old male. (**a**) Coronal TSE T2WI with FS. Hypointense fracture line (*small arrow* **a** and **b**) surrounded by hyperintense bone marrow edema (*arrow* **a** and **b**). (**b**) Coronal TSE T2WI with FS 2 months later

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Nuclear Medicine Imaging of Pelvic, Groin, Hip and Thigh Injuries

27

F. Celik

Contents

Abstract

A paucity of studies exist regarding radionuclide imaging of the pelvis, hip, groin and thigh injuries in sports medicine. The effectiveness of interpretation of the radionuclide images depends on knowledge of the nuclear physician about the mechanisms of the injury, indispensable thorough patient history, clinical manifestations and the degree of remodelling of the bone in the variety of disorders. The current available literature was reviewed focussing on the potential role of radionuclide

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bone imaging in the underlying disorders of the pelvis, hip, groin and thigh in athletes and other sportsmen. In most injuries, magnetic resonance imaging is the first-choice imaging modality. Radionuclide ^{99m}Tc-diphosphonate bone scan may aid in narrowing differential diagnosis by combining functional and anatomic information, especially when SPECT/CT is performed to provide precise anatomical localisation and details in high-spatial-resolution CT and information on abnormal bone metabolism in SPECT. The injuries in which radionuclide imaging was found most useful are disorders that showed high bone turnover due to imbalanced remodelling.

Abbreviations

CT	Computer tomography
^{18}F	Fluor-18
FAI	Femoroacetabular impingement
FDG	Fluorodeoxyglucose
HDP	Oxidronate
MDP	Methylene diphosphonate
MRI	Magnetic resonance imaging
NaF	Sodium fluoride
PET	Positron emission tomography
SPECT	Single-photon emission computer tomography
^{99m}Tc	Technetium-99 metastable

27.1 Introduction

Various pathologies of pelvis, groin, hip and thigh in athletes have been discussed in Chap. 25. This chapter reviews the role of radionuclide imaging techniques in sports injuries in pelvis, groin, hip and thigh. Radionuclide bone imaging is a sensitive, relatively inexpensive, widely available and valuable technique for diagnostic evaluation of bone and muscle abnormalities, because it can detect minor changes in metabolism and blood flow. The specificity of bone imaging, however, depends on the ability of the nuclear medicine physician to make a differential diagnosis. Knowledge of patient history, clinical presentation of injuries and the appropriate diagnostic investigations needed are important to know. An imaging modality is most effective when selected on the basis of a thorough history and clinical examination.

The acquisition and interpretation of bone scintigraphy is described thoroughly in Chap. 3 of this book. As bone scintigraphy is nonspecific, lesions with increased uptake often require further morphologic data. Combined SPECT/CT is utilised to provide precise anatomical localisation and detail in high-spatial-resolution CT and information on abnormal bone metabolism in SPECT.

The positive influence of fusion of functional and anatomic data on patient management has been widely investigated, particularly in the field of oncology. Recent studies investigated the added value of SPECT/CT compared with SPECT alone in differentiating benign and malignant bone lesions on ^{99m}Tc-MDP bone scintigraphy (Cook and Tott 2011, Helyar et al. 2010, Romer et al. 2006, Utsunomiya et al. 2006, and Horger et al. 2004). Differentiation between benign frank fractures and pathological fractures is often not possible with planar bone scintigraphy alone because of its lower specificity. There are no studies specifically mentioning the use of ^{18}F-FDG PET/CT or ^{18}F-FDG PET/MRI in sports injuries in this particular section of the body. A newer method is the use of ^{18}F-NaF PET combined with CT or MRI. ^{18}F-NaF was found more sensitive than ^{99m}Tc-diphosphonate bone scan for detecting both osteoblastic and osteolytic lesions (Schirrmeister et al. 1999a, b and Cook et al. 1998). There are data suggesting that the accuracy of ^{18}F-NaF PET in detecting bone lesions, mainly in the vertebrae, is similar to that of MRI and spiral CT (Schirrmeister et al. 1999a). The positive findings reported were spondylolysis, frank fractures, osteitis pubis, sacroiliitis and herniated discs. There are no data available that compare the value of PET/MRI directly with ^{99m}Tc-diphosphonate bone scans in sports injuries in this part of the body.

The occurrence of injury sites and types are related to the type of sport. Available epidemiological studies about radionuclide bone imaging of the extra-articular pathologies in sports injuries, including soft tissue injuries about the pelvis, hip, groin and thigh, are scarce, as is the case for radionuclide bone scanning of intra-articular sources of hip pain. Some of these injuries, particularly in which radionuclide musculoskeletal imaging may have or has a role, are discussed below.

27.2 Extra-articular Injuries

27.2.1 Stress Fractures

Stress fractures in athletes are not unusual. The incidence of stress fractures among athletes is estimated at 2–4% (Joy and Campbell 2005, Silva et al. 2006). Southam et al. (2010) mention up to 20% of runners who may experience a stress fracture while participating in their sport. In athletes, stress fractures occur for 1.6 % at the pelvis and for 0.6 % at the back (Matheson et al. 1987).

The long-term complications of fractures, such as non-union, malunion and degenerative joint disease, are uncommon. Stress fractures are of two general types. An insufficiency fracture results from normal stress applied to abnormal bone. Underlying conditions that weaken the elastic resistance of bone and predispose it to insufficiency fractures include osteoporosis, postmenopausal stage, Paget disease, hyperparathyroidism, rheumatoid arthritis, osteomalacia, osteogenesis imperfecta, rickets and irradiation. A fatigue fracture occurs when normal bone is subjected to repetitive stresses, which can lead to mechanical failure over time (Anderson and Greenspan 1996, Matheson et al. 1987).

Sacral stress fractures in athletes are a rare entity. Stress fractures of the sacrum in long-distance runners are the result of overuse. They commonly appear after the runner increases the intensity of an activity or alter the manner in which an activity is performed. The clinical presentation can mimic disc disease (Major and Helms 2000 and Wentz et al. 2011). The incidence is higher in females than in males in the athletic population (Liong and Whitehouse 2012, Wentz et al. 2011, Eren and

Holtby 1998). Lin and Lutz (2004) present a case of a young, postpartum, recreational runner who developed low back pain and radicular symptoms to be secondary to sacral stress fracture. In this report also a brief review of osteoporosis in pregnancy is given. Bone scintigraphy and MRI are of particular value for early diagnosis as the earliest features on imaging are increased activity and bone marrow oedema, respectively. At that time, the plain radiograph is normal. Some authors state that conventional radiography is relatively insensitive to stress fractures, especially early in the process and especially in the pelvis, where the sensitivity reported is between 15 and 28 %. Bone scintigraphy shows increased activity in all three phases and has a high sensitivity in the diagnosis of stress injuries, but a lower specificity, since increased activity may be related to other diagnoses such as infection, bone infarction and neoplasms. Adding the CT to the bone scan by performing a SPECT/CT will increase the specificity (Hirschmann et al 2011). CT and MRI show a characteristic linear appearance which is consistent with fracture. MRI is favoured because of the higher specificity, and it does not impose ionising radiation burden on the patient. The differential diagnoses to consider in MRI are, for example, transient marrow oedema syndrome, osteoid osteoma and Brodie's abscess.

Imaging with bone scintigraphy shows increased linear uptake that parallels the sacroiliac joint. For bone scintigraphy, a sensitivity of almost 100 % was reported (Anderson and Greenspan 1996, Lee and Yao 1988, Buckwalter and Brandser 1997). Bone scans are useful in identifying sites of microtrauma by demonstrating locally increased radionuclide uptake depending on the degree of bone turnover and local blood flow. Hyperperfusion and hyperaemia are typically present in acute stress fractures. Love et al. (2003) described focal fusiform uptake in the lesion at delayed radionuclide bone images.

Liong and Whitehouse (2012) reported that radiographic findings of periosteal reaction, fracture line or reactive sclerosis may not be manifest until 4 weeks after the onset of injury. If patients alter their activity level in response to the pain, these features may not have been observed at all. They also reported histological studies confirming that repeated mechanical stress leads initially to an increased osteoclastic activity, which exceeds the osteoblastic new bone formation. This is precipitated by a sudden increase in physical activity or an altered manner in which the physical activity is performed. When the stress continues, microfractures occur and bone marrow oedema appears on MRI. Periosteal new bone then forms and may be visible on plain radiography. With continuing physical activity, the reparative response is overwhelming resulting in full cortical fractures (Williams et al. 2002). Fractures at sites of (normally) high trabecular bone are particularly common in osteoporosis.

Orava et al. (1978) mentioned that of all reported stress fractures at physical exercise, 1.4–7.8 % are stress fractures of the pubic bones. Pavlov et al. (1982) and Hughes and Maguire (1988) showed a higher incidence in female runners. Noakes et al. (1985) found that only 38 % of clinical pelvic stress fractures can be seen on radiographs. Radiographs are predominantly normal in the early disease process. ^{99m}Tc-diphosphonate bone scintigraphy shows increased flow and radionuclide uptake in early and delayed phase, respectively, in the injured pubic ramus due to increased blood flow and osteoblastic activity (Barry and McGuire 1996). Combining radiography with bone scintigraphy increases the accuracy for diagnosing a stress fracture to 62 %, as reported by Ekberg et al. (1988).

Iwamoto and Takeda (2003) and Iwamoto et al. (2008) showed that running activities are the most common sports activities that result in stress fractures. Stress fractures in long-distance runners are seen in the sacrum at the site of trabecular bone and at the site of cortical bone in pubic rami. An apophyseal fracture site was reported in soccer players and gymnasts. Strong clinical suspicion in combination with radiological and radionuclide imaging plays an important role in the detection of stress injuries in athletes. Shin et al. (1996) showed that MRI was as sensitive as and was more specific than bone scan in determining the cause of hip pain. They reported an accuracy of 68 % for radionuclide bone scan for femoral neck stress fractures and 32 % false-positive rate. MRI showed 100 % accuracy in their study. MRI proved to be superior to radionuclide bone scanning in providing an early and accurate diagnostic tool in the young endurance athlete. MRI differentiated also between other causes of hip pain, such as iliopsoas muscle tear and tendinopathy, obturator externus tendinopathy, femoral neck stress fractures from a synovial pit, avascular necrosis of the femoral head and a unicameral bone cyst.

Stress fractures commonly occur in military populations, especially in endurance trainees. Kelly et al. (2000) reported that recruits developing pelvic stress fractures were significantly ($p<0.05$) shorter and lighter and were more frequently Asian or Hispanic than recruits without stress fractures. Stress fractures of the femoral neck diagnosed by radionuclide imaging were also described earlier (Kricun 1990). Including SPECT/CT will increase the sensitivity and specificity of the plain bone scintigraphy (Fig. 27.1). Stress fractures of the acetabulum are uncommon. Williams et al. (2002) reported that 6.7 % of 187 active duty military endurance trainees with a history of activity-related hip pain showed acetabular stress fractures on MRI and bone scan. The patient's plain radiographs of the hip and pelvis were interpreted as normal or equivocal.

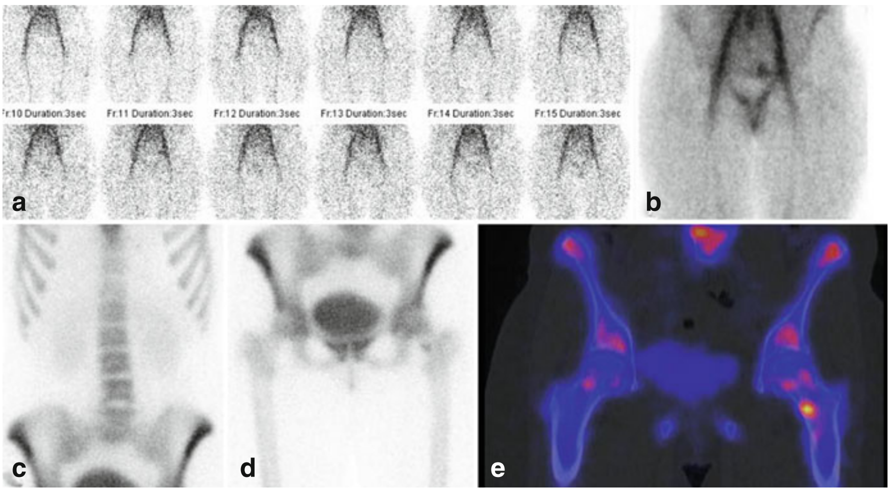

Fig. 27.1 An example of the added value of bone scintigraphy SPECT/CT. Female athlete (rowing) with pain complaints in the left hip region. Flow (**a**) and blood pool (**b**) normal. Late static images (**c**, **d**) showing slightly elevated uptake in the neck of the left femur. SPECT/CT (**e**) showing focal intense uptake in the neck of the left femur. Conclusion: small stress fracture of the left collum femoris

27.2.2 Pelvic Avulsion Injury

An apophysis is a secondary ossification centre. It first appears anterolaterally on the iliac crest, later developing posteriorly. The average age of closure of this secondary ossification centre is 16 years for males but may be as late as 20 years. In females, the apophysis usually closes at 14 years, although closure may be delayed until 18 years (Risser 1958). The external oblique abdominal muscle, the transversus abdominis muscle, the gluteus medius muscle and the tensor fascia lata all originate or insert on the anterior iliac crest.

The process of overuse injury starts when repetitive activity weakens a tendon or bone. With sufficient recovery, the tissue adapts to the demand and is able to undergo further loading without injury. DiFiori (1999) reports on the body's inflammatory response in consequence of microtrauma developing when there is no adequate recovery. Consequently, local tissue can be damaged by the release of vasoactive substances, inflammatory cells and enzymes. Doral et al. (2005) found scintigraphic detection of the injured site to be useful when clinical findings are atypical, when the fracture is not apparent radiographically or when the clinician remains unsure of the precise diagnosis and needs confirmation. A high tracer accumulation at the fracture site in all three phases of the bone scan is seen in a similar way as seen in stress fractures. SPECT/CT can depict the precise anatomical localisation and aid in further differential diagnosis.

27.2.3 Apophyseal Avulsion

Sanders and Zlatkin (2008) report that avulsion injuries usually present as an avulsion of the non-fused apophysis at the level of tendon attachment resulting from violent muscular contractions. Acute apophyseal avulsion injuries are usually easily detected with radiographs, but occasionally MRI or CT is required to detect and fully delineate the extent of injury. Familiarity with the location of various tendon attachment sites on the osseous pelvis can aid in the differentiation between aggressive and chronic lesions. Valdes et al. (2000), Sundar and Carty (1994) and Fernbach and Wilkinson (1981) describe avulsion injuries of the anterior superior iliac spine, the anterior inferior iliac spine and the ischial tuberosity in children and adolescent soccer players. The fracture was caused by a sprint or sudden flexion of the hip during the kicking phase. In bone scintigraphy, a high tracer accumulation at the fracture site in all three phases of the bone scan is seen in a similar way as seen in pelvic avulsion fractures.

27.2.4 Avulsion Injury of Iliac Crest

Rockett (1990) mentioned that radiographs usually show avulsion of the apophysis of the anterior superior iliac crest. Radiographs may appear normal if the avulsed fragment is only minimally displaced or if the injury occurs before ossification of the apophysis. In bone scintigraphy, a high tracer accumulation at the fracture site in all three phases of the bone scan is seen in a similar way as seen in all (avulsion) fractures.

27.2.5 Ischial Tuberosity Avulsion Fracture Versus Apophysitis

Kocis et al. (2003) reported on the ischial tuberosity avulsion injury. The apophysis of the ischial tuberosity usually becomes united with the hip bone by the age of 25. The highest incidence of avulsion in this region as result of overuse injuries occurs between 15 and 17 years in young active persons. Generally, strong muscles are inserted on to the apophyses (Tüzüner et al. 2003).

Apophysitis should be differentiated from an avulsion fracture of the ischial tuberosity. Concannon et al. (2011) showed a case study about the role of bone scintigraphy combined with SPECT in the detection of spondylolysis combined with apophysitis of the posterior superior iliac spine in a young adolescent athlete. The bone scan with SPECT revealed increased uptake at both injury sites. MRI showed oedema at the injury sites. There is a lack of consensus in the medical literature on the optimal approach to diagnose spondylolysis in adolescent athletes. For diagnosis, a number of authors favour the use of a bone scan with SPECT of the lumbar spine followed by CT if the SPECT is positive (Standaert and Herring 2007). Other authors advocate for the primary role of MRI in diagnosis (Masci et al. 2006). and Harvey et al. (1998) show that this approach is inferior to SPECT/CT in identifying stress reactions in the pars interarticularis.

Apophysitis describes a chronic traction injury at the tendon insertion site in chronic excessive sports activities in young persons experiencing gradual onset of pain in the region involved without clear history of injury. Apophysitis is normally confirmed by radiographic findings. However, bone scintigraphy also shows an increased uptake of isotope in the region of the acromion in case of an acromial apophysitis. Increased uptake at the ischial tuberosity may be seen in case of a fracture but also in case of an apophysitis. Kujala et al. (1997) reported in their study population of young athletes a lower mean age of the patients with apophysitis (14 years) than that of the subjects with avulsions (19 years). Apophysitis of the ischial tuberosity usually heals well without complications. Avulsions often cause more prolonged pain with referral pain to the posterior parts of the thigh which often requires operative interventions.

An apophyseal avulsion fracture of the ischial tuberosity occurs usually acute, with a displaced bony or cartilaginous fragment. Patients report usually a sudden movement during sports activities, associated with immediate pain. Radiology confirms diagnosis. Radionuclide bone scanning shows a high uptake at the fractured site and mimics normal fracture uptake patterns at the site of the anatomic substrate in hybrid imaging as in SPECT/CT.

Tendinous avulsion fractures typically occur in soccer and football players, sprinters and jumpers (Cochran 1982). A sudden violent or sustained muscle contraction across an open apophysis is the usual mechanism of injury of an avulsion fracture. Avulsion injuries are common in athletes younger than 25 (Waters and Millis 1988, Watts 1976). If conventional radiological investigation is negative, SPECT/CT can help to find the precise location of the fractured site by showing a high tracer uptake, due to increased osteoblastic activity at the fracture site.

27.2.6 Sacroiliitis

Knowledge of the anatomy and function of the sacroiliac joint, along with an understanding of running athletes' forces on the joint, is imperative to properly diagnose and treat the runner athlete. Sacroiliitis appears as erosions, sclerosis and joint space narrowing, eventually leading to ankylosis. Tuite (2008) stated that sacroiliitis-like changes of the joint can be caused by several disorders, including repetitive shear-stress injuries in athletes. The radiographic findings of sacroiliitis are often indeterminate because of difficult profiling on the images. CT usually reports the findings of sacroiliitis earlier than radiographs. MRI is mentioned as the imaging technique of choice when very early sacroiliitis is suspected and also for following treatment response. ^{99m}Tc-diphosphonate bone scans are more sensitive than MRI or CT scans. In athletes, they demonstrate focal high round uptake confined to the alae. This pattern differs usually from the classic "H" or "Honda sign" pattern, which is diagnostic for sacral insufficiency fractures, which is consistent with bilateral vertical fractures in association with a transverse fracture across the sacrum. Sacral insufficiency fractures are typically found in the elderly. Sacral stress fractures can also be seen in pregnant or postpartum recreational runners. Osteoporosis of pregnancy is reviewed and guidelines on the diagnosis and management of sacral stress fractures are discussed by Lin and Lutz (2004). Blake and Connors (2004) showed that similar bone scintigraphic patterns as in sacral insufficiency fractures are produced by sacroiliac joint dysfunction, sacroiliitis and malignancy.

27.2.7 Groin Pain

Sports injuries in the hip and groin have been noted in 5–9 % of high school athletes (Morelli and Espinoza 2005, Morelli and Weaver 2005). Sports injuries to the hip and groin region occur most commonly in athletes participating in sports that require specific (over) use of the proximal musculature of the thigh and lower abdominal muscles, such as sports that involve kicking, quick accelerations and decelerations and sudden directional changes. Because forces generated through athletic performance are transferred through the hip, injuries to these areas may limit athletes with mild pain or lead to career-ending injuries. Some of these common sports are rugby, skiing, hurdling, (ice) hockey, running and soccer (Verrall et al. 2005, Macintyre et al. 2006, Morelli and Weaver 2005). Symptoms may range from intermittent episodes of mild discomfort to severe and chronic career-ending pain. Groin injuries may result from causes in that same area (e.g. the groin hernia) or indirect groin pain caused by injuries in the hip or lumbar spine or pelvis (the hip-spine dilemma). The differential diagnosis can cover a rather broad area of possibilities. Most common groin injuries are soft tissue injuries, such as (adductor) muscular strains, tendinitis or contusions. More difficult areas to pinpoint are entities as osteitis pubis, obturator nerve entrapment, avulsion fractures and the so-called sports hernia (Anderson et al. 2001, LeBlanc and LeBlanc 2003). Other examples are hip osteoarthritis and femoroacetabular impingement (Tammareddi et al. 2013, Morelli and Weaver 2005).

Kirkendall and Dvorak (2010) stated that 10 % of all soccer injuries occur in the thorax, back, trunk, abdomen, groin and pelvis. They reported that traumatic injuries in soccer included fracture, contusion or haematoma, laceration and muscle, tendon, joint or ligament sprains. Other injuries were caused by overuse. An overuse injury is caused by prolonged repetitive microtrauma without an identifiable event responsible for the injury (Fuller et al. 2006 and Longo et al. 2012). Bone scintigraphy will reflect changes in bone remodelling in response to underlying disease, whereas the diphosphonate compound will accumulate at newly formed bone sites. The manifestation of the type of injury in combination with the thorough history and clinical differential diagnosis determines whether radionuclide bone scan will be of use.

27.2.7.1 Groin and Hip Pain in Musculoskeletal Causes

Groin injury and recurrent groin strains (muscle or tendon injuries) are also common, both in football and hockey players. Groin injury leading to chronic pain is often referred to as a sportsman's hernia (Fon and Spence 2000). The anatomy of groin hernias is well described in standard surgical textbooks. The many causes of groin pain are described by Zimmerman (1988), Hughes and Maguire (1988) and Corrigan and Stenstone (1985). Rarer causes are bone and joint disease, for example, stress fractures, snapping hip syndrome, spondylolisthesis, early osteoarthritis and slipped upper femoral epiphysis. The differential diagnosis of groin pain can cover also soft tissue injuries, such as muscular strains, tendinopathy or contusions. Athletic pubalgia or avulsion fractures are more difficult areas to pinpoint. Recurrent problems occur when treatment therefore is inadequate.

In general 10–15 % of patients presenting with hip disease also have coexisting lumbar spine disease. Patients with lower back pain frequently have limited or altered hip range of motion, and these patients routinely improve after surgical intervention for hip disease (Redmond et al. 2014). Lower back pain accounts for 5–9 % of athletic injuries (Harvey and Tanner 1991). Spondylolysis is one of the major causes of lower back pain in young athletes (Congeni et al. 1997, Sward 1992, Harvey and Tanner 1991). Micheli and Wood (1995) reported spondylolytic stress fractures or acute spondylolysis of the pars interarticularis in 47 % of 100 adolescent athletes.

At present, there is a paucity of literature examining the hip-spine dilemma in general, and there are no publications about this dilemma in sportsmen. Therefore, imaging should not only be focussed on the hip and pelvis but also include the lower back. Bone scintigraphy including SPECT/CT can be helpful in examining the lower back and the hip region, for example, in athletes with spondylolysis. In interpreting the scan, the clinical context is important. A comprehensive assessment of each patient and in particular of the complex comprising the spine and the pelvis is essential for understanding each individual's adaptation to the imbalance induced by disorders of the spine or lower limbs (Lazannec et al. 2011).

LeBlanc and LeBlanc (2003) and Hiti et al. (2011) stated that the evaluation of such patients includes a familiarity with the sport and possible mechanisms of injury, including taking a careful history and physical examination. Diagnostic investigations may or may not prove helpful in formulating a final diagnosis. The bone scintigraphy, which can particularly be useful in avulsion fractures and osteitis pubis, reflects the degree of bone remodelling that occurs at the injured site.

MRI has become the standard imaging modality for activity-related groin pain. Lesions, including rectus abdominis/adductor aponeurosis injury and osteitis pubis, are termed athletic pubalgia (Khan et al. 2013).

The diagnosis of a sportsman's hernia is difficult. The condition must be distinguished from the more common osteitis pubis and musculotendinous injuries. The sportsman's hernia is an occult "hernia" caused by weakness or tear of the posterior inguinal wall (mostly the external oblique muscle), without a clinically recognisable hernia, that leads to a condition of chronic groin pain. The most common finding at surgery is a deficient posterior wall of the inguinal canal. MRI appears to have excellent diagnostic potential for sports hernia. Most of the time, imaging is normal (Farber and Wilckens 2007, Swan and Wolcott 2007). The role of nuclear medicine imaging techniques is not defined in the sportsman's hernia. Disorders of the os pubis, stress fractures and various hip pathologies are also causes of groin pain. In osteitis pubis, triple-phase bone scanning can be positive (Morelli and Espinoza 2005).

27.2.7.2 Osteitis Pubis and Osteomyelitis

The symphysis pubis is a non-synovial amphiarthrodial joint situated at the confluence of the two pubic bones, consisting of an intrapubic fibrocartilaginous disc sandwiched between thin layers of hyaline cartilage (Gamble et al. 1986). Bony infection or inflammation of the pubic area is rare. Athletic osteitis pubis is a chronic painful inflammatory overuse injury due to repetitive avulsive trauma of the parasymphyseal pubic bone and/or pubic symphysis, involving the adductor muscles or gracilis (Verrall et al. 2005, Morelli and Smith 2001). Pyogenic osteomyelitis of the pubis in an otherwise healthy athlete can be the differential diagnosis. It is typical in sports with a lot of sprinting and sudden changes of direction, such as running, basketball, soccer, ice hockey and tennis (Fricker et al. 1991, Karpos et al. 1995 and Barry and McGuire 1996). Pauli et al. (2002) showed that both osteitis pubis and osteomyelitis pubis can appear in one patient at the same time. If there is a clinical suspicion of skeletal abnormality, radiography can be performed. Standard anteroposterior radiographs and CT scans are useful to show irregularities of the pubic bone including widening of the symphysis, sclerosis or a decrease in the bone density at the symphysis, cystic changes and marginal erosions in the subchondral bone. MRI is best to image osteitis pubis as it allows visualisation of soft tissue abnormalities and can also demonstrate bone marrow oedema.

There is an absolute role for bone scintigraphy at these indications. In osteitis pubis, the early phases in bone scanning may be or may not be tracer avid, depending on how long the osteitis pubis exists and if there is a low-grade or a high-grade infection. Bone scintigraphy may settle the diagnosis of osteitis pubis, but a negative bone scan does not fully exclude the diagnosis. In osteomyelitis, bone scintigraphy usually shows a combination of focal hyperperfusion, focal hyperaemia and focally increased bone uptake, which is virtually diagnostic for osteomyelitis in patients with nonviolated bone. This triple-phase bone scanning has an accuracy of 90 % and is always been the radionuclide procedure of choice for diagnosing osteomyelitis in bone not affected by underlying conditions (Palestro and Torres 1997, Mandell et al. 1998). Amongst bone scan, white blood cell scan and ^{18}F-FDG PET/CT scan, the bone scan showed greatest numbers of lesions. It has been previously reported that a bone scan is able to detect many asymptomatic lesions (even radiographically obscure foci of the disease). However, keep in mind that abnormalities at radionuclide bone imaging reflect increased bone mineral turnover in general, not infection specifically. It is therefore very important to combine all diagnostic and clinical information for narrowing differential diagnosis. Strobel and Stumpe (2007) reported that ^{18}F-FDG PET scan may be helpful in imaging musculoskeletal infection and might play an important role in the evaluation of chronic osteomyelitis. On the basis of a cumulated reported accuracy (>85 %) and expert opinion, vertebral osteomyelitis is one of the major indications for ^{18}F-FDG PET/CT (Jamar et al. 2013, Chong et al. 2014). ^{18}F-FDG PET is highly effective in excluding osteomyelitis, according to Zhuang et al. (2000). ^{18}F-FDG PET showed promising results for diagnosing both acute and chronic infections of the axial and appendicular skeleton.

27.2.8 Greater Trochanteric Pain Syndrome

Greater trochanteric pain syndrome has expanded to include a number of disorders of the lateral, peritrochanteric space of the hip. This includes trochanteric bursitis, tears or tendinopathy of the gluteus medius and minimus, piriformis tendinopathy and external coxa saltans (snapping hip) (Voos et al. 2007, Strauss et al. 2010, Keung Ho and Howard 2012).

During activities that require repetitive flexion, extension and abduction, an audible and potentially painful snapping of the hip is described as coxa saltans by Strauss et al. (2010). The external variety of snapping hip syndrome involves the soft tissues overlying the greater trochanter, most typically the iliotibial band but also the anterior border of the gluteus maximus.

Trochanteric bursitis is a self-limiting disorder in the majority of patients and typically responds to conservative measures. Patients have a painful hip due to snapping of the iliotibial band over the greater trochanter, resulting in trochanteric bursitis (Zoltan et al. 1986).

Diagnostic imaging in the workup of suspected abductor tendon pathology usually starts with plain radiographs of the affected hip looking for evidence of loose bodies or synovial chondromatosis, which can be causes of the internal variety of coxa saltans. However, similar to cases of trochanteric bursitis or abductor tendon pathology, plain radiographs are typically negative; however, calcification may be seen at the insertion site on the greater trochanter. Ultrasound can also be used to evaluate the abductor tendons, identifying thickening and fluid consistent with tendinosis or the presence of partial- or full-thickness tears (Rask 1980, Sarkis and Chicote–Campos 1978). MRI was shown to be an effective diagnostic tool for excluding intra-articular causes of suspected pathology of the gluteus medius and minimus tendons. Intra-articular causes of a "snapping" hip include synovial chondromatosis, loose bodies, osteocartilaginous exostosis and subluxation of the hip. Extra-articular causes include stenosing tenosynovitis of the iliopsoas tendon sheath near its insertion on the femur (Michelli 1983). Bone scintigraphy shows (mostly slightly) increased tracer accumulation at the site of the trochanteric bursa in bursitis. In literature, radionuclide imaging techniques are rarely mentioned in the workup of the greater trochanteric pain syndrome.

27.2.9 Muscle and Tendon Injury

Strains of the muscle-tendon unit of the adductors (especially tendon of musculus adductor longus, rectus femoris and abdominis) and other muscle groups occur mainly at the proximal end of the tendon itself or to the musculotendinous junction in the muscle belly. The history is important in guiding muscle and tendon injury. Brandser et al. (1995) showed the superiority of MRI to CT, due to better characterisation of muscular or musculotendinous injuries as better in outlining the extent of injury within the muscle group. Sonography is as useful as MRI in depicting acute hamstring injuries and may be the preferred imaging technique because of lower costs. However, MRI is more sensitive for follow-up imaging of healing injuries (Connell et al 2004). The role of radionuclide imaging is not clearly defined in muscle and tendon strains such as hamstring and quadriceps strains or ruptures.

27.2.10 Obturatorius Tendinopathy and Piriformis Muscle Syndrome

Petchprapa et al. (2010) describe entrapment neuropathies such as piriformis muscle syndrome as an underrecognised cause of pain and functional impairment caused by acute or chronic injury to peripheral nerves. Rohde and Ziran (2003) report on obturatorius tendinopathy as a cause of chronic hip pain.

In piriformis muscle syndrome, sciatic pain reproduced on passive internal rotation/adduction of a flexed hip is considered suggestive of the syndrome. The general consensus is that it is caused when hypertrophy, inflammation, injury or anatomical variation of the piriformis muscle result in compression of the sciatic nerve as they both exit the pelvis through the greater sciatic notch. Normally, the sciatic nerve typically passes immediately anterior to the piriformis muscle. This relationship is variable, however, as the nerve occasionally passes through the muscle or splits early, with part of it passing through the muscle. Additionally an accessory piriformis muscle which arises from the more medial part of the sacrum can be implicated. Aetiology could be a narrowed sciatic foramen (in accessory piriformis muscle, muscle hypertrophy, lumbar lordosis), spasm (such as seen in athletes, cerebral palsy) and bursitis and inflammation.

MRI is the most used imaging technique for tendinopathy of the obturatorius and/or piriformis muscle syndrome. MRI is the imaging modality of choice and can adequately visualise the region. Radiographic appearance depends on the cause, and often no abnormality is noted. If muscle injury or inflammation is present, then increased signal within the piriformis muscle may be seen on T2 MRI. An accessory piriformis muscle may be identified. The role of radionuclide bone scanning is not mentioned for these disorders in literature. In cases of a tendinopathy, bone scintigraphy, however, can be used. Figure 27.2 shows an example of obturatorius tendinopathy in an adolescent sports man. This is the case of a young adolescent male patient who was rowing very actively after which he developed pain in the left hip/buttocks. MRI showed oedema in the same region of the focal uptake on the bone scan. The perfusion and blood pool phases of the bone scan appeared negative. SPECT/CT confirmed focal uptake at the anterolateral site of the foramen obturatorius region, in the region where the tendon of the internal obturatorius muscle is attached. An obturator internus tendinitis was highly suspected. Patient was referred to the physiotherapist for treatment.

27.2.11 Myositis Ossificans

Kransdorf and Meis (1993) and Spencer and Missen (1989) described myositis ossificans traumatica (MOT) as a pseudo-inflammatory rapidly growing painful calcification or bone growth resulting from a severe or poorly treated contusion. It usually occurs as a result of impact, which causes damage to the periosteum as well as to the muscle. Quadriceps femoris haematoma predisposes to the development of myositis ossificans. Myositis ossificans can occur after a strain in deep muscles (Natsis et al. 2010). In traumatic myositis ossificans, the bone is deposited within a muscle as a result of haematoma as mentioned by Ellison et al. (1984). King (1998) identifies different mechanisms for the new bone formation within the injured muscle. As myositis ossificans develops, it passes through three characteristic phases, leading to the so-called zone phenomenon. The bone will grow 2–4 weeks after the injury and becomes mature bone within 3–6 months. MOT may be mistaken for serious pathologies such as sarcoma (Booth and Westers 1989). Standard radiographs do not disclose any anomaly in the early stages (even 2–3 weeks after onset) of myositis ossificans (Goldman 1976, Thomas et al. 1991

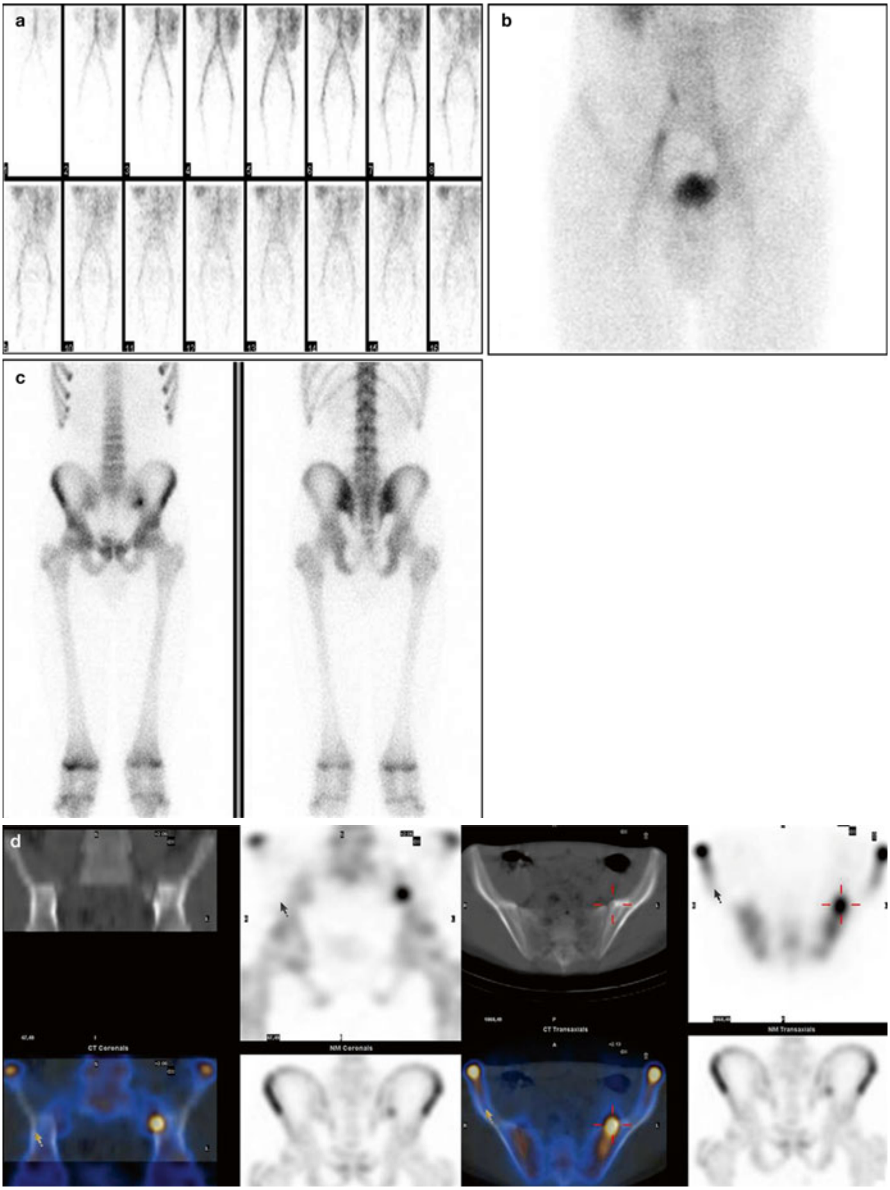

Fig. 27.2 A case of an adolescent male patient who was rowing very actively after which he developed pain in the left hip/buttocks. Three-phase ^{99m}Tc-HDP bone scan. Flow (**a**) and blood pool (**b**) were negative at the pelvic region. Late static images (**c**) and SPECT/CT (**d**) show a focal uptake anterolaterally in the obturatorius region. Obturator internus tendinitis is concluded as most probable cause of the buttock pain. Patient was successfully treated

and Lacout et al. 2012). Radiographs repeated at a later time point reveal de novo ossifications.

Ultrasonography is the most sensitive technique for early demonstration of the zone phenomenon. The role of radionuclide bone scan is not fully clear. However, high uptake at the location of myositis ossificans is expected in highly active lesions, and this may support the diagnosis, especially with the help of SPECT/CT. Bone scintigraphy SPECT/CT may help in differentiating between active and inactive myositis ossificans.

27.3 Intra-articular Causes of Hip Pain

27.3.1 Femoroacetabular Impingement

Byrd (2010) stated that femoroacetabular impingement (FAI) is a common cause of intra-articular hip pathology and secondary osteoarthritis in young athletes. Early recognition is an important first step in order to avoid the severe secondary damage that can occur. There are three types: pincer, cam and combined. History and examination usually reflect findings of joint damage amongst athletes, and radiographs can reveal the presence of underlying FAI. In the current literature, only a few case reports emphasise the diagnostic value of SPECT/CT in patients with femoroacetabular impingement (Gnanasegaran et al. 2009, Lee et al. 2008 and Mulholland et al. 2008). The scintigraphic image reflects the pattern of remodelling that occurs at the sites of impingement. The increasing availability of SPECT/CT allows fusion of the anatomic image and the early detection of FAI due to reactive scintigraphic changes. This will give the clinician the chance to do an intervention before severe degenerative joint disease intervenes.

27.3.2 Avascular Necrosis

Avascular necrosis of the femoral head following hip dislocation must not be overlooked. Avascular necrosis is mainly caused by traumatic subcapital fracture of the femoral head. Traumatic dislocation is accompanied by a variety of intra-articular hip joint pathologies, the most common being labral tears, chondral defects and intra-articular loose osteochondral fragments and disruption of the ligamentum teres. Nontraumatic risk factors include corticosteroid use, heavy alcohol consumption, sickle cell disease, Gaucher and Caisson disease and hypercoagulable states.

Murray (1998) described that disruption of arterial supply to or obstruction of venous outflow from the hip results in death of osteocytes by oxygen deprivation. Osteonecrosis can result from vascular insufficiency for at least 12 hours. Bone scintigraphy is an excellent method for diagnosing and examining the stage of the avascular necrosis. In the acute phase of vascular compromise, no radiotracer is delivered to the bone tissue. At radionuclide bone scintigraphy, the affected part of the bone appears as a photopenic defect (Fig. 27.3). After revascularisation,

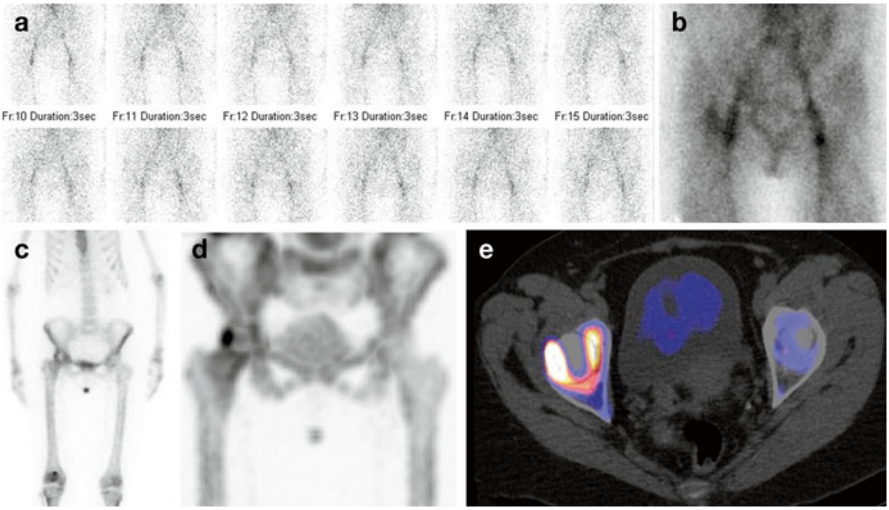

Fig. 27.3 An example of avascular necrosis of the femoral head. (**a**) Normal flow. (**b**) Increased blood pool at the region of the right femoral head. (**c**) Late static image (anterior view) showing a photopenic area at the right femoral head with slightly elevated uptake around it. (**d**) SPECT and (**e**) SPECT/CT image showing a central photopenic area in the femoral head and intense uptake around it

exuberant osteoblastic repair shows as intense radiotracer uptake. Subsequently, when repair is complete, radiotracer uptake may return to baseline levels.

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Part IX

The Musculoskeletal System Topographically: The Knee

Injuries of the Knee

28

Hendrik P. Delport

Contents

Abstract

The knee is one of the body parts most often injured. Sports, falls, and motor vehicle accidents account for the vast majority of injuries to the knee.

The different types of injuries to the knee are defined by the affected anatomy of the knee and the mechanism by which it is injured.

This chapter gives a non-exhausting overview of common injuries both acute and chronic to the knee joint.

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Although bony lesions or fractures are more spectacular, most of the injuries around the knee joint affect the soft tissue envelope. This envelope offers a precious system balancing the joint during most of our activities.

However, good knowledge of the functional anatomy remains of utmost importance for the clinician to come to a correct diagnosis.

Abbreviations

ACL	Anterior cruciate ligament
AP	Anteroposterior
ELPS	Excessive lateral pressure syndrome
ITB	Iliotibial band
LCL	Lateral collateral ligament
MCL	Medial collateral ligament
MRI	Magnetic resonance imaging
NSAID	Nonsteroidal anti-inflammatory drug
OSD	Osgood-Schlatter disease
PAES	Popliteal artery entrapment syndrome
PFM	Patellofemoral malalignment
PFPS	Patellofemoral pain syndrome
PCL	Posterior cruciate ligament
US	Ultrasound

28.1 Introduction

28.1.1 Epidemiology

While knee injuries are treated by a wide range of clinicians, patients with knee injuries frequently present to emergency departments. The knee is the most commonly injured joint in adolescent athletes with an estimated 2.5 million sports-related injuries presenting to the US emergency departments from 1999 through 2008 (Gage et al. 2012). The most common diagnoses were strains and sprains (42.1 %), contusions and abrasions (27.1 %), and lacerations and punctures (10.5 %). The most common general categories causing injury were sports and recreation (49.3 %), building industry (30.2 %), and interior decoration (13.6 %). Several gender and age group differences were identified. For example, males sustained a higher proportion of basketball-related injuries (11.1 %) than females (3.6 %) (Boling et al. 2010). Although knee injuries will likely continue to occur most frequently among youth and young adult athletes, anticipating and responding to trends such as an increase in the incidence of knee injuries among adult and senior patients will enable clinicians to better anticipate caseloads, allocate resources, and determine best practices for diagnosis and treatment of knee injuries in different age groups.

28.1.2 Functional Anatomy

Although the knee joint may look like a simple joint, it is one of the most complex. Moreover, the knee is more likely to be injured than is any other joint in the body. We tend to ignore our knees until something happens to them that causes pain. It is also the most vulnerable because it bears most of the weight of the body and pressure loads while providing flexible movement. When we walk, our knees support 1.5 times our body weight; climbing stairs is about 3–4 times our body weight and squatting about 8 times.

The knee joint is a synovial joint which connects the femur, the longest bone in the body, to the tibia, the second longest bone. There are two joints in the knee—the tibiofemoral joint, which joins the tibia to the femur, and the patellofemoral joint which joins the patella to the femur. These two joints work together to form a modified hinge joint that allows the knee to bend and straighten, but also to rotate slightly and from side to side.

The knee is part of a chain that includes the pelvis, hip, and upper leg above and the lower leg, ankle, and foot below. All of these work together and depend on each other for function and movement.

When we are sitting, the tibia and femur barely touch; standing they lock together to form a stable unit. The main parts of the knee joint are bones, ligaments, tendons, cartilages, and a joint capsule. The bones give strength, stability, and flexibility in the knee. Four bones make up the knee: femur, tibia, fibula, and patella. The function of ligaments is to attach bones to bones and give strength and stability to the knee: medial collateral ligament (MCL), lateral collateral ligament (LCL), anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and patellar ligament. The articular cartilages of the knee cover the ends of the femur, the top of the tibia, and the back of the patella. In the middle of the knee are the menisci—disc-shaped cushions that act as shock absorbers. The muscles in the leg keep the knee stable, well aligned, and moving: the quadriceps and hamstrings. The capsule is a thick, fibrous structure that wraps around the knee joint. Inside the capsule is the synovial membrane which is lined by the synovium, a soft tissue that secretes synovial fluid when it gets inflamed and provides lubrication for the knee. There are up to 13 bursae of various sizes in and around the knee located underneath the tendons and ligaments. Plicae are folds in the synovium.

28.1.3 Etiology and Injury Mechanism

While direct blows to the knee will occur, the knee is more susceptible to twisting or stretching injuries, taking the joint through a greater range of motion than it can tolerate. If the knee is stressed from a specific direction, then the ligament is trying to hold it in place against that force. Twisting injuries to the knee put stress on the cartilage or meniscus and can pinch it between the tibial surface and the edges of the femoral condyle, causing tears. Injuries of the muscles and tendons surrounding the knee are caused by acute hyperflexion or hyperextension of the knee or by overuse. There can be inflammation of the bursae (bursitis) of the knee that can occur because of direct blows or chronic use and abuse.

28.2 Injuries

28.2.1 Anterior Knee Pain

28.2.1.1 Patellofemoral Pain Syndrome

Patellofemoral pain syndrome (PFPS) is a common cause of anterior knee pain that can be treated in over 2/3 of patients through rehabilitation protocols designed to reduce pain and return function to the individual patient. Sources of pain include patella malalignment, chondromalacia, osteoarthritis, osteochondral fractures, synovial plica, prepatellar bursitis, tendinopathy, and patella instability. An understanding of knee anatomy, as it relates to the mechanism of injury, is important in establishing a diagnosis; ancillary tests may be required to finalize the diagnosis. Plain radiography showed a lack of information in patients with PFPS (Haim et al. 2006). Other radiographic measures (sulcus angle, Laurin angle, Merchant angle, and Insall-Salvati index) are inconclusive. Minimal evidence exists regarding the validity of clinical and radiographic features commonly used for diagnosing PFPS. Physical examination is clearly more useful than plain radiography.

In the 1970s anterior knee pain was related to the presence of patellofemoral malalignment (PFM). PFM was defined as an abnormality of patellar tracking in the sense of lateral displacement of the patella, lateral tilt of the patella, or both, in extension, that reduces in flexion. Excessive lateral pressure syndrome (ELPS) would be a type of PFM (Ficat et al. 1975).

In the 1990s, Scott F. Dye, of the University of California, San Francisco, and his research group came up with the tissue homeostasis theory (Dye et al. 1999). According to Dye, the loss of both osseous and soft tissue of the peripatellar region homeostasis is more important in the genesis of anterior knee pain than biomechanical/structural characteristics. He suggests that patients with PFPS are often symptomatic due to supraphysiologic loading of anatomically normal knee components. In fact, patients with anterior knee pain often lack an easily identifiable structural abnormality to account for the symptoms. According to the Dye theory of envelope of load acceptance, overuse or cyclical overload of soft tissue or bone areas may explain anterior knee pain in some patients. It appears that anthropometric variables are not associated with PFPS (Witvrouw et al. 2000). We feel it is important to know that females have 2.23 times higher incidence of PFPS compared to males. Researchers speculate there are many biomechanical and anatomical alignment factors that may lead to the increased incidence of PFPS in females compared with males (Boling et al. 2010). These factors include differences between males and females on measures of q-angle, dynamic frontal plane alignment, and lower extremity muscle strength. While the initial treatment is usually nonoperative, it is sometimes necessary to perform surgery to permanently solve the problem.

Malalignment, along with acute or repetitive trauma, can lead to degenerative changes on the surface of the patella or femoral groove. Softening and erosive changes are referred to as chondromalacia. Initial treatment includes activity modification, ice, and NSAIDs. As the pain subsides, an exercise program is begun that usually focuses on stretching and strengthening. For those patients with recalcitrant cases, their physician may need to modify their treatment plan and consider surgical intervention (Kuroda et al. 2001; Palmer et al. 2004; Pritsch et al. 2007).

28.2.1.2 Tendinopathy of the Patella and Quadriceps Tendons, Jumpers Knee

Patellar tendinopathy is a common injury following overuse or repetitive trauma to the extensor mechanism, such as jumping sports, i.e., basketball, volleyball, and high jump. Patients usually present with pain in the front of their knee over the patellar tendon adjacent to the patella apex, which is associated with limited flexion and swelling. Treatment is directed toward a period of relative rest to allow the symptoms to subside followed by activity modification that limits high impact sports to prevent further structural damage. Stretching and strengthening exercises with the purpose to strengthen tendon structure are believed to favor collagen synthesis; they are installed once the pain subsides. Ice and short courses of NSAIDs are helpful adjuncts to treat the paratenonitis component of the disorder.

In a similar fashion, the quadriceps tendon may become painful and irritated. This is usually manifested with tenderness in the soft tissue just above the patella. Treatment is similar to patellar tendinopathy. Quadriceps tendinopathy is uncommon; it is an overuse condition typically found in cyclists.

28.2.1.3 Hoffitis

Hoffa's disease is a painful impingement of the infrapatellar fat pad. This occurs when the normal pad of fat that sits behind the patellar tendon gets irritated and inflamed. It then becomes vulnerable to getting pinched in the knee joint causing pain. This can be triggered by a single injury with a blow to the knee, or by hyperextension of the knee, or can be part of an overuse injury with repetitive microtrauma to the fat pad. Occasionally it can also be seen as a consequence of arthroscopic surgery.

The patient will feel pain below the kneecap at the front of the knee. It will be most prominent when the knee is fully straight and may be worse with walking or running. There may be a visible bulge on either side of the kneecap tendon in severe cases.

Careful examination is all that is needed; however, an MRI scan can be useful to exclude other problems.

Applying ice to the area can be helpful to calm things down. Physiotherapy, taping, and anti-inflammatory medication are useful. Steroid injections to reduce the inflammation can help to break the vicious cycle in very recalcitrant cases, but need to be administered to the right spot. Occasionally patients with Hoffa's disease without any other concomitant pathology can expect resolution or long-term improvement in their symptoms and function after arthroscopic resection.

28.2.1.4 Osgood-Schlatter Disease

Osgood-Schlatter disease (OSD) is an overuse injury that occurs in the knee area of adolescents. The symptoms are related to inflammation of the patellar tendon and non-fused growth area of the tuberositas tibiae where it attaches to the tibia. Young adolescents who participate in twisting and jumping sports similar to patellar tendinopathy, including soccer, gymnastics, basketball, and distance running, are most at risk for this disease. It is one of the most common causes of knee pain in adolescents; it is a real overuse injury. OSD can be quite painful, but usually resolves itself within 12–24 months. OSD usually strikes active adolescents around the beginning of their growth spurts, the approximately 2-year period during which they grow most rapidly. Growth spurts can begin any time between the ages of 8 and 13 for girls, or 10 and 15 for boys. OSD has been more common in boys, but as a growing number of girls participate in sports, this is changing.

Teens increase their risk for OSD if they play sports involving running, twisting, and jumping, such as basketball, football, volleyball, soccer, tennis, figure skating, and gymnastics. Doctors disagree about the mechanisms that cause the injury but agree that overuse and physical stress are involved.

Growth spurts make kids vulnerable because their bones, muscles, and tendons are growing quickly and not always at the same time. With exercise, differences in size and strength between the muscle groups place unusual stress on the growth plate at the top of the tibia.

Other symptoms may include pain that worsens with exercise and relief from pain with rest.

Once clinical diagnosis has been made, treatment is aimed at reducing the pain and swelling. This may include the use of nonsteroidal anti-inflammatory drugs and wrapping the knee until the child can enjoy activity without discomfort or significant pain after sports participation.

Symptoms that worsen with activity may require rest for several months, followed by a conditioning program. In some patients, Osgood-Schlatter symptoms may last for 2–3 years. However, most symptoms will completely disappear with completion of the adolescent growth spurt, around age 14 for girls and age 16 for boys. Actual sports management in youngsters is focused on prevention based on load reduction during the individually determined vulnerable time span with growth spurt.

28.2.1.5 Sinding-Larsen-Johansson

Sinding-Larsen-Johansson disease is related to OSD and is one of the osteochondroses. It can be a cause of anterior knee pain. It is usually seen in a boy in his preteens (9y girls and 11y boys). Pain is usually related to jumping and twisting activity and is typically over the inferior pole of the patella. The mechanism in Sinding-Larsen-Johansson disease is thought to be persistent traction at the cartilaginous junction of the patella and the patellar tendon, usually at the inferior patellar pole (patella apex). It is essentially a chronic stress injury with overuse of the patella-patellar tendon junction. Similar symptoms can sometimes occur proximally, at the junction of the quadriceps tendon and the patella. Knee radiograph can show calcification or ossification at the junction between the patella and the patellar ligament. US and MRI can be used.

Physiotherapy is the mainstay of treatment, including quadriceps strengthening exercises. Surgery is not usually needed. As the skeleton matures, symptoms usually improve, and in this way, it is regarded as a self-limiting process. However, symptoms may be present for at least a year.

28.2.1.6 Bursitis

Several bursae overly bony prominences around the knee. Acute and repetitive trauma from overuse or, more commonly, chronic irritation results in local inflammation and fluid collection within the bursa. The prepatellar bursa, an adventitious non-synovial lined bursa, is the most commonly affected related to acute trauma or gout. The bursa at the attachment of the medial hamstrings or pes anserinus tendons on the tibia is located between the tibial part of the medial collateral ligament and the pes anserinus; it can also become inflamed. This is usually termed as pes bursitis and is usually caused by repetitive activity such as running. Treatment is directed at stopping the irritating activity. Ice and a short course of NSAIDs are useful. A compressive wrap is sometimes helpful. Aspiration is sometimes required for extreme cases. Another bursa that may be inflamed is the deep infrapatellar bursa, this synovial lined bursa is located deep to the distal patellar tendon, and the condition might be related to Osgood-Schlatter disease. The superficial infrapatellar bursa is an adventitious bursa superficial to the tuberositas and distal patellar tendon insertion and when inflamed is called “housemaid’s knee”; this condition is related to local friction with kneeling down and is not that frequent in sports but related to working activities like flooring.

28.2.1.7 Plica Synovialis Mediopatellaris

Plica syndrome of the knee is a constellation of signs and symptoms that occur secondary to injury or overuse. An otherwise normal structure, a plica can be a significant source of anterior knee pain. Once an inflammatory process is established, the normal plical tissue may hypertrophy into a truly pathologic structure. During embryonic development, the knee is initially divided by synovial membranes into three separate compartments. By the third or fourth month of fetal life, the membranes are resorbed, and the knee becomes a single synovial chamber. If the membranes resorb incompletely, various degrees of septation may persist. These embryonic remnants are known as synovial plicae. Four types of synovial plicae of the knee have been described in the literature.

The suprapatellar plica, or plica synovialis suprapatellaris, divides the suprapatellar pouch from the remainder of the knee. Rarely, this plica may initiate a suprapatellar bursitis or perhaps chondromalacia, and symptoms secondary to these conditions may be present. Anatomically, the suprapatellar plica can rarely be complete or more frequently in the form of a porta, which only partially separates the compartments. It courses from the anterior femoral metaphysis or the posterior quadriceps tendon to the medial wall of the joint. The suprapatellar plica most commonly begins proximal to the superior pole of the patella but may begin anywhere.

The mediopatellar plica is the most frequently cited cause of plica syndrome. It lies on the medial wall of the joint, originating suprapatellar, and courses obliquely down to insert on the infrapatellar fat pad. This plica, sometimes known as a shelf, lies in the coronal plane.

The rare and poorly documented lateral synovial plica is a wider and thicker band than the medial plica. It is located along the lateral parapatellar synovium, inserting on the lateral patellar facet. The lateral plica has been argued to be derived from the parapatellar adipose synovial fringe rather than being a vestigial septum.

28.2.2 Other Injuries Around the Knee

28.2.2.1 Iliotibial Band Friction Syndrome or Runner's Knee

Runner's knee is a specific clinical diagnosis. Symptoms of iliotibial band friction (ITB) syndrome consist of pain on the lateral side of the knee, more specifically at or around the lateral epicondyle of the femur. It starts during running activity and gradually gets worse. Often the runner has to stop his/her running activity. After a period of rest, the pain returns when running starts again. The pain is normally aggravated by running, particularly downhill. Pain may be felt when bending and straightening the knee which may be made worse by palpating over the sore part. There might be tightness in the ITB which runs down the outside of the femur. A therapist or trainer may use Ober's test to assess this. Weakness in hip abduction is another common sign. Tender trigger points in the gluteal muscles or buttocks area may also be present. Certain factors favor the development of runner's knee or ITB syndrome. A naturally tight or wide ITB may make someone more susceptible to this injury. Weak hip muscles, particularly the gluteus medius, are also thought to be a significant factor. Overpronation or poor foot biomechanics may increase the risk of injury. Other factors include leg length difference and running on hills or on cambered roads.

In early cases inflammation is present between the ITB and the lateral femur condyle; in late cases and only rarely, tendinopathy at the area of the conflict may exist and be responsible for recurrent friction syndrome. Diagnosis of tendinopathy is made with US or MRI. Rest and cold therapy or ice to reduce any inflammation can help. Iliotibial band stretches after training and throughout the day are important.

Anti-inflammatory medications such as NSAIDs are helpful. Dry-needling techniques or acupuncture may be beneficial also. Use of electrotherapeutic treatment techniques such as TENS or ultrasound may help reduce pain and inflammation. A rehabilitation strategy which includes stretches and exercises to strengthen the hip abductors and core stability is important. In acute or prolonged cases, a corticosteroid injection into the site of irritation may provide pain relief. In those few cases that do not respond to a conservative regimen, surgical excision of tissues deep to the band also has an established track record of effectiveness.

28.2.2.2 Pes Anserinus Tendinopathy

The tendons of the superficial pes anserinus may become overused. Pes anserinus is the anatomical term used to describe the common insertion point of the sartorius, gracilis, and semitendinosus on the anterior-medial aspect of the knee. The frequency of this problem is not known, but from my viewpoint, it is more common than previously believed. With repetitive use, these muscles can become strained and develop micro tears. Although very small the body must still repair this microtrauma and does so by depositing scar tissue adhesions in and around the injured area. Unfortunately, these adhesions make the tissues less flexible, causing the muscles to pull on their insertion at the anterior-medial knee or to compress a small bursa located underneath the tendon where it inserts onto the knee. Either of these situations will cause pain on the front/inside aspect of the knee. When the bursa is involved, this is commonly referred to as pes anserine bursitis.

In most cases, biomechanical factors such as muscle imbalances at the hip and thigh or core muscle weakness may play a role in the development of this type of injury.

The signs and symptoms are gradual onset of pain at or just below the anterior-medial aspect of the knee, pain aggravated by climbing up stairs, and tenderness and/or swelling just below the medial knee; if the bursa is involved night pain may occur; in the early stages pain symptoms usually improve with warm-up or exercise; and in later stages pain may worsen and be present during activity. This can be due to a change in training or in the intensity of the training program. Also a change in footwear may lead to symptoms. There are many other problems which also could contribute. The hip muscles may be either too weak or too tight—or a combination!

As with all running injuries, the first treatment step is to stop running and rest the knee. Ice should be applied for the first few days at regular intervals for 15 min at a time to ease pain and inflammation. Anti-inflammatory medications may also be advised. An assessment of the movement patterns, strength, and flexibility will help identify areas of weakness or tightness which may be contributing. Hip exercises which may be recommended include stretches for the hip flexors and rotators, as well as hip abductor strengthening. A therapist may apply electrotherapy such as ultrasound, and if treatment is not successful, then corticosteroid injections have been shown to be effective.

28.2.2.3 Popliteus Tendon Tendinopathy

A condition that can cause popliteal pain is popliteus tendinopathy. This is an inflammation of the tendon sheath of the popliteal muscle. It is quite an uncommon pathology which often occurs in athletes and people with a history of other knee ligament injuries after trauma. The popliteus tendon is sensitive to overuse activity and may become inflamed causing pain at the back of the knee, aggravated during deep squats. The patient may also have trouble fully straightening the knee. Acute pain is experienced behind the knee immediately after the injury. This is often accompanied by redness and swelling. The pain may prohibit walking, especially soon after the injury is sustained. However, in some cases the pain can be less pronounced or even unnoticeable to start with. The area around the popliteus tendon is likely to be tender. The diagnosis should be largely established with a careful history and physical examination. Usually patients have symptoms that include tenderness along the course of the proximal popliteus tendon and pain with resisted external rotation (Howard et al. 1992). Pressure is placed on the popliteus tendon during such everyday movements as the feet hitting the ground. Running downhill can put a strain on the tendon if practiced excessively. Treatment consists in stopping all strenuous physical activities involving the legs until the symptoms have subsided, which may take around 6 weeks. Ice the area to reduce pain and swelling, and anti-inflammatory pain medication may be used if necessary. If the tendinopathy is severe, appropriate surgery is rarely necessary.

28.2.2.4 Biceps Tendon Tendinopathy

Inflammation of the paratenon in the biceps femoris tendon as it sweeps along the back of the knee may give rise to pain in this area. The biceps femoris tendon is one of the hamstrings tendons. It may become injured via overuse during running or cycling, where the tendon abrades over the bone of the femur at the back of the knee. The pain is experienced at the lateral and posterior side of the knee.

28.2.2.5 Baker's Cyst

One of the common causes of popliteal pain is Baker's cyst (or gastrocnemio-semimembranosus recess, popliteal cyst). This is a fluid-filled joint recess at the back of the knee with an anatomical connection between the main joint cavity and a lubricating "pocket" at the back of the knee. This joint recess may become inflated with joint fluid through a one-way valve formed by the crossing of the medial gastrocnemius tendon and the semimembranosus tendon during knee flexion-extension movement. Thus, pressure is build up within the recess eventually up to a level of tear of the recess. The cyst is caused by increased fluid at the knee joint related to a wide variety of articular knee problems. Even if the knee is stressed for any reason, excessive synovial fluid can be secreted. It is not related to the pathology at the cyst itself. When the fluid builds up under pressure, synovial fluid can leak into the popliteal bursa to form a cystic swelling known as Baker's cyst (or popliteal cyst). The cyst may be obvious to the eye or it may be palpable as a tense "balloon-like" swelling on the inner (medial) aspect of the back of the knee. In case of rupture of the cyst, local inflammation at the calf hampers clinical discrimination with deep venous thrombosis. It is very important always to look for the real cause of this kind of cyst which is often the result of intra-articular pathology.

28.2.2.6 Gastrocnemius Tendinopathy

The other tendon that may cause pain at the back of the knee is medial or lateral gastrocnemius tendinopathy. Pain may be experienced on the medial or lateral aspect of the back of the knee. Gastrocnemius tendinopathy is an example of repetitive strain injury. As the gastrocnemius is overused, it can lead to "microtrauma". When scar tissue builds up in the gastrocnemius, it cannot stretch or contract as well since pain will develop. Gastrocnemius tendinosis may progress to an interstitial tear, longitudinal split tear, partial tear, or very rarely a complete tear. This injury occurs commonly in sports activities (e.g., hill running, jumping, tennis), but it can occur in any activity. A medial calf injury is often seen in the intermittently active athlete, often referred to as the "weekend warrior". The condition has also been termed "tennis leg" because of its prevalence in this particular sport, but medial calf injury can happen in a variety of sports or other activities. Clinical symptoms usually develop gradually and may include local pain and tenderness, as well as swelling at the posteromedial or posterolateral knee and proximal lower leg, weakness, and limited range of motion. It is important to realize that many cases of gastrocnemius tendinopathy are actually caused by a problem at the hip. The proper treatment of gastrocnemius tendinopathy must not only address pain and tissue damage at the gastrocnemius itself, but must correct any biomechanical problem at the hip or pelvis. Eccentric loading in gastrocnemius tendinopathy results in improved healing with collagen deposition and restoration of the matrix component. The MRI techniques can be used as an adjunct to clinical evaluation by monitoring (Shalabi et al. 2004).

28.2.3 Popliteal Artery Lesions

28.2.3.1 Popliteal Artery Entrapment Syndrome

Popliteal artery entrapment syndrome (PEAS) is a rather uncommon pathology, which results into claudication and chronic leg ischemia. The popliteal artery may be compressed behind the knee, due to congenital deformity of the muscles or tendon insertions at the popliteal fossa. This repetitive trauma may result in stenotic artery degeneration with complete artery occlusion. The syndrome was first described in 1879 by Anderson Stuart, a medical student, in a 64-year-old male. PAES refers to symptomatic compression or occlusion of the popliteal artery due to a developmentally abnormal relationship with the medial head of gastrocnemius or less commonly with the popliteus. Arterial compression can result in chronic vascular microtrauma and local premature arteriosclerosis and thrombus formation. This can result in distal ischemia. Stenosis and turbulent flow may lead to poststenotic ectasia or aneurysm formation (Hai et al. 2008). Five anatomic types of entrapment are typically described:

- Type I: Popliteal artery has aberrant medial course around the medial head of the gastrocnemius (MHG).
- Type II: Artery is not displaced but the MHG inserts more lateral than usual; the artery passes medial and beneath the muscle.
- Type III: Accessory slip of MHG slings around the artery.
- Type IV: Artery lies deep in the popliteal fossa entrapped by the popliteus or fibrous band.
- Type V: Both popliteal artery and vein are entrapped.

During the recent years, the increasing frequency with which popliteal artery entrapment is reported strongly suggests a greater awareness of the syndrome. Accessory gastrocnemius muscle bellies ("third head of the gastrocnemius") have been associated with vascular claudication due to extrinsic vascular functional compression or entrapment, though the majority of these congenital lesions are asymptomatic. MRI is the best imaging modality to demonstrate the underlying anatomic type of entrapment, which helps guide surgical management (Macedo et al. 2003).

28.2.3.2 Popliteal Artery Aneurysm

A popliteal aneurysm is a defect of the popliteal artery where the wall of the artery loses its elasticity and the artery bulges out into a spindle shape. This condition usually occurs in older people and the cause is usually age-related loss of elasticity and hardening of the artery wall; rarely this condition is caused by a traumatic event. No obvious relationship with sports is reported but it remains a possible differential diagnosis.

The bulging of the aneurysm can cause local compression and pain, but more important symptoms may be the result of clots forming on the walls and shooting down to the lower leg, obstructing the blood supply initially causing claudication (pain in the calf and foot on walking) and later more advanced arterial obstruction and a cold white foot (a medical emergency).

28.2.4 Patellar Dislocation

When a patellar dislocation (luxation) occurs, the patella typically shifts toward the lateral aspect of the knee joint, leaving the femoral groove laterally (Stanitski and Paletta 1998). A partial dislocation (subluxation) of the patella occurs when the patella slips out of its normal alignment within the femoral groove but spontaneously returns to its position. Changes in the shape of the patella or the femoral groove or abnormal tension in the structures around the patella can lead to a dislocation. The patella can dislocate or sublux when it is pulled from the femoral groove by muscle force or as a result of acute trauma. Most patellar dislocations are lateral, and return of the patella to its anatomically normal position (reduction) is accomplished by applying pressure to the lateral margin during extension of the flexed knee. Acute dislocation of the patella is usually reduced without surgery (closed reduction).

The first episode of patellar dislocation often occurs during adolescence. Episodes of repeated subluxation and dislocation can occur, and with each episode, the restraining structures become more lax, compounding the problem and leading to recurrent patellar instability. After an initial acute dislocation, up to 49 % of individuals will develop recurrent patellar instability and experience intermittent episodes of patellar subluxation and dislocation (Coleman 1948). Associated fractures of the patella or lateral femoral condyle occur in 5 % of cases; osteochondral and chondral injuries are reported in 71 % of patellar dislocations (Rorabeck and Bobechko 1976). Individuals with patellar dislocation can be divided into two groups: those with anatomical predisposition for dislocation (e.g., lateral hypermobility, dysplasia of distal vastus medialis muscle, proximal and lateral patellar placement) or a history of patellar instability and those with no obvious signs that predispose toward dislocation. Individuals with an anatomical predisposition for knee dislocation have the greatest long-term benefit from acute surgical repair of knee injury, while nonoperative treatment produces good to excellent results in first-time or non-predisposed patellar dislocation.

Dislocation of the patella occurs more commonly in women than in men because the wider shape of the female pelvis creates a lateral pull on the patella. Risk for patellar dislocation is greater in individuals who participate in athletic activities requiring running or jumping; dislocation often results from a sudden change in direction while running or from rotating the leg while the foot is planted, which puts the knee under stress. Patellar dislocation is also more common in individuals with genu valgum. About 24 % of individuals with patellar dislocation have a family history of such problems; most affected individuals are between the ages of 16 and 20 years, with the condition rarely seen in individuals over age 30. Among athletes, the injury is most often associated with soccer, weight lifting, running, football, baseball, and basketball.

Swift reduction of the patella is necessary; sometimes, the dislocation reduces spontaneously during transit to the emergency room. Reduction provides immediate pain relief. The physician usually will perform a closed reduction by gently flexing the hip, extending the knee, and applying direct lateral-to-medial pressure to the patella to help relocate it. Following reduction, treatment is directed toward controlling inflammation, providing pain relief, and protecting the joint. The knee can be protected by immobilizing it with a brace or cast with the leg almost fully extended. Typically, a knee immobilizer is used for 10 to 14 days after injury. Gentle active range-of-motion exercises are then begun to prevent the development of excessive scar tissue (arthrofibrosis) and to encourage collagen formation. Exercises that strengthen the quadriceps muscle are important. Walking on crutches with weight bearing as tolerated may begin in the first week following immobilization. Analgesics and anti-inflammatory drugs may be used to treat pain and swelling. Proper foot support and alignment with orthotics and shoes may be helpful in cases of anatomical abnormalities. There is controversy on the effectiveness of knee braces. Patellar taping can be used to restore proper alignment and to control pain.

In cases of recurrent patellar dislocations, surgical procedures designed to restore muscle balance around the patella may be indicated (e.g., proximal realignment or distal realignment). These procedures may be performed as open surgeries; occasionally, surgery may be done arthroscopically on an outpatient basis (Rae and Khasawneh 1988).

28.2.5 Meniscal Problems

28.2.5.1 Meniscal Tears

Traumatic meniscal tears usually result from a twisting injury. Because the medial meniscus is less mobile than the lateral meniscus, it has a greater chance of being entrapped between the femur and tibia in the knee joint. Beyond the physical exam and radiographs, MRI has been useful in confirming the diagnosis. While some meniscal tears may heal with rest and activity modification, failure to respond to nonoperative treatment or repetitive episodes of catching or locking suggest that a surgical arthroscopy should be considered. Depending on the pattern and extent of the tear, the arthroscopy may involve either a partial meniscectomy or meniscal repair. Following arthroscopy, an exercise program facilitates restoration of motion and strength.

28.2.5.2 Degenerative Meniscopathy

The meniscus also suffers degenerative changes over time and that makes it weak. These menisci can tear with minimal trauma or even in usual movements like standing up from squatting. These menisci usually present many small tears. Treatment involves excision of damaged tissue.

28.2.5.3 Meniscus Cysts

Meniscal cysts occur when synovial fluid becomes encysted secondary to a meniscal tear. When they extend beyond the margins of the meniscus, they are termed parameniscal cysts. The frequency of these cysts is 4–6 % using knee MR studies (Helms 2002).

Clinically the patient with meniscal cysts may present with a palpable soft tissue swelling with or without knee pain.

High-resolution musculoskeletal ultrasound usually shows the cystic nature of the lesion. It may also demonstrate the associated meniscal tear.

MRI is the investigation of choice. Many of the cysts are non-palpable and these patients present with knee pain; hence, MRI can demonstrate the meniscal tear as well as the cyst.

Surgical excision of the cyst can be performed along with repair of the underlying meniscal tear.

28.2.6 Knee Ligament Injuries

Knee ligament sprains are injuries to the ligaments that stabilize the knee. There are multiple ligaments that stabilize the knee and keep it in alignment. The ACL and PCL stabilize the knee in anteroposterior (AP) and rotational movement. The MCL and LCL stabilize the knee against lateral sliding.

Ligament sprains are graded by the amount of stretching or tearing of the ligament fibers and the instability it causes as follows:

- Grade 1 knee sprain: The ligament is stretched and painful, but fibers are not torn and no instability is present.
- Grade 2 knee sprain: The ligament fibers are torn partially, and mild instability may be evident.
- Grade 3 knee sprain: The ligament fibers are completely torn and the knee is unstable.

28.2.6.1 Anterior Cruciate Ligament Injuries

ACL tears are becoming more common, with an incidence of 250,000 cases per year in the United States. They are also more commonly diagnosed because of increased awareness and diagnostic facilities. Women experience up to a sevenfold increase in ACL tears compared with men in competitive sports. The ACL is often torn during running and cutting sports when the foot is planted and the knee twists with a change of direction. Classically the individual feels a “pop” in the knee and is unable to continue running or playing because of pain and a sense of instability. In many cases, a hemarthrosis develops within one hour. Besides a physical examination and radiographs, it may be necessary to perform an MRI to confirm the diagnosis. Even in partial thickness tears, the ACL stays deficient if treated conservatively; because of the disruption of vascularity, the ligament often disappears and stays deficient due to elongation or reinsertion on the PCL. Treatment may be either operative or nonoperative and is dependent upon the individual's level of activity and clinical degree of instability. It is important that the individual is counseled about the natural history of an ACL-deficient knee before embarking on a course of treatment.

Nonoperative treatment involves physical therapy for restoration of motion, strength, and coordination. Most athletes return to sports in 6–12 weeks provided that they have achieved appropriate strength. The use of a brace is debatable, but may provide some subjective benefit. If an athlete suffers episodes of giving way during sports activities, it should be assumed that the knee is functionally unstable, and reconstructive surgery should be considered.

Current reconstructive techniques use an arthroscopic approach. The graft choices for an ACL reconstruction include the central one-third bone-patellar tendon-bone, hamstring tendons, and quadriceps tendon. Sometimes, allograft tissue is considered. Following the reconstructive procedure, a supervised and specialized rehabilitation program is necessary to restore motion and strength. In general most athletes return to sports by 6–9 months after surgery, but each case is individualized.

28.2.6.2 Posterior Cruciate Ligament Injuries

PCL injuries occur less often than ACL tears. Two common mechanisms of injury include first a fall on a hyperflexed knee with the foot plantar flexed and secondly striking the front of the tibia with the knee flexed—like a dashboard injury in a motor vehicle accident. In contrast with the ACL, fibrosis and bridging of even a complete thickness tear with functional ligament is possible in PCL tears. Treatment may be operative or nonoperative depending upon the degree of instability and involvement of associated structures. A study involving MRI follow-up imaging found that all low-grade and mid-grade PCL injuries healed with continuity, and 19 of 22 high-grade injuries healed (four healed with normal contour; 15 healed with continuity and altered morphology). In many cases that involve less severe PCL tears, patients are recommended to undergo conservative therapy with a progressive rehabilitation program (Servant et al. 2004).

28.2.6.3 Medial Collateral Ligament Injuries

The MCL is a broad, flat band that extends from the medial femoral epicondyle to the medial meniscus, tibial plateau, and adjacent shaft. It consists of superficial and deep components. The superficial component attaches distally to the medial aspect of the tibia and proximally to the medial femoral epicondyle. The deeper component originates from the medial joint capsule and attaches to the medial meniscus and is part of the meniscofemoral and meniscotibial ligaments. The superficial component is about 10 cm long and flat. The bursa separates the capsule and the medial meniscus of the superficial component. It may be one or more bursae. The superficial component of the medial collateral ligament crosses, in its way down to the *medial and postero-medial* surface of the tibia, the tendons of the sartorius, gracilis, and semitendinosus *which* are located superficial to the ligament and are separated by the pes anserine bursa. Below the ligament run the medial inferior genicular vessels and nerve and the anterior section of the semimembranosus tendon. The deeper component is shorter than the superficial and descends posteriorly to the medial tibial plateau, proximal to the groove for and insertion of the semimembranosus.

The MCL is a ligament, with a role in stabilizing the knee joint. The long fibers of the MCL primarily stabilize the medial side of the knee against valgus and external rotatory stress. The deeper part of this ligament also helps the anterior cruciate ligament in avoiding an anterior translation of the tibia on the femur. The concept of isometry of the collateral ligaments is important (Delport et al. 2013a). Ligaments of the knee joint traditionally are seen as mechanical and structural joint stabilizers, but an abundant body of evidence indicates that the ligaments also have a sensory (essentially proprioceptive) role (Sjölander et al. 1989). The presence of mechanoreceptors nocireceptors in the structures around the human knee joint has long been reported but underrecognized by surgeons (Delport et al. 2013b).

MCL injuries of the knee are very common sports-related injuries. The MCL is the most commonly injured knee ligament. Injuries to the MCL occur in almost all sports and in all age groups. Contact sports such as hockey, wrestling, rugby, football, and judo are responsible for most MCL injuries. Those injuries are tested in 30° of flexion which relaxes the posterior capsule and the cruciates are in their most relaxed state. With instability in extension, the posterior portion of the MCL, posterior oblique ligament, ACL, medial portion of posterior capsule, and possibly PCL are disrupted. The location of tears can be femoral if the ligament is avulsed from the medial epicondyle; sometimes this may elevate a small bony fragment with it. A mid-substance tear occurs when the ligament is torn at its midpoint. In that event, the defect becomes palpable and tenderness at the level of the medial joint line can be palpated. A tibial tear occurs when tenderness is felt 6–8 cm down the medial tibial shaft (along length of the ligament insertion).

Optimum healing of the medial collateral ligament occurs when the torn ends are in contact since healing potential is directly related to size of the gap between the torn ends. Maturation of the scar occurs from 6 weeks to up to 1 year. Injuries to the medial collateral ligament could not be demonstrated to benefit from surgical treatment (Saxon, Sandberg et al. 1987).

28.2.6.4 Pellegrini-Stieda Syndrome

Pellegrini-Stieda syndrome is a relatively infrequent phenomenon. It is commonly associated with sporting injuries. Pellegrini-Stieda syndrome is a condition in which a calcification occurs on the medial side of the knee. This calcium deposit develops at the attachment of the medial collateral ligament on the medial condyle. The cause of Pellegrini-Stieda syndrome is an injury to the attachment site of the medial collateral ligament at the medial condyle of the femur. This may occur after a direct trauma to the site, like a hit on the inside of the knee with a ball at high speed or after an overstretching (valgus) injury to the medial collateral ligament and joint capsule. A hematoma with inflammatory edema may be the result of tearing and shredding of fibers at their femoral attachment. These soft tissues degenerate with angiogenesis, and deposition of calcium salts may occur. The inflammation then subsides with partial or complete resorption of the calcium salts; in the chronic stage the non-resorbed calcification mass may become ossified and connected to the femoral condyle. The last is called Pellegrini-Stieda syndrome. The term "Pellegrini-Stieda" is only reserved for the few patients who are symptomatic.

Most of the patients with posttraumatic calcification of the proximal aspect of the MCL are asymptomatic. The use of aspirin or nonsteroidal anti-inflammatory preparations could be prescribed in the treatment of this condition. And if pain persists, infiltration of a corticosteroid agent to the tender medial collateral ligament attachment is useful. In some cases, patients undergo surgery with disappearance of the pain and recovery of full range of motion.

28.2.6.5 Lateral Collateral Ligament Injuries

LCL injuries result from a varus force across the knee. A contact injury, such as a direct blow to the medial side of the knee, or a noncontact injury, such as a hyperextension stress, may result in a varus force across the knee injuring the LCL. Symptoms of a lateral collateral ligament (LCL) sprain can vary from being very mild to a complete rupture of the ligament. Lateral ligament sprains are categorized into grade 1, grade 2, or grade 3 sprains depending on the extent of the injury.

Grade 1 lateral ligament sprain symptoms include tenderness over the ligament. Usually there will be little or no swelling. When the knee is bent to 30° and force applied to the inside of the knee which puts the ligament under stress, pain is felt but there is no joint laxity.

Grade 2 knee ligament injury symptoms consist of significant tenderness over the lateral ligament. Some swelling can be seen over the ligament. When the knee is stressed as for grade 1 symptoms, there is pain and some laxity in the joint, although there is a definite end point indicating the ligament is still intact.

Grade 3 lateral ligament sprain is a complete tear of the ligament. Pain can vary and may be actually less than a grade 2 sprain. When stressing the knee, there is significant joint laxity. The athlete may complain of having a very unstable knee. The ligament is most commonly injured in sports by a direct impact to the inner surface of the knee joint, such as by a rugby or a football tackle. A lateral ligament sprain is less common than those affecting the medial collateral ligament. The ligament is not connected to the lateral meniscus in the joint, and so unlike medial ligament injuries, they are not normally associated with meniscal tears. However, injury to the anterior cruciate or posterior cruciate ligaments can occur at the same time.

One can assess the extent of the damage by applying a force to the inner surface of the knee joint and comparing its laxity to the unaffected knee (varus knee test). In more serious cases, an MRI and/or radiograph may be necessary.

In grade 1 and 2 tears, conservative methods of treatment are usually preferred. In grade 3 sprains, particularly when other structures such as the ACL or PCL are damaged, surgery may be needed to prevent future instability. This may involve suturing or stitching the torn ends of the LCL or reconstructing the ligament with a part of a tendon, e.g., hamstrings tendon (Krukhaug et al. 1998).

28.2.7 Cartilage Problems/Osteoarthritis

28.2.7.1 Chondral and Osteochondral Injuries

An osteochondral injury is an injury to the smooth surface on the end of bones, called articular cartilage (chondro), and the bone (osteo) underneath it. The degree of injury ranges from a small crack to a piece of the bone breaking off at the subchondral bone with loose fragment in situ or displaced inside the joint. These fragments can be of many sizes and depths and can stay in situ and attached (stable) to the injured area or become loose (unstable) in situ or displaced inside the joint. This injury is more common in adolescents and young adults and typically occurs at the knee, ankle, or elbow.

Symptoms are pain with weight-bearing activities, swelling, instability of the joint, occasional catching and locking of the joint, tenderness over the injured area, and decreased motion.

Treatment is variable depending upon the size of the bone fragment, age of the patient, and activity level of the patient. It also depends on whether the bone fragment is attached to the area or bone that was injured or loose and displaced in the joint. Skeletally immature patients—patients with open growth plates at the knee—typically respond well to conservative treatment. This means decreasing the pain and inflammation through anti-inflammatory medication, ice, and modified activity followed by rehabilitation to improve strength, flexibility, and alignment. Operative treatment is needed if the fragment is unstable or loose in the joint. Surgery may be necessary to remove and repair the injured area. Operative treatment might also be necessary if patients do not respond well to conservative treatment. A period of immobilization might be necessary after surgery. Gradual strengthening *excercises for* the injured joint, sports, and activity-specific rehabilitation are the final phases to restore function.

28.2.7.2 Osteoarthritis

Osteoarthritis is a heterogeneous group of conditions that lead to joint symptoms and signs associated with defective articular cartilage and changes to the underlying bone and joint margins. Excessive participation in sports is believed to increase the risk of developing osteoarthritis. The development of osteoarthritis appears to depend on the amount, type, and intensity of sports participation (Vingard et al. 1993). There are a number of factors other than sporting activity itself that appear to influence the risk of sports-related osteoarthritis, such as certain physical characteristics of the participant (e.g., body weight), biomechanical factors (e.g., gait), biochemical factors (e.g., joint lubrication), age, gender, hormonal influences, nutrition, playing surfaces, features of particular sports, and duration and intensity of exercise participation (Saxon et al. 1999).

28.2.8 Knee Fractures

The knee is one of the most common parts of the body to be fractured. Sports, falls, and motor vehicle accidents account for the vast majority of injuries to the knee. The different types of injuries to the knee are defined by the affected anatomy of the knee and the mechanism by which it is injured. Knee fractures occur from direct blows to the bones. Patella, or kneecap, fractures occur when a person falls directly down onto the knees and the kneecap cracks due to the force. Collapse of the top of the tibia bone in the knee (tibia plateau fracture) can occur from sudden compression injury to the knee, especially in people with osteoporosis. Other fractures of the long bones (fibula, tibia, and femur) are rare with isolated injuries to the knee. Bone contusions and fractures at the knee are also related to indirect trauma; in these injuries of soft tissue, supportive structures with instability are related to a specific trauma mechanism, for example, compression fracture of the lateral femur condyle in pivot shift trauma with associated MCL, ACL, and medial meniscal tear also known as O'Donoghue's triad.

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Radiologic Imaging of Knee Injuries

29

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Abstract

Many advances have been made in knee imaging, particularly in the field of magnetic resonance imaging (MRI). Today, MRI of the knee is the most frequently requested MR examination of the musculoskeletal system. It is common practice to acquire an MRI after clinical examination and radiographs in the workup of suspected knee derangement. Frequently, it is the definitive examination, providing critical information regarding the decision to treat conservatively or surgically. These factors have led to the wide acceptance by the clinical community of MR knee studies as a noninvasive replacement for diagnostic arthroscopy.

In this chapter, the spectrum of imaging modalities that are commonly used in the knee will be described first. Second, the most common knee disorders will be discussed, emphasizing the role of MRI.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ACL	Anterior cruciate ligament
BME	Bone marrow edema
CR	Conventional radiography
CT	Computed tomography
DEFT	Driven equilibrium Fourier transform
DESS	Double echo steady state
DF	Distance factor
EFOVS	Extended field-of-view ultrasound
ETL	Echo-train length
FLASH	Fast low-angle shot
FOV	Field of view
FS	Fat suppression
GRE	Gradient-recalled echo
ITBS	Iliotibial band friction syndrome
IW	Intermediate-weighted
MCL	Medial collateral ligament
MPR	Multiplanar reformat
MRI	Magnetic resonance imaging
PAES	Popliteal artery entrapment syndrome
PAT	Parallel acquisition technique
PCL	Posterior cruciate ligament
PD-WI	Proton density-weighted imaging
PLC	Posterolateral complex
PS	Pellegrini-Stieda
SNR	Signal-to-noise ratio
SPACE	Sampling perfection with application-optimized contrasts using different flip-angle evolutions
SSFP	Steady-state free precession
ST	Slice thickness

T	Tesla
TA	Acquisition time
TE	Time to echo
TF	Turbo factor
TR	Repetition time
TSE	Turbo spin-echo
US	Ultrasound

29.1 Introduction

The knee is a common site for bone or soft tissue injury and overuse syndromes. With a variety of operative and nonoperative treatment options available, the detailed information provided by imaging studies may be extremely helpful for optimal treatment planning (Farjoodi 2010). Although conventional radiographs are the initial radiologic study in most suspected knee disorders, there is an increasing trend toward early primary care use of magnetic resonance imaging (MRI) for the diagnosis of knee injuries (Gupta et al. 2011). Because of its exquisite contrast resolution and ability simultaneously to display the osseous and soft tissue structures of the knee in virtually any plane, MRI plays a central role in the workup of a patient with suspected knee pathology (Milewski et al. 2011). Computed tomography (CT) is used most frequently to evaluate intra-articular fractures of the knee, for planning complex orthopedic procedures, and for postoperative knee evaluation (West et al. 2009). Also, combining CT with arthrography makes it a good alternative for the detection of internal knee derangements in patients with absolute contraindications for the use of MRI (Kalke et al. 2012). Ultrasound is largely limited to an evaluation of the extra-articular soft tissues of the knee, in particular overuse conditions of the extensor apparatus (Gupta et al. 2011). This chapter addresses the spectrum of imaging modalities that are commonly used in the knee and describes their specific advantages and limitations. The most common knee disorders will be discussed with emphasis on MRI diagnosis.

29.2 Imaging Modalities

29.2.1 Conventional Radiography

Conventional radiography (CR) is used in clinical practice to define the presence of fractures and to assess for degenerative joint disease. A standard CR series consists of an anteroposterior and lateral standing projection. A 30° or 45° flexed postero-anterior standing view of the knee is much more sensitive to detect early articular cartilage loss (Messieh et al. 1990). This view also allows accurate definition of the width of the intercondylar notch and is useful to demonstrate intercondylar osteophytes. In patients with anterior knee symptoms, a Merchant view, providing a "sunrise" projection of the patella articulating with the trochlea, can evaluate the patellofemoral joint space and its alignment. The main shortcoming of CR is its lack of soft tissue depiction. Controversy exists whether CR should be obtained routinely when MRI is being performed in young adults presenting with non-acute knee complaints (ter Braak et al. 2007).

29.2.2 Computed Tomography

With the advent of ever-increasing numbers of rows of detectors allowing for much more details, faster acquisition and less radiation, computed tomography (CT) retains an important place in knee imaging (West et al. 2009; Kalke et al. 2012). Modern multislice helical CT scan obtains thinly (submillimeter) collimated images quickly that can be reformatted into multiplanar 2D reconstructions (MPRs) or 3D volume-rendered images. It is mainly used for imaging of acute trauma and the assessment of complex bony injuries, such as fractures of the tibial plateau. Using CT with MPRs provides superior demonstration of the fractures compared with CR, allowing accurate preoperative planning (Fig. 29.1). Other indications for CT of the knee include assessment of complications after knee replacement surgery (loosening or periprosthetic fracture) (Fig. 29.2) and measurement of rotational alignment of the knee. The major indication for CT arthrography (CTA) is evaluating suspected internal knee derangement in patients who are unable to undergo MRI (Kalke et al. 2012). Besides offering merely an alternative, in some situations, CTA may be superior to MRI. Following partial meniscectomy of the knee, CTA has been shown to have a sensitivity of 93 % and specificity of 89 % for recurrent tears (De Filippo et al. 2009; Mutschler et al. 2003) (Fig. 29.3). Also, CTA has higher sensitivity than MRI for the detection of chondral lesions of the knee joint (Vande Berg et al. 2002) (Fig. 29.4). Disadvantages of CT include the use of ionizing radiation and its limited value for detection of associated ligamentous and/or soft tissue disorders.

29.2.3 Ultrasound

Ultrasound (US) is largely limited to an evaluation of the extra-articular soft tissues of the knee (Fig. 29.5). Due to the excellence of spatial resolution, US keeps its leading edge when dealing with muscle and tendon pathology around the knee (Peetrons 2002). The major indication for US in clinical practice is evaluating overuse conditions of the extensor apparatus or affirming a clinically suspected Baker's cyst. High-frequency (13.5 MHz) linear-array probes are used to perform US examinations of the knee. US palpation is a very valuable tool, trying to find the point of maximal tenderness or swelling (Peetrons 2002). Dynamic US study may be very helpful to assess a "snapping" sensation that is felt by the patient during knee movement. Major advantages of US are its low cost, wide availability, short examination times, and lack of radiation exposure. An addition of color power Doppler imaging to US has allowed for the noninvasive study of blood flow and vascularization within anatomic structures and lesions. Although initial studies (Weinberg et al. 1998) reported that increased tendon vascularization is typically correlated with clinical symptoms, more recent studies have reported the opposite (Tol et al. 2012). Furthermore, US provides image guidance for interventional procedures such as drainage of fluid collections and cysts. The trade-off for high-frequency, linear transducers is their small, static scan field. Extended field-of-view ultrasound (EFOVS) overcomes this disadvantage by generating a panoramic image (Fig. 29.6). With this technique, sequential registration of images along a broad examination region and their subsequent combination into an image of larger dimension and

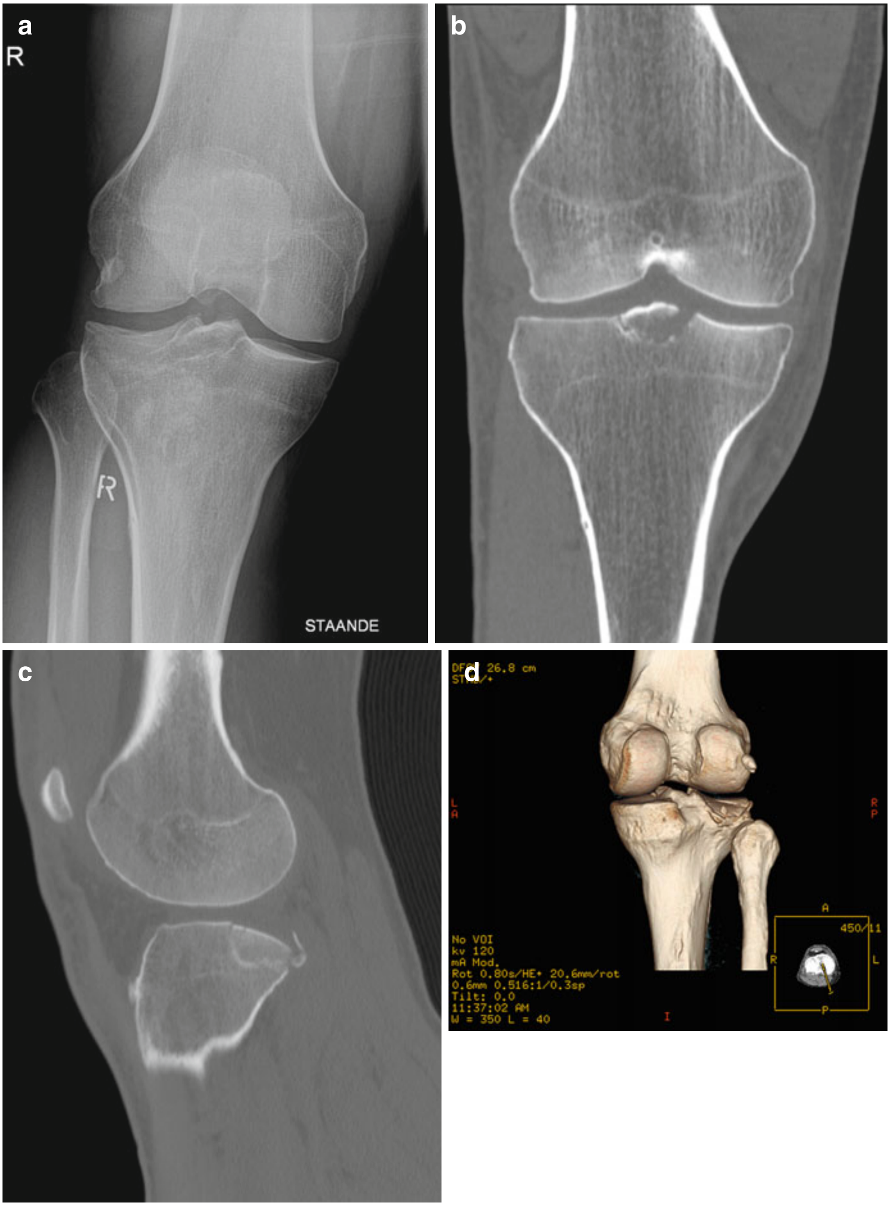

Fig. 29.1 Tibial plateau fracture. (**a**) AP radiograph, (**b**) coronal and (**c**) sagittal reformatted CT image, and (**d**) 3D reconstruction. The fracture lines at the eminentia tibia and posterolateral tibial plateau are clearly delineated by CT

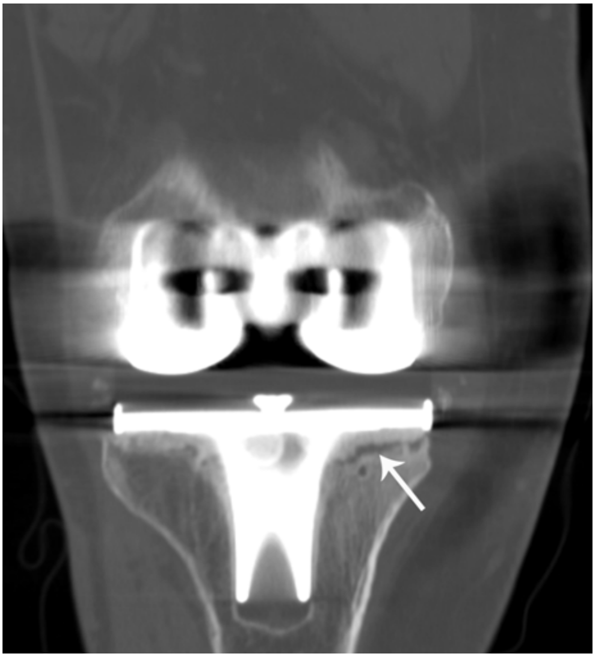

Fig. 29.2 Loosening TKP. Coronal reformatted CT image shows periprosthetic reduced bone density with translucency at the medial tibial plateau (*arrow*)

format is obtained (Weng et al. 1997). Disadvantages of US include operator dependency, selective and often incomprehensible documentation, and the inability to evaluate the articular structures of the knee joint.

29.2.4 Magnetic Resonance Imaging

The noninvasiveness of magnetic resonance imaging (MRI) combined with its relatively low cost has led to its acceptance by the orthopedic community, and MRI of the knee is the most frequently ordered MR examination of the musculoskeletal system (Farjoodi et al. 2010). Numerous diagnostic studies have compared MRI and arthroscopy of the knee, and most have shown good diagnostic performance of MRI in detecting internal derangements of the knee (Oei et al. 2003). MRI not only contributes to diagnosis but also serves as an important guide to treatment planning and prognostication (Milewski et al. 2011).

Diagnostic knee MRI can be performed using a variety of magnet designs (closed bore, whole body, open whole body, dedicated extremity). Also, a variety of magnetic field strengths can be used but the current standard for clinical knee imaging is 1.5 tesla (T). The patient is positioned supine with the affected knee completely or near completely extended. A local coil is positioned to provide adequate anatomic coverage. Typically, an extremity knee coil that completely surrounds the knee is used to ensure maximal and uniform signal-to-noise ratio (SNR) across the entire image.

Fig. 29.3 Recurrent tear after medial partial meniscectomy. Coronal reformatted CT arthrography image shows contrast leakage in medial meniscal residue (*arrow*)

A complete MR exam of the knee requires that images be obtained in the axial, sagittal, and coronal planes. Although techniques for knee MRI vary widely, a typical imaging protocol uses a field of view (FOV) of 160 mm or smaller, a slice thickness in the sagittal and coronal plane of 3 mm or less, and an imaging matrix with at least 140 steps in the phase direction and 256 steps in the frequency direction for 2D imaging (Tuite et al. 2012). The use of a contrast agent (e.g., DOTAREM®) is only indicated when dealing with a tumoral or tumorlike mass, in cases of knee inflammation, or as part of arthrography (performed only for postoperative knee imaging when conventional MRI reveals equivocal findings).

Knee MRI can be performed with a wide variety of pulse sequences. Most commonly, the proton-density (PD) and T2-weighted 2D turbo spin-echo (TSE) sequence and the T1-weighted 3D gradient-recalled (GRE) sequence are used for routine imaging of the knee (Recht et al. 2005; Kijowski 2010; Trattnig et al. 2009).

TSE sequences are advantageous in daily clinical practice because they allow assessment of the menisci, ligaments, and bony structures in addition to the articular cartilage, in a relatively short time (Recht et al. 2005). Fat suppression (FS) TSE images are most sensitive to bone marrow and soft tissue edema or joint effusion.

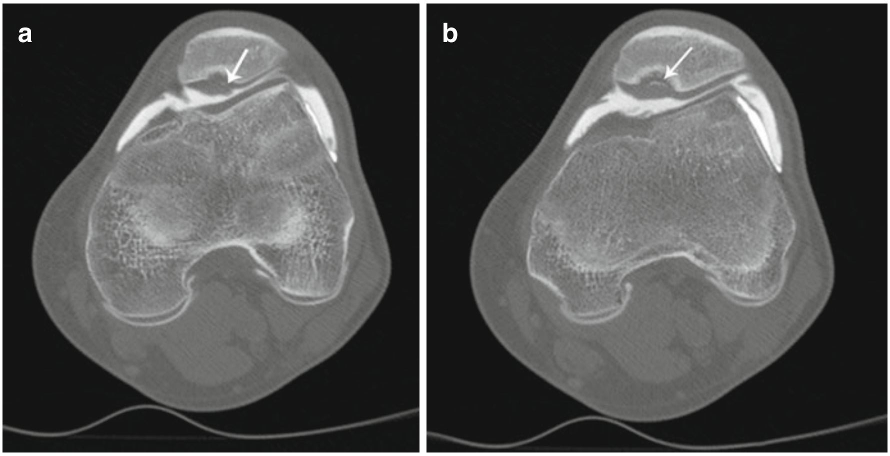

Fig. 29.4 Osteochondritis dissecans (OCD) of the patella. (**a**, **b**) Axial-reformatted CT arthrography images show OCD lesion at the patella. Cartilage fissure with contrast leakage at the base of the OCD lesion is seen (*arrow*)

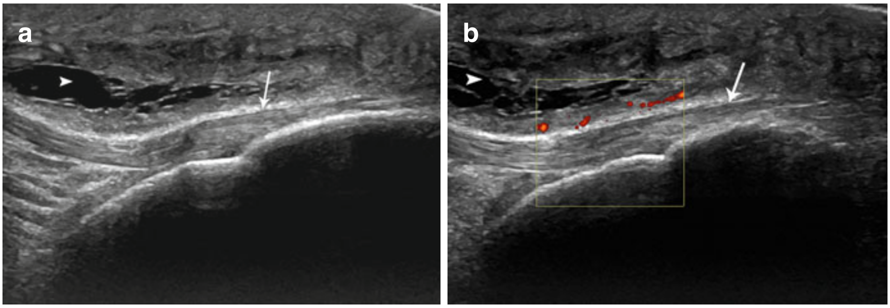

Fig. 29.5 Superficial infrapatellar bursitis. Longitudinal grayscale (**a**) and color Doppler (**b**) US images of infrapatellar region demonstrate thickening of prepatellar soft tissues with increased vascularity and distended infrapatellar bursa (*arrowhead*). The patellar tendon is normal (*arrow*)

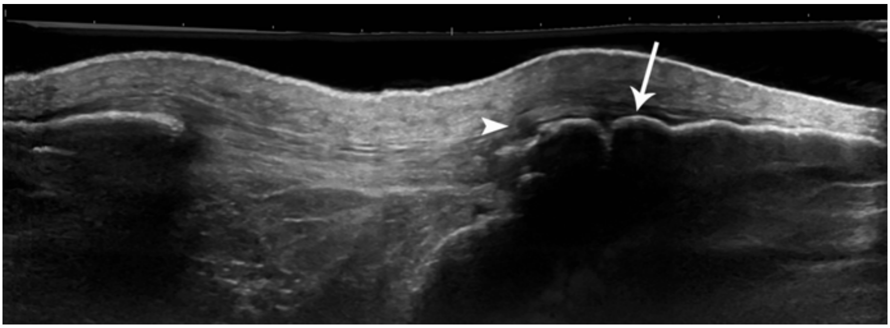

Fig. 29.6 Longitudinal extended field-of-view US image of the infrapatellar region reveals thickening of distal patellar tendon and adjacent soft tissues (*arrowhead*). Note bony hypertrophy at the tibial tuberosity (*arrow*) in keeping with chronic Osgood-Schlatter disease

Different FS techniques are available (spectral FS, Dixon method, inversion recovery technique), but in our institution, we prefer the spectral FS technique because of its better SNR and spatial resolution compared to the other FS techniques (Fleckenstein et al. 1991). Also, for good detection of fluid with preservation of anatomic detail and good differentiation between joint fluid and articular cartilage, we include an FS TSE intermediate-weighted sequence (TR/TE = 3,500/30–35 ms) in at least one imaging plane in our routine knee MR protocol (Fig. 29.7). Although 2D TSE acquisitions provide excellent tissue contrast and high in-plane spatial resolution, they may suffer from partial volume averaging artifacts because they use relatively thick slices with small gaps between the slices, possibly obscuring pathology (Hargreaves et al. 2003; Link et al. 2007). To overcome this disadvantage, 3D TSE sequences with isotropic resolution have recently been developed and are now commercially available on many MR vendor platforms. These sequences include 3D fast spin-echo (FSE) cube (GE Healthcare), 3D Fourier transform (FT, Philips Medical Systems), and sampling perfection with application-optimized contrasts using different flip-angle evolutions (SPACE, Siemens Medical Systems) (Kijowski and Gold 2011; Gold et al. 2007; Notohamiprodjo et al. 2009; Ristow et al. 2009). The advantage of these new 3D TSE acquisitions is their capability of mimicking the contrast properties of conventional 2D TSE PD-weighted acquisitions (Gold et al. 2007). In addition, high quality MPR images may be created in any orientation from the volumetric source data (Fig. 29.8). Although the first clinical results on the diagnostic performance of 3D isotropic resolution TSE sequences were encouraging, it remains uncertain whether a single 3D TSE acquisition has potential for replacing the multiple conventional 2D

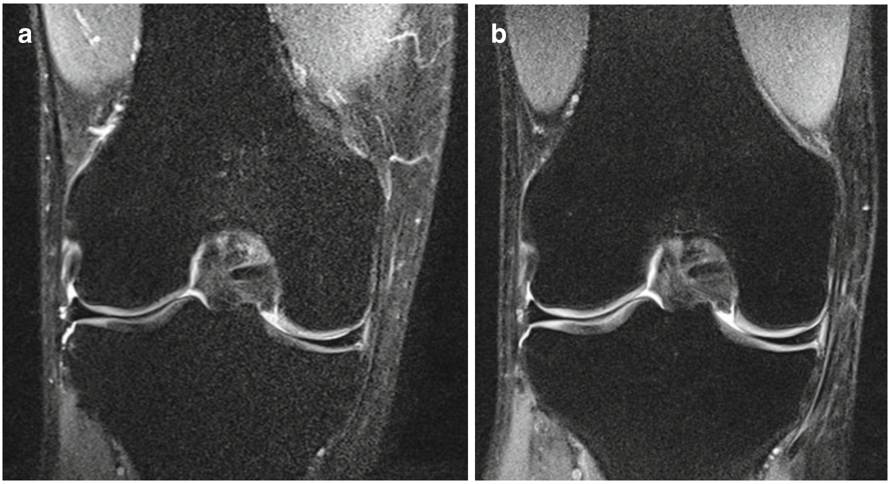

Fig. 29.7 Coronal fat-suppressed intermediate-weighted MR images obtained at 1.5 T (**a**) and 3 T (**b**). Better delineation of articular cartilage (intermediate signal intensity) from joint fluid (high signal intensity) is seen at 3 T compared to 1.5 T

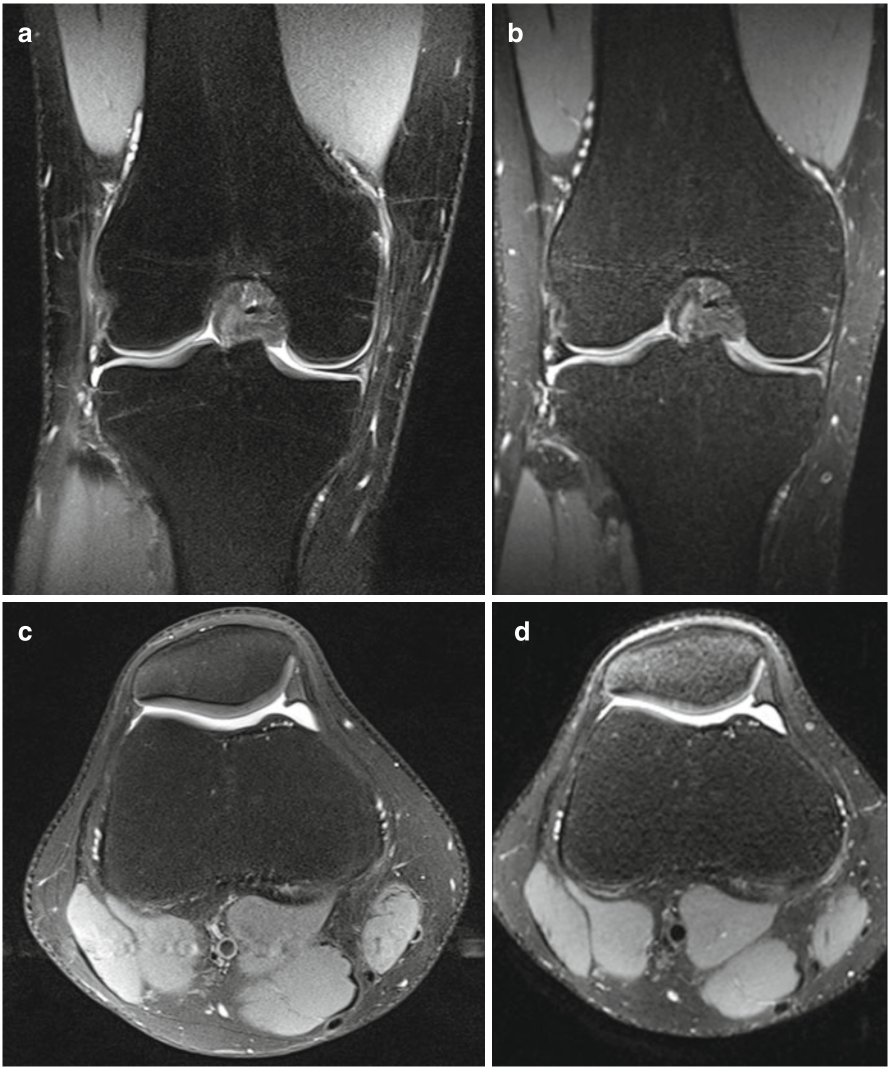

Fig. 29.8 Conventional 2D versus isotropic 3D fat-suppressed intermediate-weighted turbo spin-echo (TSE) images of the knee at 3 T. Conventional 2D TSE images in the coronal (**a**) and axial (**c**) plane with corresponding 3D TSE SPACE images (**b**, **d**). Note similar contrast properties of bone, cartilage, menisci, and ligaments with both 2D and 3D TSE imaging

acquisitions currently used (Notohamiprodjo et al. 2009; Jung et al. 2009; Kijowski et al. 2009, 2012b; Subhas et al. 2011; Van Dyck et al. 2012b).

Thin-partitioned, 3D gradient-recalled echo (GRE) sequences, either using selective FS (FS 3D SPGR) or selective water excitation (WE) (WE 3D FLASH; WE 3D DESS), also have been used to assess the knee. These sequences provide higher spatial and contrast resolution but require longer acquisition times (7–10 min) and are more vulnerable to magnetic susceptibility and metallic artifacts. Moreover, GRE images can be used for evaluating the articular cartilage of the knee joint but the menisci, ligaments, and bone marrow are only poorly visualized with this sequence (Kijowski and Gold 2011).

MRI has the disadvantage of not always being accepted well by patients, of being incompatible with dynamic maneuvers, and of not always being possible in emergency conditions. Also, specific MRI safety measures and contraindications for the use of MRI (e.g., claustrophobia, filters, stents, clips, cardiac pacemakers, etc.) must be considered.

29.3 Specific Disorders

29.3.1 Meniscus

The suspicion of a tear of the knee meniscus constitutes one of the leading indications for MRI examination of this articulation. Although arthroscopy is still considered the most reliable standard in the assessment of meniscal tears, MRI has emerged as the most important modality in the noninvasive evaluation of the knee meniscus and has proved useful as a screening procedure to avoid diagnostic arthroscopy (Milewski et al. 2011).

Normal menisci demonstrate low signal intensity on MRI because of their fibrocartilage composition. They are triangular in cross section. MR criteria used for diagnosis of meniscal tear include one or more of the following: (1) abnormal meniscal signal touching an articular surface, (2) missing meniscal tissue, and (3) displaced meniscal fragment. Because abnormal meniscal morphology (with or without displaced meniscal fragment) is less frequent, MR diagnosis of a meniscal tear usually comes down to “grading” the abnormal meniscal signal, as proposed by Lotysch et al. (1986):

Grade 0, overall low signal intensity, normal; grade I, intrasubstance globular-appearing signal not extending to an articular surface; grade II, linear increased signal not extending to an articular surface; grade III, abnormal signal extending to an articular surface. Grades I and II represent intrasubstance degeneration in an adult or prominent vascularity in a child – not a tear – and are not clinically relevant. Only an unequivocal grade III signal that is seen on 2 or more images represents an arthroscopically evident tear (Fig. 29.9). This observation has been referred to as the “two-slice-touch rule” (De Smet 2012).

Meniscal tear types most commonly seen on MRI include horizontal, vertical, radial, bucket handle, flap, and complex tears (Fox 2007). Extrusion of joint fluid

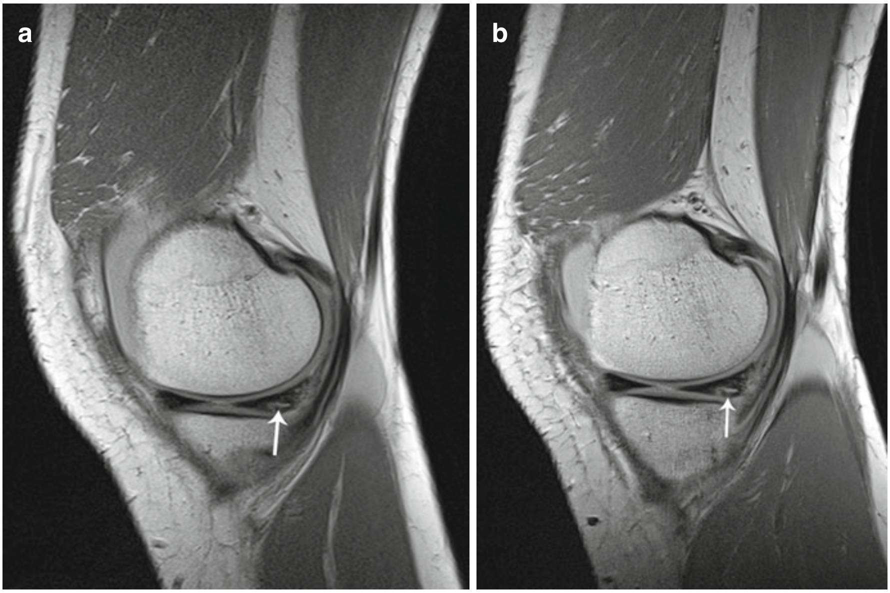

Fig. 29.9 Posterior horn medial meniscal tear. Sagittal proton density-weighted images of the knee obtained at 1.5 T (**a**) and 3.0 T (**b**) show surfacing hyperintense grade III signal in the posterior horn of the medial meniscus (*arrow*). Despite improved image quality at 3 T, the tear is clearly identifiable at both field strengths. Posterior horn medial meniscal tear was confirmed by arthroscopy

through a meniscal tear may give rise to a fluid collection in the parameniscal soft tissues, called a *meniscal cyst*. Meniscal cysts are frequently located adjacent to the posterior horn of the medial meniscus (Campbell et al. 2001).

A *discoid meniscus* is a large, congenitally dysplastic meniscus that has lost its normal shape and has a broad disklike configuration. Lateral discoid menisci are more common than medial discoid menisci. They are susceptible to tears and cysts (Yoo et al. 2012).

PD-weighted TSE sequences are used most frequently to examine the menisci. Although several authors have advised against the use of TSE sequences for the menisci because of image blur, more recent studies have indicated that properly optimized TSE imaging compares favorably with conventional SE imaging for this purpose (Ramnath et al. 2006).

The evaluation of menisci with MRI is a highly accurate endeavor with sensitivities ranging between 80 and 100 %, specificities ranging between 72 and 100 %, and accuracies ranging between 75 and 96 % (Oei et al. 2003). Sensitivity for diagnosing lateral meniscal tears is still lower than for the diagnosis of medial meniscal tears, particularly on the posterior horn of the lateral meniscus in cases with a background of anterior cruciate ligament (ACL) injury (Savoye et al. 2011). A meta-analysis of articles published between 1991 and 2000, including studies performed with magnets operating in a range from 0.1- to 1.5-T, revealed that diagnostic performance for meniscal tears is only modestly improved with increased magnetic field strength (Oei et al. 2003). One could suppose that with 3-T MRI, the confidence and accuracy of detecting meniscal tears will continue to increase (Gold et al. 2004; Ramnath 2006; Magee 2007; Krampla et al. 2009). Although initial reports on the detection of meniscal tears with 3-T MRI showed that 3-T imaging has a sensitivity and specificity greater than previously reported results at 1.5- T or less field strength (Magee and Williams 2006), further studies are required to determine the true impact of 3-T in evaluating the meniscus of the knee (Fig. 29.9).

29.3.2 Cruciate Ligaments

MRI is most frequently chosen to confirm the diagnosis of ACL injury and to document the extent of associated injuries.

On MRI, the normal ACL can be followed as a continuous band of low signal intensity from the femoral to the tibial attachment on the sagittal, coronal, and axial images. Oblique imaging planes may be useful to accurately depict the normal double-bundle anatomy of the ACL (Steckel et al. 2006). Tears of the ACL are primarily diagnosed on MRI on the basis of the presence of abnormalities seen in the ligament itself. Replacement of the ACL by an edematous mass with nonvisualization of its fibers and a wavy contour of the ligament is considered a sign of a complete tear. Also, if there is ligament retraction and no identifiable central ligament present, the tear is designated as complete. Hyperintense signal within the ACL substance, distortion of fibers without obvious complete discontinuity, and attenuation and/or abnormal orientation of the ACL with respect to the roof of the intercondylar notch (Blumensaat's line) are all considered MR signs of a partial ACL tear (Moore 2002). If fiber disruption can clearly be detected in the anteromedial or posterolateral bundle of the ACL, an isolated bundle tear is reported (Van Dyck et al. 2012a). Diffuse ACL thickening with a fluidlike signal separating the longitudinally oriented fiber bundles ("celery stalk appearance") is typical of mucoid degeneration of the ACL and should not be reported on MRI as a partial tear (Bergin et al. 2004). Secondary MR signs of ACL injury, including lateral bone bruise, anterior translation of the tibia with respect to the distal femur, uncovering of the posterior horn of the lateral meniscus, and an increased buckling of the posterior cruciate ligament (PCL), if present, are helpful signs in the diagnosis of an ACL tear (Van Dyck et al. 2012c).

Many investigators demonstrated success with MRI in the diagnosis of ACL tears, reporting sensitivities between 92 and 100 %, specificities between 85 and 100 %, and accuracies between 89 and 100 % (Moore 2002). Only few MR studies have considered complete and partial ACL tears separately, and in these studies, MRI has not been shown to be accurate in the differentiation of complete from partial ACL tears, nor were they successful in the identification of partial ACL tears (Defranco and Bach 2009; Steckel et al. 2006). For partial ACL tears, a sensitivity range of 40–75 % and specificity range of 62–89 % have been published (Umans et al. 1995). According to the meta-analysis performed by Oei et al. (2003), higher magnetic field strength significantly improves the diagnostic performance of MRI in the detection of ACL tears. Although initial reports on the detection of partial tears with 3-T MRI showed that 3-T imaging has a sensitivity comparing favorably with previously published results at 1.5-T or less field strength (Van Dyck et al. 2011), further studies are required to determine the true impact of 3-T in evaluating the ACL (Fig. 29.10).

Injury to the PCL is not as common as injury to the ACL. The PCL is often injured in conjunction with the ACL and, in particular, the lateral collateral ligament and the posterolateral corner (Cummings and Pedowitz 2005). This combination can lead to early osteoarthritis and failure of PCL reconstruction if the associated injuries are not addressed properly (Covey 2001). Because not all PCL injuries are apparent on clinical examination, even under general anesthesia, and the PCL may be difficult to identify at arthroscopy in the presence of an intact ACL, MRI plays an important role in the assessment of these lesions (Grover et al. 1990). The normal PCL has homogeneous low signal intensity on MRI and is typically about twice the thickness of the ACL. Intrasubstance or discrete tears of the PCL are identified commonly due to the tight synovial sheath within which the ligament is invested (Grover et al. 1990). The PCL is often injured as a result of a direct trauma to the anterior aspect of the tibia with the knee in flexion ("dashboard trauma"), and this may result in a bone contusion of the anterior aspect of the proximal part of the tibia. Therefore, the presence on MRI of such a bone contusion in the anterior tibia should prompt a detailed search for associated lesions of the PCL and posterior capsule of the knee (Fig. 29.11) (Cummings and Pedowitz 2005).

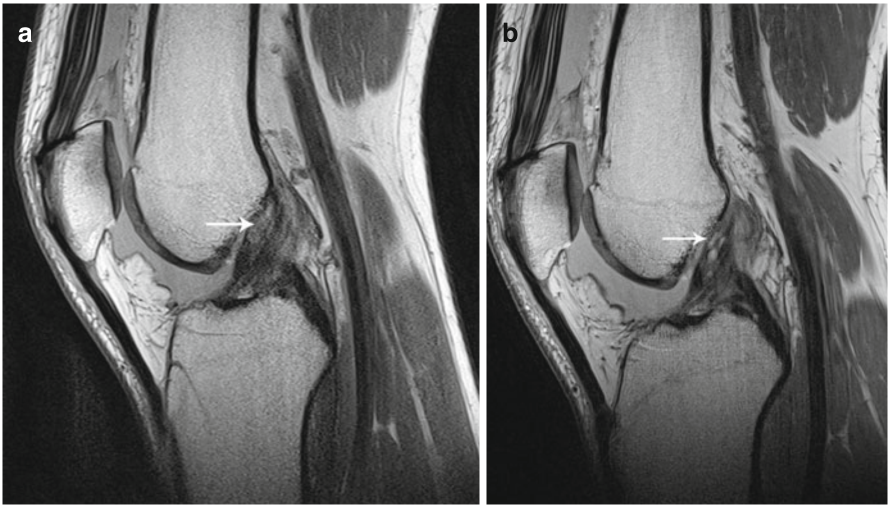

Fig. 29.10 Partial ACL tear. Sagittal proton density-weighted images of the knee obtained at 1.5 T (**a**) and 3 T (**b**) show hyperintense signal abnormality and cyst formation at the ACL origin (*arrow*) in keeping with partial ACL tear. Improved image quality is seen at 3 T. Partial ACL tear was confirmed by arthroscopy

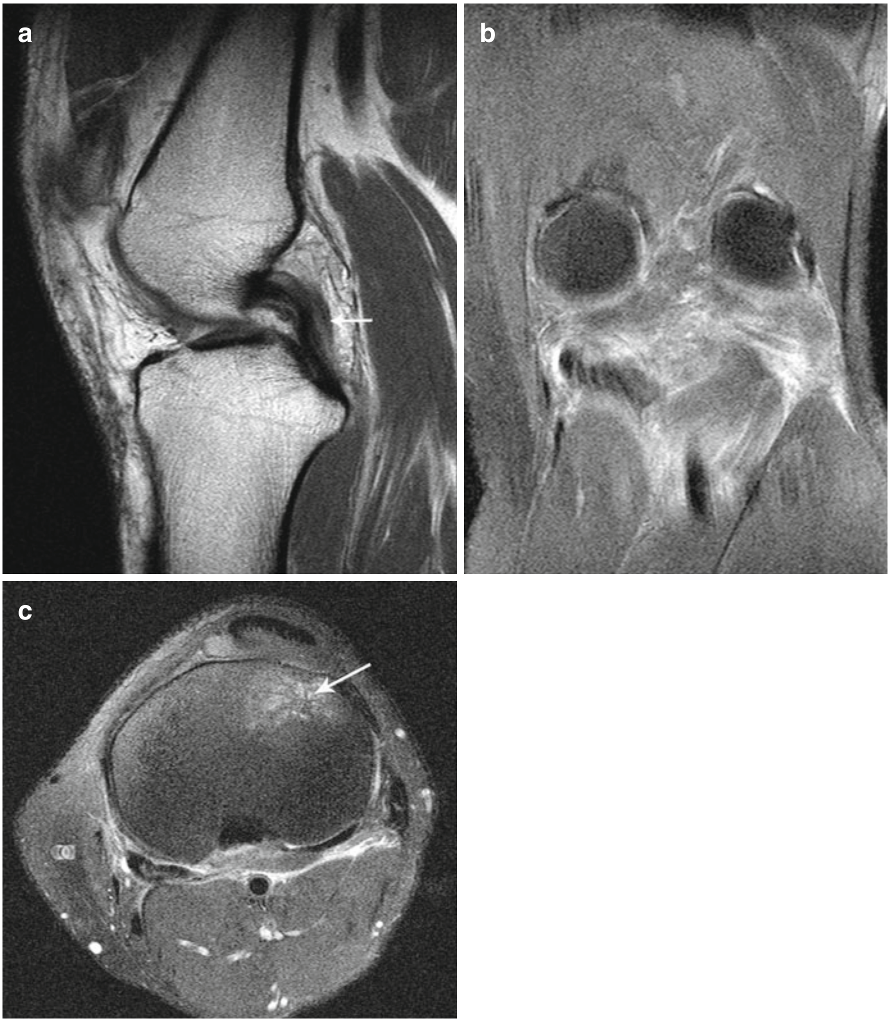

Fig. 29.11 Dashboard trauma of the knee. Sagittal proton density-weighted image (**a**) shows hyperintense signal in posterior cruciate ligament due to mild sprain (*arrow*). Coronal (**b**) and axial (**c**) fat-suppressed intermediate-weighted images show extensive edema in the posterolateral soft tissues in keeping with capsular sprain. Also note bone contusion at the anterior aspect of the tibia in (**c**) (*arrow*)

29.3.3 Articular Cartilage and Bone

Accurate assessment of the articular cartilage of the knee in patients undergoing MRI is clinically important (Milewski et al. 2011). The appearance of cartilage lesions on MRI depends on whether they are degenerative or posttraumatic in cause (Recht et al. 2005; Kijowski 2010). Early degenerative cartilage lesions appear as fibrillation or fissuring of the articular surface. As the degeneration process progresses, partial- and full-thickness cartilage defects with obtuse margins may develop. In patients with advanced osteoarthritis, cartilage lesions are typically associated with subchondral bone marrow edema (BME), presenting as ill-defined areas of high signal intensity on T2-weighted images. The presence of these subchondral bone marrow changes has been correlated with pain (Felson et al. 2001). Traumatic cartilage lesions tend to have more acutely angulated margins that may also involve the underlying subchondral bone. Cartilage flap tears or delamination injuries at the junction between the cartilage and subchondral bone may occur due to shearing forces (Recht et al. 2005). Posttraumatic BME ("contusions or bruises") results from impaction or traction forces acting on the joint. Impaction injuries, whether resulting from direct or indirect trauma, typically appear on MRI as areas of extensive BME. The traction or avulsion BME pattern is less extensive. Moreover, the avulsed bone fragment may be very difficult to detect on MRI. In most instances, a small avulsion is far better demonstrated on CR or CT. Chronic repetitive stress injuries about the knee typically involve the tibia. MRI has become the imaging modality of choice not only for diagnosing these lesions but also to grade the severity of the stress injury, thereby assisting in the clinical management of the patient (Kijowski et al. 2012a).

The most common sequences used in clinical practice to evaluate the articular cartilage of the knee joint are 2D TSE sequences with PD/T2-weighted or intermediate-weighted contrast (Recht et al. 2005; Kijowski 2010; Roemer et al. 2011). Various 3D imaging sequences also have been used to evaluate the articular cartilage of the knee joint (Hargreaves et al. 2003; Kijowski and Gold 2011). These 3D sequences can be broadly divided into dark-fluid (e.g., spoiled gradient-recalled echo [SPGR], fast low-angle shot [FLASH]) and bright-fluid (e.g., dual echo in the steady state [DESS], driven equilibrium Fourier transform [DEFT]) sequences on the basis of the signal intensity of the synovial fluid (Fig. 29.12). Balanced steady-state free precession (SSFP) sequences are additional 3D sequences that have been used to evaluate the knee cartilage. Balanced SSFP sequences have higher cartilage SNR and greater contrast between cartilage and adjacent joint structures than 2D TSE sequences (Kijowski 2010).

Multiple studies have evaluated the accuracy of MRI for detecting articular cartilage defects in the knee joint. The results of these studies vary over a wide range and are difficult to compare because of differences in MR hardware, imaging parameters, patient populations, and reader experience (Figueroa et al. 2007). Therefore, there is no consensus on the single best MR sequence for evaluating knee cartilage. Recently, Kijowski et al. (2011) have shown that the of use of time-consuming 3D sequences along with 2D TSE sequences to evaluate the articular cartilage of the knee joint is clinically advantageous, and the improvement in performance justifies the increase in MR examination time required to carry them out. With the arrival of 3-T MRI, the potential exists to achieve greater spatial resolution and higher SNR within a reasonable scan time. By using optimized protocols, 3-T systems can create images with greater contrast-to-noise ratios (CNR) between articular cartilage and adjacent joint structures (Gold et al. 2004; Ramnath 2006; Magee 2007). Previous animal studies have shown

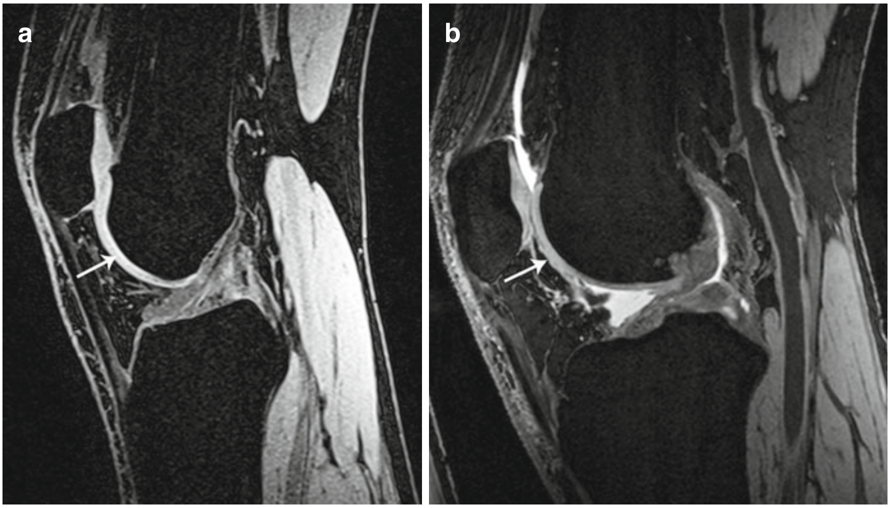

Fig. 29.12 Cartilage-specific MR imaging sequences. Sagittal 3D SPGR (**a**) and DESS (**b**) images of the knee. Both "dark" (**a**) and "bright" (**b**) fluid 3D sequences clearly demonstrate hyaline cartilage of the knee (*arrow*)

improved diagnostic performance of 3-T as compared with 1.5-T systems in the detection of cartilage lesions within the knee (Link et al. 2006; Masi et al. 2005). Future clinical studies providing a direct comparison of 1.5-T and 3-T MRI of the knee obtained in the same individuals with arthroscopic correlation are required to determine the true impact of 3-T in evaluating the articular cartilage of the knee (Fig. 29.13).

29.3.4 Collateral Ligaments

MRI is commonly used to assess the involved structures in patients with injuries to the medial side of the knee (Wijdicks et al. 2010). As compared to clinical examination, Yao et al. (1994) found an accuracy of MRI of 87 % for the assessment of medial collateral ligament (MCL) injuries. Also, Rasenberg et al. (1995) found a very high degree of agreement between the results in grading acute MCL injuries with MRI and an instrumented valgus-varus laxity tester. Moreover, MRI can depict important, clinically undetected, additional lesions which can determine the treatment of the MCL injury. The superficial MCL has been reported to have an abundant vascular supply (Wijdicks et al. 2010). A chronically healed MCL is referred to as "Pellegrini-Stieda (PS)" disease (Fig. 29.14). According to Mendes et al. (2006), ossification in PS disease is not confined to the MCL but may also involve the adductor magnus tendon. In some cases, it can be related to the anatomic proximity of these two structures. PS disease should therefore not be regarded as synonymous with ossification of the MCL.

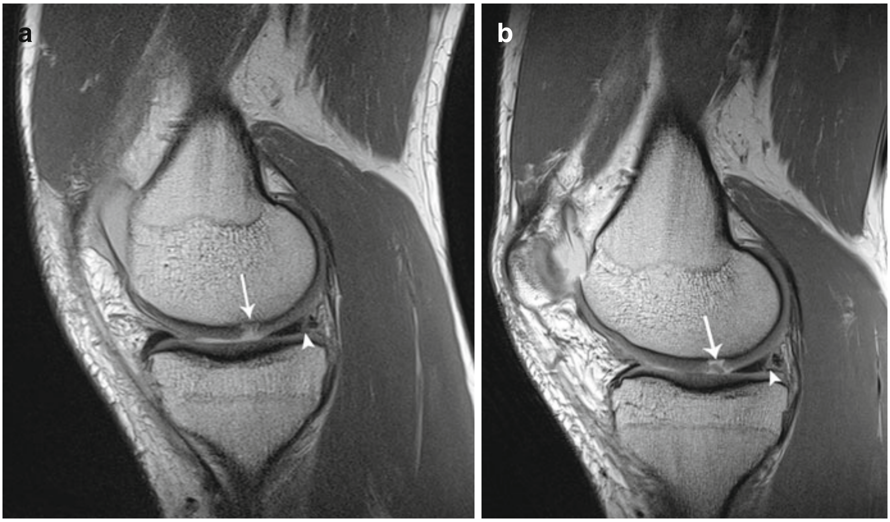

Fig. 29.13 Traumatic cartilage defect at the medial femoral condyle. Sagittal proton density-weighted images of the knee obtained at 1.5 T (**a**) and 3 T (**b**) show full-thickness cartilage defect with acutely angulated margins at the medial femoral condyle (*arrow*). Due to improved image quality at 3 T, the lesion is better delineated on 3-T image. Also note tear in the posterior horn of the medial meniscus (*arrowhead*). Both lesions were confirmed by arthroscopy

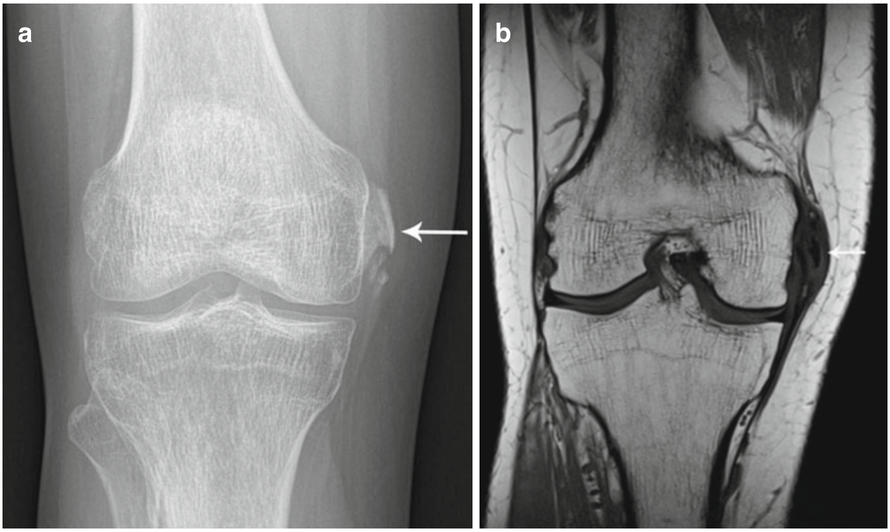

Fig. 29.14 Pellegrini-Stieda lesion. (**a**) AP radiograph shows ossification at the medial femoral condyle (*arrow*). (**b**) Coronal T1-weighted image of the knee shows thickening and ossification at the level of the medial femoral condyle (*arrow*)

The posterolateral corner (PLC) is a complex functional unit, consisting of several structures, which is responsible for posterolateral stabilization. It includes the popliteal tendon, the lateral collateral ligament, the biceps femoris, the popliteofibular ligament, and the posterolateral capsule, which is reinforced by the arcuate ligament and the fabellofibular ligament. Injuries of the PLC are infrequent but can cause severe disability due to both instability and articular cartilage degeneration. PLC lesions are typically associated with injuries of the cruciate ligaments, menisci, bone, and soft tissue (Covey 2001; Cummings and Pedowitz 2005). CR of a knee with posterolateral injury is usually normal but, occasionally, may show abnormal widening of the lateral joint space, an arcuate fracture of the fibular head, avulsion of Gerdy's tubercle off of the tibia, or a Segond fracture. Patients with chronic posterolateral instability may have radiographic changes consistent with arthritis of the medial or lateral compartment or with patellofemoral arthritis (Covey 2001). MRI potentially demonstrates the entire spectrum of PLC injuries and associated lesions of the knee (Bolog and Hodler 2007). However, it has been our experience that detailed anatomic interpretation of MRI may be difficult when a large amount of edema or blood from the injury is present in the posterolateral soft tissues (Fig. 29.11).

29.3.5 Extensor Mechanism and Patellofemoral Joint

Chronic overuse syndromes are the most likely cause of *injury to the extensor apparatus* of the knee. In patients with tendinopathy, US may demonstrate hypoechogenicity with loss of normal fibrillar pattern of the involved tendon, presence of tendon thickening, and neovascularization on color power Doppler imaging. In patients with suspected extensor tendon tear, US can assess the degree of tendon disruption and amount of retraction. Dynamic scanning with the knee flexed can help differentiate a partial tear from a non-retracted complete tear (Bianchi et al. 1994).

Sinding-Larsen-Johansson (fragmentation of inferior pole of patella) and *Osgood-Schlatter disease* (fragmentation around tibial tuberosity) (Fig. 29.6) represent chronic activity-related traction injuries in skeletally immature patients. Soft tissue changes associated with these abnormalities, such as focal tendinopathy and bursa formation, are easily demonstrated with US (Gupta et al. 2011).

Patellar dislocation is frequently not considered clinically before MRI is performed, and this is the diagnosis most frequently confused with acute ACL injury by referring physicians. MRI best demonstrates the characteristic findings seen in acute patellar dislocation, including bone bruises at the lateral femoral condyle and medial patella (with or without associated osteochondral injury), medial patellofemoral ligament injury, and hemarthrosis (Lance et al. 1993) (Fig. 29.15).

The *mediopatellar plica* originates from the medial wall of the knee joint, runs obliquely downward, and inserts into the synovium covering the infrapatellar fat pad. If it is large, its free border can extend over the medial face of the trochlea or under the medial facet of the patella. Thickening (>2 mm) and contour irregularity

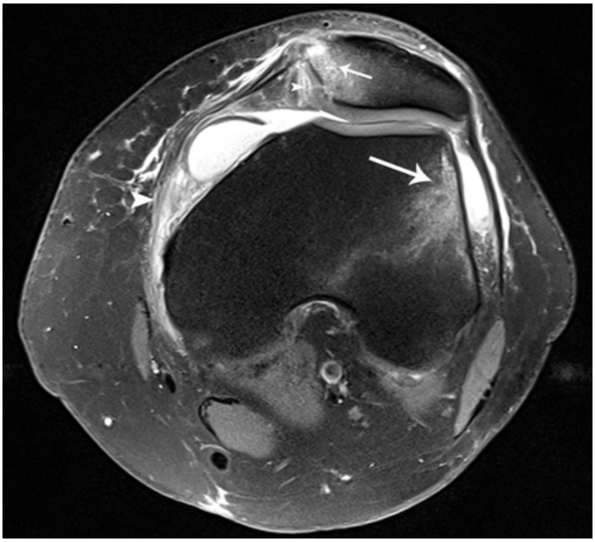

Fig. 29.15 Transient patellar dislocation. Axial fat-suppressed intermediate-weighted MR image of the knee shows bone contusions at the anterior aspect of the lateral femoral condyle (*large arrow*) and at the medial patella (*small arrow*). Note cartilage lesion at the medial patella facet (*small arrowhead*) and tear of the medial patellofemoral ligament (*large arrowhead*)

are the primary MR characteristics that suggest plica impingement (Boles and Martin 2001) (Fig. 29.16).

Traumatic lesions of *Hoffa's fat pad* most commonly follow arthroscopy (Fig. 29.17), but intrinsic signal abnormalities can also be due to posterior and superior impingement syndromes and following patellar dislocation. MRI is the single best modality to confirm the diagnosis (Saddik et al. 2004). In the acute phase, high signal intensity on T2-weighted images is seen due to the presence of edema and hemorrhage. In chronic phases, presence of fibrosis produces low signal intensity on MRI. According to Abreu et al. (2008), abnormalities of Hoffa's fat pad, such as focal and diffuse edema, tears, scars, and synovial proliferation, are more common in knees with torn ACLs. Hoffa's fat pad also contains residual synovial tissue, meaning that primary neoplastic conditions of synovium may originate and be confined to the fat pad.

29.3.6 Miscellaneous

Popliteal artery entrapment syndrome (PAES) is a congenital anomaly of muscle or tendon insertion in relation to the popliteal artery that causes functional occlusion of the artery. The most widely accepted classification divides PAES into six types, according to the gastrocnemius medial head anatomical variation (Kim et al. 2006):

Type 1: aberrant medial arterial course around normal medial head of gastrocnemius
Type 2: abnormal head of gastrocnemius which is laterally inserted on distal femur with medial displacement of popliteal artery
Type 3: aberrant accessory slip from medial head of the gastrocnemius wraps around the normally positioned popliteal artery and entraps it
Type 4: popliteal artery located deep in popliteus muscle or beneath fibrous bands in popliteal fossa
Type 5: any form of entrapment that involves popliteal artery and vein
Type 6: functional type, normally positioned popliteal artery which is entrapped by normally positioned gastrocnemius with hypertrophy

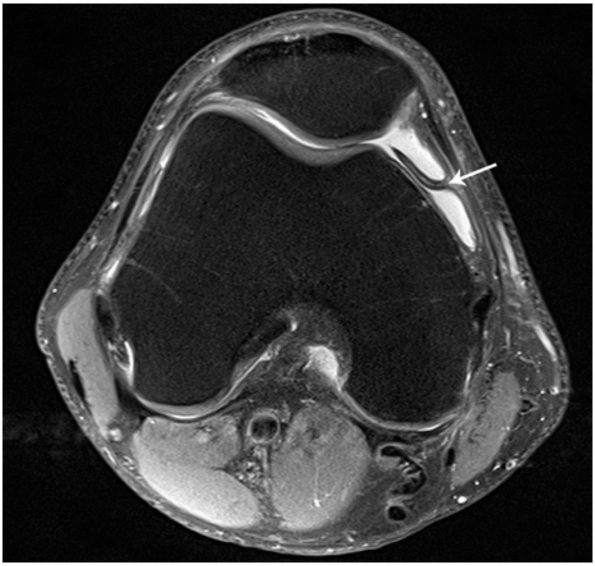

Fig. 29.16 Mediopatellar plica. Axial fat-suppressed intermediate-weighted MR image of the knee demonstrates synovial fold located between the medial articular facet of the patella and the trochlea (*arrow*)

MRI provides detailed information including classification of PAES, combined anomaly of the gastrocnemius muscle and the relationship of the artery to adjacent structures.

Iliotibial band friction syndrome (ITBS) is an overuse syndrome that presents as lateral distal thigh or lateral knee pain. It frequently occurs in long-distance runners and cyclists. MRI is the imaging modality of choice because it not only assesses the extra-articular soft tissues but also the lateral knee joint structures. In the case of ITBS, MRI typically shows ill-defined areas of high signal intensity on T2-weighted

Fig. 29.17 Diffuse arthrofibrosis. Sagittal proton density-weighted image of the knee shows diffuse fibrosis in the notch and Hoffa's fat pad after ACL reconstruction

images deep to the ITB (Fig. 29.18). Occasionally, formation of a small fluid collection may be seen between the ITB and lateral femoral condyle, which is believed to represent an adventitial bursa (Muhle et al. 1999).

The *pes anserine complex* is the term used to describe the tendons and bursa of the sartorius, gracilis, and semitendinosus muscles as they cross the distal aspect of the MCL (Fig. 29.19). Pes anserine syndrome is a combination of pes anserine bursitis and tendinopathy and is typically seen in long-distance runners or patients with osteoarthritis. MR or US may show a fluid-filled bursa that can be loculated or septated. The prevalence of fluid in this bursa in asymptomatic patients is 5 %, suggesting that fluid-filled bursa is not equivalent to bursitis (Rennie and Saifuddin 2005; Gupta et al. 2011).

Fig. 29.18 Iliotibial band friction syndrome. Coronal fat-suppressed intermediate-weighted MR image of the knee shows edema deep to the ITB, lateral to the lateral femoral condyle (*arrow*)

Fig. 29.19 Pes anserine tendinopathy. Coronal fat-suppressed intermediate-weighted MR image of the knee shows edema at the pes anserinus (*arrow*)

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Nuclear Medicine Imaging of Knee Injuries

30

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Abstract

This chapter deals with the clinical value of nuclear medicine, in particular SPECT/CT, in patients with knee injuries. A thorough overview of nuclear medicine imaging protocols, diagnostic algorithms and the clinical value for different knee pathologies is given. These knee pathologies or variants include patients with anterior knee pain; jumper's knee; runner's knee; patellar dislocation; patellar maltracking; patellar fractures; meniscal lesions; ligament tears such as anterior cruciate ligament, posterior cruciate ligament or collaterals; Stieda-Pellegrini lesion; cartilage lesions; osteochondral lesions; overloading of a knee compartment; osteoarthritis and fractures. The clinical value is further illustrated by images and typical instructional case descriptions.

Abbreviations

CT	Computerized tomography
SPECT	Single-photon emission computerized tomography
MRI	Magnetic resonance imaging
PPV	Positive predictive value

30.1 Introduction

In the last decades, nuclear medicine imaging has undergone a significant technical evolution (Bybel et al. 2008; Collier et al. 1985; Cook and Fogelman 1996; Delbeke et al. 2009; Dorchak et al. 1993; Dye and Chew 1993; Dye and Boll 1986; Franc et al. 2012; Gnanasegaran et al. 2009; Gregory et al. 2004; Hart et al. 2008; Hogervorst et al. 2000a, b; Jeer et al. 2006; Kim et al. 2008; Lorberboym et al. 2003; Madsen 2007; Murray et al. 1990; Naslund et al. 2005; O'Connor and Kemp 2006; Petersson et al. 1998; Scharf 2009). First, there was a clear diagnostic shift from conventional planar scintigraphic imaging (bone scans), which only offered 2D images of a 3D pathology, to 3D scintigraphic imaging and single-photon emission computerized tomography (SPECT) (Dorchak et al. 1993; Dye and Chew 1993; Dye and Boll 1986; Hart et al. 2008; Hogervorst et al. 2002; Hogervorst et al. 2000a, b; Jeer et al. 2006; Kim et al. 2008; Lorberboym et al. 2003; Murray et al. 1990; Petersson et al. 1998; Van Den Eeckhaut et al. 2003; Vellala et al. 2004; Yildirim et al. 2004). Then, hybrid single-photon emission tomography (SPECT/CT) systems, which combine conventional computerized tomography (CT) with SPECT, were introduced and are now available for clinical routine use in an increasing number of institutions worldwide (Bybel et al. 2008; Delbeke et al. 2009). In the last 3 years, SPECT/CT has been increasingly recognized by the orthopaedic and sports medicine fraternity as a clinically helpful diagnostic imaging modality in patients after knee injuries or before/after surgical procedures (Hirschmann et al. 2010a, b; 2011a, b, c, d; 2012c; Horger et al. 2007; Konala et al. 2010; Scharf 2009; Strobel et al. 2012).

The introduction of multimodality hybrid imaging, mainly SPECT/CT, into clinical routine has multiplied the clinical value of nuclear medicine imaging in orthopaedics (Amarasekera et al. 2011; Biersack et al. 2012; Breunung et al. 2008; Gnanasegaran et al. 2009; Graute et al. 2010; Hirschmann et al. 2010a, b; 2011a, b, c, d; 2012b, c; Horger et al. 2007; Konala et al. 2010; Lee et al. 2008; Madsen 2008; Mohan et al. 2010; Pagenstert et al. 2009; Scharf 2009; Strobel et al. 2012). It is not only the sensitivity but also the specificity and along with these the diagnostic confidence in detecting and interpreting bone and joint pathologies that has been significantly increased (Amarasekera et al. 2011; Biersack et al. 2012; Breunung et al. 2008; Gnanasegaran et al. 2009; Graute et al. 2010; Hirschmann et al. 2010a, b; 2011a, b, c, d; 2012b, c; Horger et al. 2007; Konala et al. 2010; Lee et al. 2008; Madsen 2008; Mohan et al. 2010; Pagenstert et al. 2009; Scharf 2009; Strobel et al. 2012).

Major advantage of SPECT/CT is the combined evaluation of precise anatomical and mechanical information (CT) and of data on bone metabolism (SPECT). SPECT/CT often demonstrates disease prior to abnormalities being detected on conventional radiographs, CT or even magnetic resonance imaging (MRI) (Hirschmann et al. 2012b).

SPECT/CT visualizes the loading history of the different knee compartments (patellofemoral, medial and lateral tibiofemoral) (Hirschmann et al. 2012b). In our own work, we have further demonstrated that the intensity and distribution of SPECT/CT tracer uptake correlated with mechanical and anatomical axes (Hirschmann et al. 2012b). In patients with a mechanical varus axis, increased tracer uptake in the medial tibiofemoral knee compartment and, in patients with a mechanical valgus axis, increased tracer uptake in the lateral tibiofemoral knee compartment were observed (Hirschmann et al. 2012b). The degree of osteoarthritis according to Kellgren and Lawrence also correlated with the intensity and location of SPECT/CT tracer uptake (Hirschmann et al. 2012b). In an unpublished work, we could also demonstrate that patellar position and tilt significantly influence SPECT/CT tracer uptake intensity and distribution. Buck et al. found that increased tracer uptake in bone scintigraphy was more sensitive for medial knee pain than bone marrow oedema on MRI (Buck et al. 2009).

We strongly believe that due to its limitations and inferior diagnostic confidence, a planar scintigraphy and single SPECT should only be the exception and not the standard imaging modality anymore. In most of the patients with knee injuries, a SPECT/CT is recommended. There has been tremendous effort to establish diagnostic standards and guidelines for the use of SPECT/CT in orthopaedics and sports medicine (Hirschmann et al. 2010b; 2012c). An increasing number of clinical indications and scenarios have been identified, in which SPECT/CT holds the promise of establishing a better more specific diagnosis (Hirschmann et al. 2010a, b; 2011a, b, c, d; 2012b; Konala et al. 2010). However, further clinical studies need to explicitly determine the good and the bad indications for the use of SPECT/CT in terms of diagnostic quality, cost-efficacy, benefits to the orthopaedic surgeon and impact on further treatment.

PET/CT or PET/MRI is still experimental and has not yet reached the clinical practice but might in future enrich the diagnostic armamentarium in patients with knee injuries. Hence, we will concentrate in this chapter on SPECT/CT imaging. With this chapter, we describe the basic principles of SPECT/CT imaging and protocols in patients with knee injuries and review the current evidence for different pathologies and potential clinical applications.

30.2 SPECT/CT Imaging

SPECT/CT is a combination of 3D scintigraphy (SPECT) and a single or preferably multislice conventional computerized tomography (CT). Generally, for bone imaging, patients are injected intravenously with 10–20 mCi (340–740 MBq) of technetium-labelled diphosphonates, which reflect the osteoblastic activity in the delayed phase. Within the first minute after tracer injection, planar two-plane perfusion images and, 2–5 min after tracer injection, planar two-plane blood pool images are obtained. Finally, SPECT is performed at 3–5 h after tracer injection (delayed phase), followed immediately by a CT with the patient in the same table position. For musculoskeletal imaging, low-dose protocols, which reduce the radiation exposure to the patient, have been reported. Using our published protocol for SPECT/CT knee imaging, which includes for the CT 3 mm slices of the femoral head, 0.7 mm slices of the knee and 3 mm slices of the ankle joint, the radiation dose is approximately 3 mSv. Using this protocol, not only structural and metabolical data (pattern and intensity distribution) but additional information on anatomical and mechanical alignment of the knee joint are available.

30.3 Pathologies of the Knee

30.3.1 Patellofemoral Problems (Patellar Dislocation, Patellar Maltracking, Patellar Fractures)

Pain within the patellofemoral joint is one of the most frequent problems in orthopaedics and sports medicine (Hirschmann et al. 2011a, b). The establishment of the correct diagnosis and cause of the problem is often difficult. The history, the clinical examination and radiological investigations such as conventional radiographs, computerized tomography (CT), magnetic resonance imaging (MRI) or SPECT very often do not unambiguously guide towards the right diagnosis (Hirschmann et al. 2011a, b). Often all fail to identify the origin of the patient's pain (Hirschmann et al. 2011a, b). Conventional radiographs are the primary imaging in patients with patellofemoral problems, but in these only gross malposition, malalignment and clear osteoarthritis can be identified (Hirschmann et al. 2011a, b). CT and MRI clearly offer more anatomical detail but as static investigation do not elucidate the pathology of patellar maltracking. However, the correlation between radiographic, CT and MRI abnormalities and patellofemoral pain is poor.

Lorberboym et al. compared the findings in ^{99m}Tc-MDP-SPECT with arthroscopy in 27 patients with anterior knee pain (Lorberboym et al. 2003). They found that when compared to arthroscopy, SPECT had a sensitivity of 100 % and a specificity of 64 % for patellofemoral abnormalities (Lorberboym et al. 2003). In the patellofemoral joint, SPECT often lacks precise anatomical detail and is limited due to poor localization ability.

SPECT/CT combining the advantages of SPECT and CT provides a view into the loading and remodelling of the bone, helps to identify patellar maltracking and evaluates the efficacy of realignment procedures in offloading the patellofemoral joint (Fig. 30.1) (Hirschmann et al. 2011a, b).

30.3.2 Cartilage and Osteochondral Lesions

The importance of the integrity of the subchondral bone plate has not only recently gained increasing interest. Generally, MRI is the standard imaging procedure in patients with suspected cartilage lesions (Hayashi et al. 2012). It is able to accurately characterize the size and depth of the cartilage lesions (Hayashi et al. 2012). In addition, it has been shown that the bone oedema present in MRI is a predictive factor for outcome of these cartilage lesions. However, it is very unspecific and it remains unclear what pathophysiology the bone oedema reflects (Buck et al. 2009). The major advantage of SPECT/CT in patients before and after cartilage surgery lies in its strength to evaluate the integrity of the subchondral bone plate (Hirschmann et al. 2012b). We believe that in contrast to MRI, SPECT/CT helps to differentiate between pure chondral and osteochondral pathologies. Hence, we use SPECT/CT preoperatively to establish the optimal indication for chondral or osteochondral surgery and postoperatively to follow up patients after osteochondral repair procedures (Fig. 30.2).

Etchebehere et al. noted that bone scans precede radiographic changes in osteonecrosis of the knee (Etchebehere et al. 1998). Another established indication of SPECT/

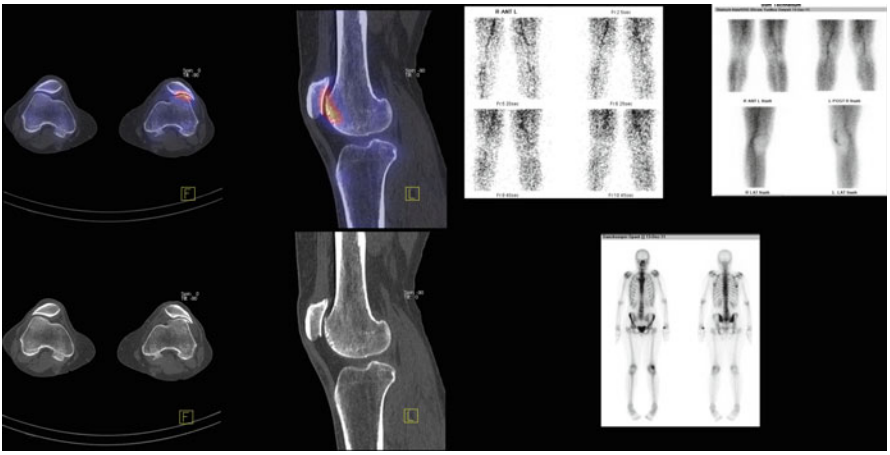

Fig. 30.1 A 55-year-old female patient presenting with symptomatic patellofemoral osteoarthritis due to patellar maltracking and increased lateral patellar tilt – SPECT/CT images show an increased ^{99m}Tc-HDP tracer uptake within the lateral part of the patellofemoral joint

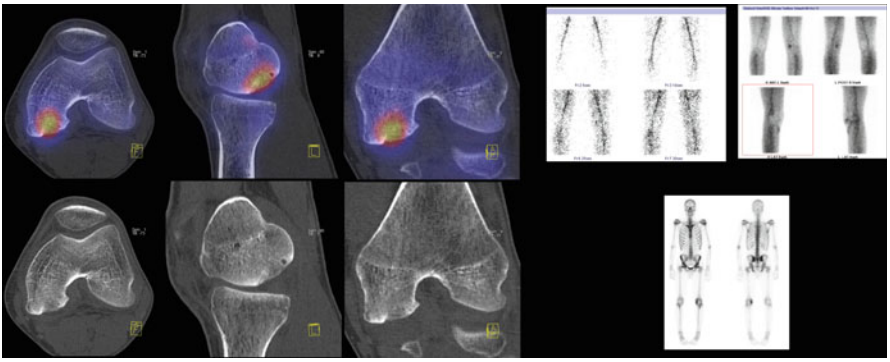

Fig. 30.2 An asymptomatic 19-year-old patient 1 year after osteochondral grafting (MaioRegen, Finceramica, Italy) due to osteochondritis of the medial femoral condyle

CT is the assessment of osteochondritis dissecans (OCD) (Konala et al. 2010). Konala et al. described that SPECT/CT was helpful in patients with pain after refixation of OCD (Konala et al. 2010). In particular in cases of delayed healing and suspected non-union, SPECT/CT proved beneficial to judge the healing and integration of the osteochondral fragment and guide further treatment (Konala et al. 2010). In our experience, SPECT/CT arthrography further improves the assessment of stability of the OCD fragment and subsequent decision-making pre- and postoperatively (Fig. 30.3).

30.3.3 Meniscal Lesions

Clearly, MRI is considered to be the gold standard in the diagnosis of meniscal lesions. Most studies looking into bone scans or SPECT for diagnosing meniscal lesions were performed before the introduction of MRI (Collier et al. 1985; Dorchak et al. 1993; Murray et al. 1990).

However, there are still some indications for nuclear medicine modalities as second-line diagnostics, for example, when a patient has metal implants around the knee joint causing extensive metal artefacts or an implanted pacemaker.

Grevitt et al. investigated 60 patients using SPECT, which then underwent an arthroscopy of the knee due to a suspected meniscal lesion (Grevitt et al. 1993). They reported a sensitivity of 90 %, specificity of 81 % and accuracy of 84 % in diagnosing meniscal lesions (Grevitt et al. 1993). Typically a crescent-shaped pattern of tracer uptake was found (Grevitt et al. 1993). Collier et al. found similar results in terms of sensitivity and specificity (Collier et al. 1985). The biggest problem with these studies is that in most of these studies, chondral and osteochondral lesions as well as the type of meniscal lesion were not taken into account. It is further unclear what the tracer uptake pattern really reflects. Some believe that the uptake is within the vascular zone of the meniscus, others believe that the traction on the coronary ligaments occurring at the time of meniscal trauma and subsequent bony lesions on the attachment site or subchondral bone are responsible for the development of this uptake pattern (Collier et al. 1985; Grevitt et al. 1993). Changes

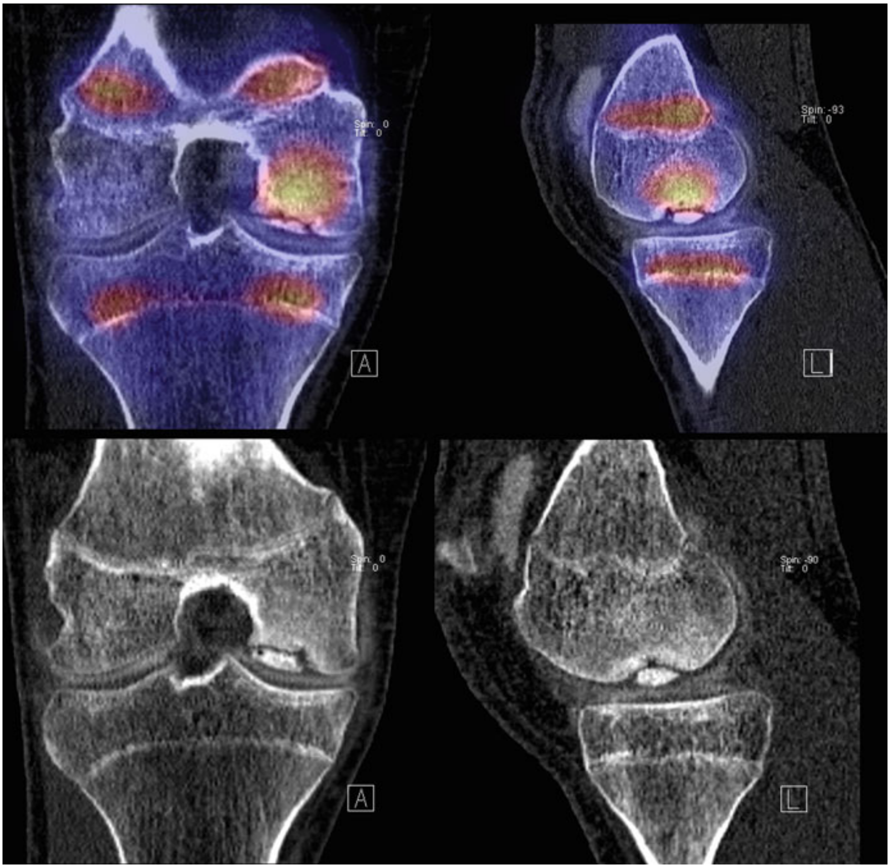

Fig. 30.3 ^{99m}Tc-HDP arthro-SPECT/CT (*upper images*) and CT (*lower images*) of a 16-year-old patient with an osteochondritis dissecans (OCD) of the right medial femoral condyle. The arthro-SPECT/CT shows an intact surface of the OCD and physiologically increased bone tracer uptake at the growth plates

within the adjacent femoral condyles are also taken into consideration for posterior horn lesions (Collier et al. 1985; Grevitt et al. 1993).

In our experience, SPECT/CT is helpful to visualize and identify mechanical overloading of the different knee compartments, which could be regularly seen in patients after total or subtotal meniscectomy (Fig. 30.4). If SPECT/CT is not available, SPECT could also be used considering its limitations. SPECT/CT is also beneficial before and after meniscal substitution surgery, e.g. using polyurethane or collagen meniscus implants. One could evaluate if the preoperatively existing SPECT/CT tracer uptake within the overloaded knee compartment disappears or is at least reduced due to the performed surgery. Using SPECT/CT, the orthopaedic surgeon, sports physician and patient have a direct view into the joint homeostasis and biological state of the knee joint (Hirschmann et al. 2010a; 2011a, b; 2012b). In a currently unpublished date, Hirschmann et al. have shown that in comparison to MRI, the overloading of the knee

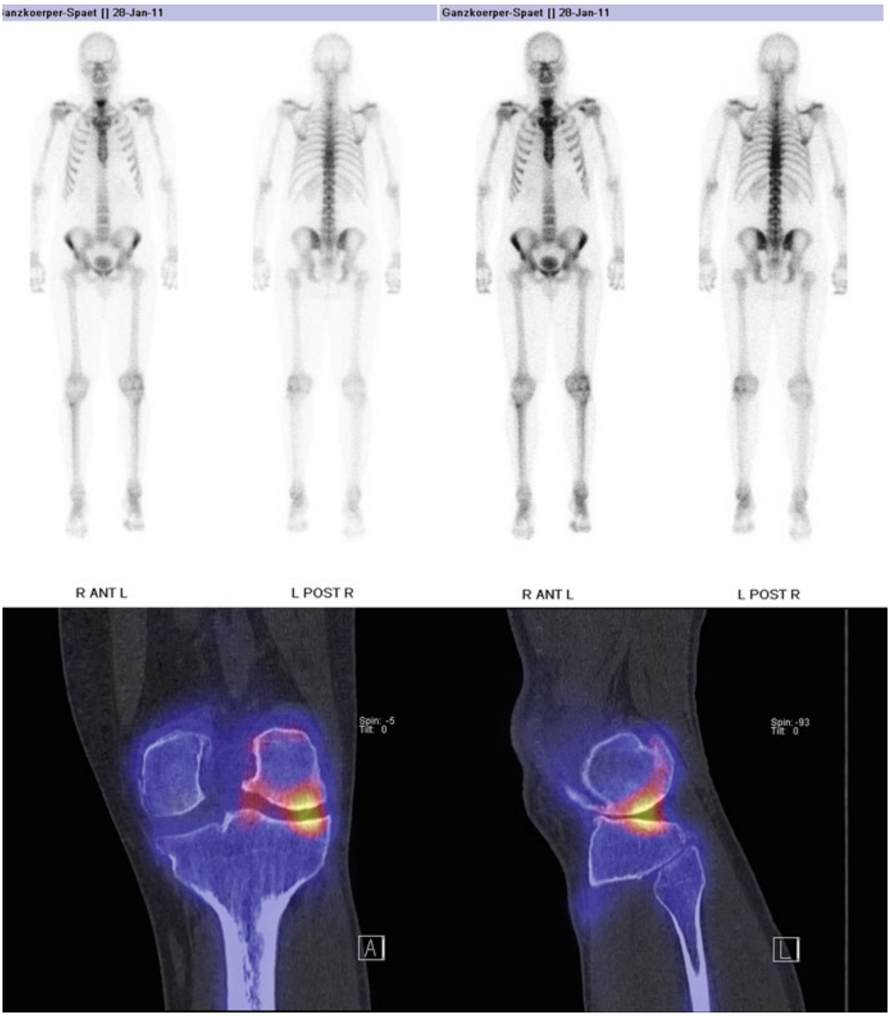

Fig. 30.4 ^{99m}Tc-HDP SPECT/CT of a 55-year-old female patient 10 years after lateral subtotal meniscectomy indicating an overloading of the lateral knee compartment

compartment can be visualized. It was found that bone marrow oedema does not reflect overloading, but bone tracer uptake does. It then guides the optimal treatment (e.g. meniscal substitution, high tibial osteotomy, cartilage or osteochondral repair).

30.3.4 Mechanical Overloading of Knee Compartments

Mechanical overloading of the knee joint is characterized by a disbalance of knee protective factors and mechanical loading of the different knee compartments. It is well understood that one of the most important factors leading to mechanical overloading of the medial tibiofemoral knee is a proximal tibial varus deformity, in which the mechanical axis passes medially from the knee centre. Mechanical overloading inevitably leads to an increased risk of osteoarthritis. A variety of nonsurgical such as deloader braces or insoles and surgical therapeutic options (e.g. distal femoral or proximal tibial osteotomies, patellofemoral realignment procedures) aim to reduce the loading in the corresponding medial, lateral or patellofemoral knee compartment.

Conventional radiographs in anterior-posterior, lateral and patella skyline views and long leg radiographs to assess the mechanical leg axis are considered to be the primary imaging in patients under suspicion of a mechanical overloading. In the last decades, bone scans and SPECT have been mainly used as second-line imaging in patients not doing well after correction osteotomy. However, in the last 5 years, the clinical value of SPECT/CT in these patients has been increasingly recognized (Hirschmann et al. 2012b). SPECT/CT offers the combined assessment of structure, mechanical and anatomical alignment and functional information. Only recently Hirschmann et al. reported that the anatomical and mechanical alignment of the knee correlated significantly with the distribution pattern and intensity values of SPECT/CT tracer uptake (Hirschmann et al. 2012b). Mechanical varus alignment showed increased tracer uptake on the medial compartment and a valgus alignment on the lateral side (Hirschmann et al. 2012b). To our knowledge, this is the first study showing a clear relationship between knee alignment and compartment-specific tracer uptake in SPECT/CT.

Based on these findings, SPECT/CT was proposed to be used in clinical practice for twofold: firstly, it should be used as preoperative imaging modality to characterize the pattern of overloading aiming for a better targeted treatment such as nonsurgical therapy, osteotomies and partial or total knee replacements. Secondly, it should also be considered for postoperative follow-up of patients after osteotomies. SPECT/CT could differentiate between optimal, over- or undercorrection (Fig. 30.5) (Hirschmann et al. 2012b).

30.3.5 Ligament Lesions

The radiological diagnostics of ligament lesions such as anterior cruciate ligament tears clearly is the domain of MRI. However, in particular in patients with a retear after ligament reconstruction, MRI could be disturbed by metal artefact splatter. In addition, the evaluation of the tunnel position as well as the assessment of tunnel widening is preferably performed on CT. Numerous authors have emphasized the benefits of 3D-CT for the assessment of tunnel position after ACL reconstruction (Basdekis et al. 2009; Hirschmann et al. 2012a; Purnell et al. 2008).

To date, bone scans or SPECT did not play an important role in the diagnostics of patients with a ligament lesion. However, Even-Sapir et al. correlated the findings of 94 SPECT/CTs of the knee with arthroscopy ($n = 74$) and MRI ($n = 37$) or both (Even-Sapir et al. 2002). The patients were suspected to have an ACL lesion or a meniscal tear (Even-Sapir et al. 2002). In 38 patients, an ACL injury was present (Even-Sapir et al. 2002). In these SPECT identified the indirect signs of increased

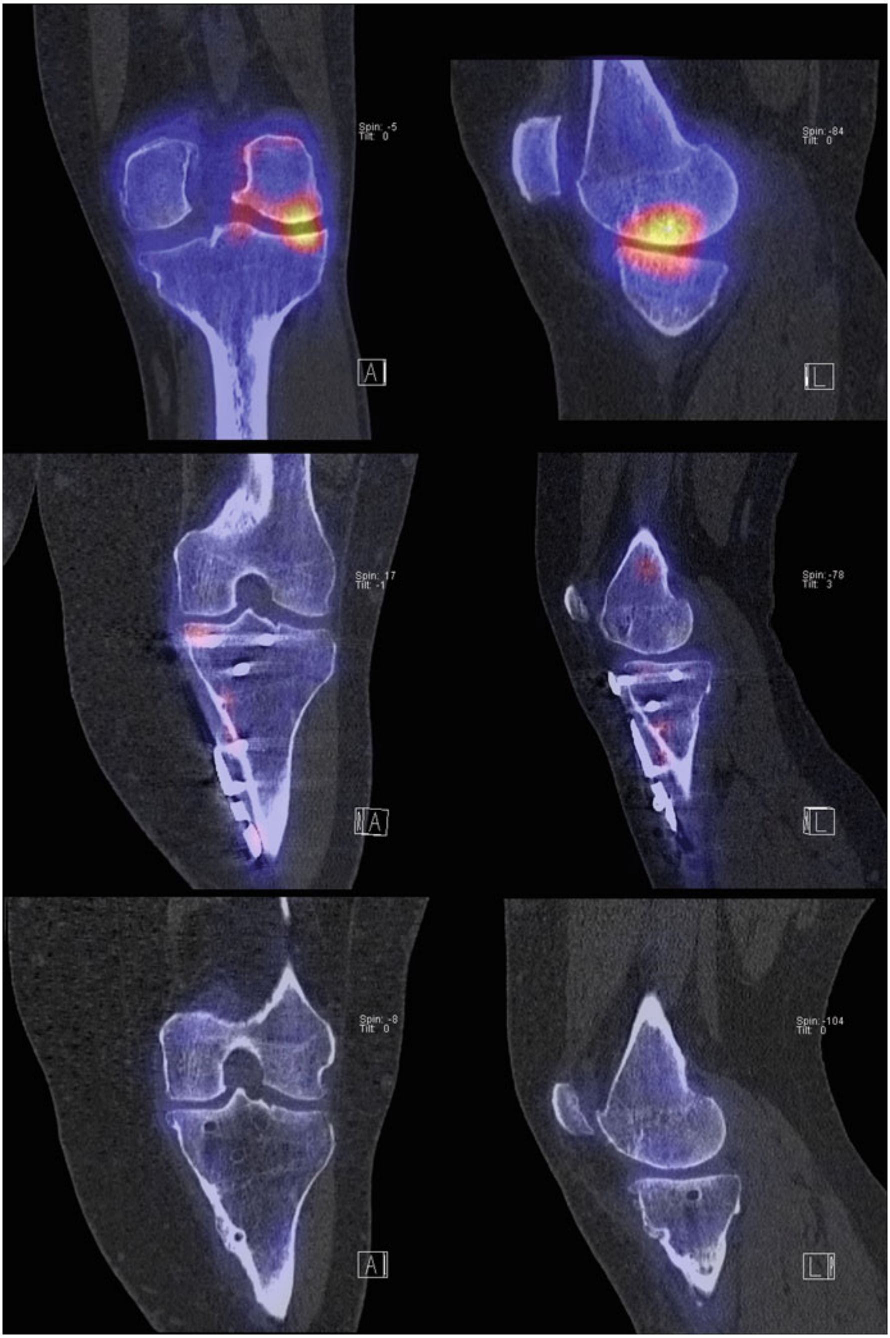

Fig. 30.5 Images of a 42-year-old female patient before and 1 year and 2 years after high tibial osteotomy for correction of varus-deformed knee. ^{99m}Tc-HDP preoperative SPECT/CT (*upper images*) showed increase tracer uptake within the medial femoral knee compartment indicating a mechanical overloading. The 2- and 2-year-follow-up SPECT/CT images showed no tracer uptake anymore indicating an adequate correction of the varus deformity

tracer uptake in the posterior lateral tibial plateau (positive predictive value 93 %, negative predictive value 97 % (Even-Sapir et al. 2002). Only in 55 % of these patients, increased tracer uptake was also seen in the lateral femoral condyle (Even-Sapir et al. 2002). On MRI bone bruise was present in 64 %, while all patients had increased tracer uptake in the posterior lateral tibial plateau (Even-Sapir et al. 2002).

In contrast, So et al. reported that an increased SPECT tracer uptake at the ACL attachment site is a primary sign of an anterior cruciate ligament lesion (So et al. 2000). The positive predictive value (PPV) of this primary sign was 94 %, while the PPV of the secondary sign of increased SPECT tracer activity in the tibia or femur was only 81 % (So et al. 2000).

Hogervorst et al. investigated the tibial bone tunnels of 68 patients 2 years after ACL reconstruction using bone scans (Hogervorst et al. 2000b). They found that increased scintigraphic uptake was associated with tibial tunnel enlargement of more than 35 % and a graft length in the tibial tunnel over 14 mm (Hogervorst et al. 2000b). The tracer uptake was also significantly correlated with tunnel enlargement, and tunnel enlargement was significantly correlated with the graft length inside the tibial tunnel (Hogervorst et al. 2000b). They further concluded that return to normal osseous tracer uptake at the tibial tunnel can take more than 2 years when fixation is more than 14 mm below the joint (Hogervorst et al. 2000b).

Just recently the clinical value of SPECT/CT was highlighted for patients after ACL reconstruction (Hirschmann et al. 2012a). We have reported a specific algorithm to analyse and report the position of the tunnels and SPECT/CT tracer uptake in patients after ACL reconstruction (Hirschmann et al. 2012a). High inter- and intraobserver reliability were reported (Hirschmann et al. 2012a). Major advantage is the combined assessment of mechanical alignment, tunnel position and loading of the joint (Fig. 30.6) (Hirschmann et al. 2012a). Its clinical value has to be seen in complex revision cases, in which all these aspects have to be taken into consideration for optimal planning of the subsequent surgical treatment.

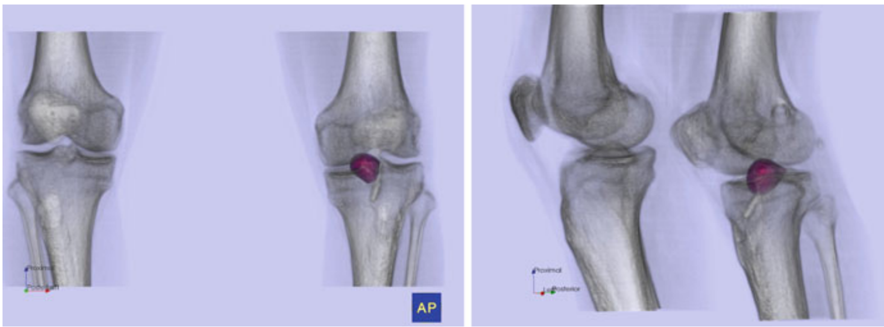

Fig. 30.6 3D reconstructed transparent SPECT/CT images of a 40-year-old patient with a cyclops lesion 1 year after ACL reconstruction (OrthoExpert©)

30.3.6 Osteoarthritis

Bone scintigraphy and SPECT and recently SPECT/CT have proven to be very sensitive for diagnosing osteoarthritis (OA) in early stages, which is the major advantage of nuclear medicine imaging over radiographs, CT or MRI (Hirschmann et al. 2012b). In conventional radiographs as well as CT and even MRI, osteoarthritis can only be diagnosed when the disease already has caused structural damage. SPECT and SPECT/CT open up new vistas into the aspect of biological joint homeostasis. In our experience, SPECT/CT enables the surgeon to precisely characterize the extent and grade of osteoarthritis. This more accurate evaluation of the grade and type of osteoarthritis of the knee could lead to a more targeted and less invasive treatment. Hart et al. found that SPECT helps the surgeon to identify if a patient is instead of total knee arthroplasty suitable for a less invasive procedure such as a high tibial osteotomy or medial unicondylar knee arthroplasty (Hart et al. 2008).

If OA and overloading of the knee joint are identified early, even before any symptoms occur, treatment could be specifically tailored to a more preventive approach. As overloading and overuse injuries are common in sports, SPECT/CT could be used to improve and develop training and prevention programmes, which consider the biological and functional state of the knee joint.

30.3.7 Shin Splint Syndrome, Fractures, Pseudoarthrosis and Osteonecrosis

Bone scans, SPECT and SPECT/CT are very sensitive and specific diagnostic tools for the diagnosis of shin splint syndromes, stress fractures, occult fractures, delayed healing of fractures and pseudoarthrosis (Marks et al. 1992; Ryan and Fogelman 1994).

Yildirim et al. evaluated the knees of 42 active asymptomatic soccer players using bone SPECT to identify stress fractures (Yildirim et al. 2004). In 66 % of patients, increased SPECT tracer uptake indicated a stress fracture (tibia 62 %, femur 5 %).

Etchebehere et al. highlighted that in case of delayed healing of fractures, bone scans are able to differentiate between avascular and hypervascular non-unions and delayed unions (Etchebehere et al. 1998). They further noted that SPECT accurately detects decreased metabolism associated with posttraumatic closure of the physeal plate, which could then lead to growth arrest and leg deformities.

30.3.8 Insertion Tendinopathies (Enthesopathy) and Friction-Related Peritendinous Disease

Insertion tendinopathies are typical overuse injuries, which at the beginning only are symptomatic during and shortly after activity (Adams 2004; Molnar and Fox 1993; Taunton et al. 1987). The iliotibial band friction syndrome is common in runners, that is why it is called runner's knee (De Geeter et al. 1995; Van Den Eeckhaut et al. 2003). It is caused by friction of the iliotibial tract on the lateral femoral epicondyle (De Geeter et al. 1995; Van Den Eeckhaut et al. 2003). Other common insertion tendinopathies of the knee are the jumper's and reversed jumper's knee (Fig. 30.7) (Adams 2004; Molnar and Fox 1993; Taunton et al. 1987).

In SPECT and SPECT/CT, all these pathologies typically show increased SPECT tracer uptake at the site of mechanical irritation or insertion (De Geeter et al. 1995; Van Den Eeckhaut et al. 2003). In contrast to planar bone scans, SPECT and SPECT/CT are able to clearly identify these lesions, which is due to its accurate localization ability.

30.3.9 Accessory Bones

The most common accessory bones of the knee are the fabella and bi- or multipartite patella (Hirschmann et al. 2011b). In our own work, we have demonstrated that SPECT/CT is able to detect symptomatic bipartite patella in patients with knee problems (Hirschmann et al. 2011b). In the case presented here, the patient, who is a world-class downhill skier, suffered from osteoarthritis of the fabellar bone in his knee, which was unambiguously identified. Using SPECT/CT, the orthopaedic surgeon or sports medicine physician is enabled to accurately localize the pain generator (Fig. 30.8). In particular clear differentiation of OA of the fabellar or lateral femoral joint is possible.

30.4 Summary and Future Perspectives

There is growing clinical evidence indicating good clinical value of SPECT/CT in patients with musculoskeletal knee problems. Although there are yet no clear diagnostic guidelines for patients with knee injuries, the use of SPECT/CT has proven

Fig. 30.7 ^{99m}Tc-HDP SPECT/CT with increased tracer uptake of the insertion of the quadriceps tendon indicating an insertion site tendinopathy of the quadriceps tendon

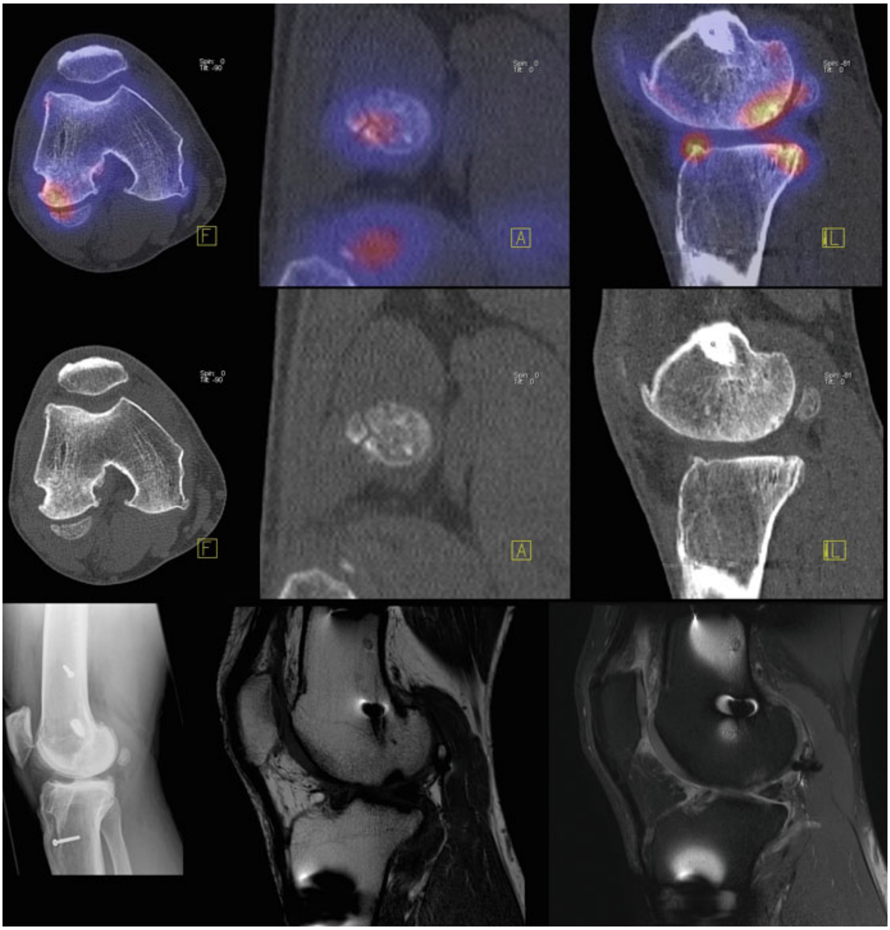

Fig. 30.8 ^{99m}Tc-HDP SPECT/CT images of a 33-year-old professional skier complaining about posterior activity-related knee pain. In contrast to radiographs, MRI or CT, SPECT/CT was able to identify the overloading of the fabellar bone

beneficial in diagnosing a variety of different knee pathologies. In comparison to bone scans or SPECT, the introduction of SPECT/CT significantly raised the diagnostic confidence, sensitivity and specificity.

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Part X

The Musculoskeletal System Topographically: Lower Leg

Lower Leg Injuries

31

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Contents

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Abstract

Lower leg pain and injury is a common occurrence in athletes that has been described in the medical and athletic literature. The various pathoanatomic processes, which could present as lower leg pain in the athlete, include medial tibial stress syndrome (MTSS), chronic exertional compartment syndrome (CECS), stress fracture, tendinopathy, nerve entrapment syndromes, vascular syndromes, and muscle injuries. The etiopathogenesis and clinical presentations of these conditions are described, and a brief account of diagnostic studies and treatment options is discussed.

Abbreviations

AMA	American Medical Association
CECS	Chronic exertional compartment syndrome
EMG	Electromyography
ERLP	Exercise-related leg pain
MRI	Magnetic resonance imaging
MTSS	Medial tibial stress syndrome
NIRS	Near-infrared spectrometry
PAES	Popliteal artery entrapment syndrome
PNI	Peripheral neurogenic inflammation
SPECT	Single-photon emission computed tomography

31.1 Introduction

Lower leg pain and injury is a common occurrence in athletes that has been described in the medical and athletic literature as early as 1913. Over time, this pain has received multiple nomenclatures, including spike soreness, shin splints, posterior medial pain, and exercise-related leg pain (ERLP). The various pathoanatomic processes which could present as lower leg pain in the athlete include medial tibial stress syndrome (MTSS), chronic exertional compartment syndrome (CECS), stress fracture, tendinopathy, nerve entrapment syndromes, vascular syndromes, and muscle injuries. Of these, MTSS, stress fractures, and CECS are the most likely in an athlete followed by nerve entrapment and vascular etiologies (Clanton and Solcher 1994; Edwards et al. 2005). Today, the lay person often refers to all of the above as simply "shin splints." The American Medical Association seems to lend credence to this concept and defines a shin splint as "pain and discomfort in the leg from repetitive running on a hard surface or forcible excessive use of foot flexors." However, it is the job of the astute clinician to differentiate the true etiology of the leg pain, thereby allowing more efficient treatment and return to activity. It is an additional challenge that several pathologies may coexist in the lower limb (Zimmermann 2013a; McCrory 2000).

31.1.1 Epidemiology

Even though lower leg pain is commonly experienced in athletes, there have been few studies investigating the epidemiology of these injuries. It appears to be most frequent in runners; however, other sports also at risk include basketball, gymnastics, soccer, field hockey, dance, and basic military training (Yates and White 2004). The overall incidence of injury varies from 13 to 50 %, depending on the study and sport involved (Clement et al. 1981; Reinking 2006).

31.2 Medial Tibial Stress Syndrome

MTSS presents as diffuse pain along the posteromedial aspect of the tibia. This complex syndrome has been referred to by many names based on the investigators' proposed etiology which include shin splints, soleus syndrome, medial tibial syndrome, tibial stress syndrome, posterior tibial syndrome, and periostitis (Slocum 1967; Puranen 1974; Clement et al. 1981; Mubarak et al. 1982; Holder and Michael 1984; Michael and Holder 1985).

The term medial tibial stress syndrome, as coined by Drez, is a condition which causes pain in the posteromedial aspect of the distal third of the tibia (Mubarak et al. 1982). At that time, it was suggested that periostitis was an essential etiology of MTSS. However, later histologic studies refuted these claims (Johnell et al. 1982). In addition, nuclear medicine investigations were consistent with the histologic findings. A true inflammatory process would show increased perfusion and blood pool on the first two phases of a bone scan, yet this is not the case in MTSS. Instead, the increased uptake is demonstrated in the late phase, suggesting a more metabolic cause (Rupani et al. 1985).

31.2.1 Epidemiology

It has been difficult to determine the precise incidence of MTSS because of the varied and inconsistent terminology. Reports range from 4.1 to 35 % (Andrish et al. 1974; Yates and White 2004).

31.2.2 Etiology

Though the anatomic site in MTSS is known, the exact pathophysiology leading to the syndrome is still debated. Based on location of the pain, initially the tibialis posterior muscle was implicated as the cause (James et al. 1978; Saxena et al. 1990). However, subsequent anatomic studies demonstrated that the origin of the tibialis posterior muscle is much more lateral than originally thought, thereby eliminating it as the source of pain (Michael and Holder 1985).

More recently the fascial insertion for the soleus has been implicated (Bouche and Johnson 2007; Stickley et al. 2009). Holder and Michael are credited to first point out the characteristic abnormality on the triple-phase bone scan where there was diffuse increased uptake on the posteromedial tibia only on the late phase of the scan (Holder and Michael 1984). Later, in cadaveric and EMG studies, they discovered that this area corresponded to the fascial insertion for the soleus called soleus bridge. Other studies pointed instead to the flexor digitorum longus (FDL) as a potential source as it appears to have a similar distribution of origin as the soleus (Garth and Miller 1989; Beck and Osternig 1994).

However, the most accepted etiology of MTSS is the traction theory. The medial portion of the soleus must contract eccentrically during the stance phase when the foot moves from supination to pronation. This results in increased stress at the fascial insertion for the soleus and disrupts the Sharpey's fibers, thereby producing MTSS (Michael and Holder 1985).

31.2.3 Biomechanics and Risk Factors

Apart from the traction explanation, many other theories have been put forward to explain MTSS. Another explanation is that repeated bending or bowing causes MTSS similar to a stress fracture. The point of the most profound bending is at the site where the tibia is narrowest, the junction of the mid- and distal thirds (Milgrom et al. 1989). The evidence to this theory was provided by Franklyn et al. in a cohort study. They showed that subjects with MTSS and tibial stress fractures were less adapted than aerobic controls to axial loading, torsion, and maximum and minimum bending rigidity (Franklyn et al. 2008). Further support to this hypothesis is provided by Magnusson who demonstrated that MTSS is associated with low regional bone mineral density (Magnusson et al. 2001).

Excessive foot pronation is the front-runner as a risk factor for MTSS. Bennett et al. reported a positive correlation between navicular drop used as a measure of pronation and incidence of MTSS (Bennett et al. 2001). Excessive pronation of the foot combined with repetitive impact activity has been implicated (Viitasalo and Kvist 1983; Messier and Pittala 1988; Sommer and Vallentyne 1995). Viitisalo et al. found in a cinematographic analysis of runners that individuals with MTSS had a greater degree of pronation than control subjects who did not have MTSS (Viitasalo and Kvist 1983). Messier et al. reconfirmed the above finding in their cinematographic anthropometric study. In addition to greater maximum pronation, subjects with MTSS also demonstrated increased maximum velocity of pronation (Messier and Pittala 1988). Varus forefoot and hindfoot abnormalities have also been associated with this syndrome (Sommer and Vallentyne 1995).

Multiple risk factors are considered significant in the development of MTSS. In addition to excessive pronation, these include female sex, BMI greater than 21, previous history of MTSS, increased hip rotation, and small calf girth (Burne et al. 2004; Yates and White 2004; Plisky et al. 2007; Hubbard et al. 2009; Moen et al. 2012a). Other risk factors implicated include increase in running intensity, longer running distance, change in running shoes, and running on different terrain, but they are not supported by appropriate evidence (Beck 1998; Kortebein et al. 2000).

31.2.4 Clinical Presentation

31.2.4.1 History

The most common complaint is a dull aching pain along the posteromedial aspect of the distal tibia. Initially, the pain usually occurs at the beginning of the run and resolves with continued exercise, only to recur later at the end of the workout. Eventually, the pain does not subside during the exercise and will only be relieved with rest. With continued exercise, the pain may sharpen during exercise and even persist at rest. However, there are no complaints of paresthesias. The patient may give history of abrupt increase in frequency, duration, or intensity of training. A recent change in workout terrain or shoes may also be elicited.

31.2.4.2 Physical Examination

There typically will be diffuse tenderness along the posteromedial tibia involving the most distal 1/3 of the posterior medial tibial border (Yates and White 2004). Palpable pain locations in the muscles may be attributed to trigger points and/or peripheral neurogenic inflammation (PNI) (Zimmermann 2013b). Occasionally, there may be evidence of swelling or warmth in the region (Clanton and Solcher 1994; Fredericson et al. 1995). Less commonly, discomfort could be reproduced on stretching or contraction of the soleus muscle (Barry and McGuire 1996). The muscle could be loaded in different ways to reproduce the symptoms. These maneuvers include forced passive dorsiflexion, active plantar flexion against resistance, one-/two-legged standing toe raises, or one-/two-legged standing hop (Clement 1974; James et al. 1978).

Careful evaluation of foot position for hyperpronation and subtalar valgus should be performed. Individuals with MTSS have greater subtalar motion as compared to controls. A standing foot angle of $<140°$ is also associated with MTSS (Slocum 1967; Sommer and Vallentyne 1995).

31.2.5 Imaging

The necessity of imaging studies in the setting of a thorough history and examination is at best questionable as the diagnosis is more clinical than radiological. However, imaging could be sought to differentiate from other entities, especially stress fracture. Plain radiographs are of little help in MTSS (Anderson et al. 1997; Magnusson et al. 2001; Aoki et al. 2004). Infrequently cortical hypertrophy may be noted (Batt et al. 1998). If any other findings such as scalloping, subperiosteal lucency, or a black line are seen, a stress fracture should be suspected.

A triple-phase bone scan is by far the most sensitive test for MTSS (Gaeta et al. 2005). It was first described by Holder and Michael and shows diffuse increase in uptake in the delayed phase along the posteromedial tibia (Holder and Michael 1984). The bone scan is also helpful to differentiate MTSS from the stress fracture. Medial and lateral spot views are required to clearly delineate the region of uptake. A limitation of the triple-phase bone scan is that it lacks specificity (Batt et al. 1998). Adding SPECT-CT to the late phase may help to increase the specificity.

MRI scan also has been shown to have a high sensitivity and specificity (Batt et al. 1998; Gaeta et al. 2005). MRI demonstrates diffuse abnormalities adjacent to the insertion of all the deep flexor compartment muscles. The other MRI findings reported include increased periosteal fluid and bone marrow edema (Anderson et al. 1997; Mattila et al. 1999). Fredericson et al. developed a grading system for stress reaction in runners based on clinical findings, bone scan, and MRI and concluded that there is no correlation between bone scintigraphy and MRI findings, which was later refuted by another study (Fredericson et al. 1995; Batt et al. 1998).

High-resolution computed tomography is another modality that has been evaluated. It demonstrated posteromedial cortical osteopenia in patients with MTSS with a sensitivity of 42 % and specificity of 100 % (Gaeta et al. 2006).

Despite the imaging modalities available, differentiating between an early stress fracture and MTSS is still a radiologic challenge.

31.2.6 Treatment

Initial management of MTSS usually involves relative rest. Specifically, running activity should be avoided completely, or the intensity and duration should be drastically reduced so that pain scores do not exceed 4 out of 10 on a self-scoring scale.

If the pain is brought on by activities of daily living, a period of non-weight bearing is advisable which should be continued until the patient is pain-free. Cross-training exercises such as swimming, cycling, or water running should be utilized to maintain cardiorespiratory fitness of the athlete. Other modalities such as cryotherapy, ice massage, phonophoresis, and bone stimulation have been advocated without any evidence as to efficacy of such treatment (Kortebein et al. 2000). Bracing on its own has shown no additional value (Moen et al. 2010). Compression sleeves do not improve time to onset of symptoms in patients with MTSS (Zimmermann 2013a), but they are appreciated by patients for their sense of support and comfort (Moen et al. 2012b; Zimmermann 2013a).

Adequate calcium balance and vitamine D optimization is recommended, especially in females. As MTSS is not an inflammatory disorder, routine and prolonged use of NSAIDs is not warranted. Acetaminophen is advised if analgesia in desired.

If required, correction of malalignment with appropriate orthotics is attempted (Loudon and Dolphino 2010). Once pain-free, the training is gradually increased in duration and intensity, progressing at the rate of 10 % per week.

Two studies reported good results with ESWT for recalcitrant cases (Rompe et al. 2010; Moen et al. 2012b). Nissen et al. investigated low-energy laser treatment for MTSS and found no statistical difference between those treated with the laser and those with placebo (Nissen et al. 1994). In recalcitrant cases, surgical procedures such as fasciotomy of the posteromedial superficial and deep fascia or periosteal strip excision along the involved tibial border could be pursued, but the results are modest (Wallensten 1983).

Athletes and coaches should be made aware of the preventative measures for MTSS to include correction of improper running technique, maintenance of strength and flexibility, changing of footwear after every 300 miles, shock-absorbing insoles, and proper training programs (Beck 1998).

31.3 Stress Fractures

Stress fractures of the lower extremity account for up to 80 % of all stress fractures (Brewer and Gregory 2012). The tibia is the most common site (23.6 %). The other bones include the tarsal navicular (17.6 %), metatarsal (16.2 %), fibula (15.5 %), femur (6.6 %), and pelvis (1.6 %) (Brukner et al. 1996). Persons who participate in repetitive high-intensity training such as athletes and military recruits are more likely to suffer from stress fractures. Recreational runners who run at least 25 miles per week are also likely to suffer from stress fractures. Also at increased risk are athletes in soccer, track and field, and dancing (Bennell and Brukner 1997). Women are more at risk than men to develop stress fractures (Matheson et al. 1987).

31.3.1 Etiology

Stress fractures are caused by repetitive loading with resulting bony microfracture. Imbalance in bone turnover with lagging bone production could also potentiate a stress fracture. This is especially found in the setting of sudden change in intensity, duration, or frequency of training (Boden et al. 2001). Another contributory factor could be muscle fatigue whereby the muscles fail to provide adequate shock absorption and thus allow more forces to be delivered to the bone (Meyer et al. 1993). Other possible factors implicated include poor nutrition, hormonal imbalance, and metabolic disorders, particularly in the female athletes (Bennell et al. 1999).

Although many other variables like age, bone mineral density, limb alignment, limb length discrepancy, and alcohol consumption have been suggested as risk factors, definitive evidence is lacking.

31.3.2 Clinical Presentation

The initial presentation is gradual-onset activity-related pain that initially improves with rest. With continued chronicity and development of fracture, the pain is constant and ultimately present with all weight-bearing activities. The patient may admit to sudden increase in duration or intensity of training. Other considerations include general nutritional status and dietary and menstrual history.

On examination, focal tenderness is elicited over the area of pathology. As the tibia is the most common bone fractured, both stress fracture and MTSS present with similar local findings. However, the pain in MTSS is more diffuse as compared to the focal tenderness in stress fracture. Edema may not be evident. The single-leg hop test is an often used physical exam test for stress fractures. Another diagnostic test used is the tuning fork test, that is, applying a vibrating tuning fork to the fracture site to elicit pain (Lesho 1997). A fulcrum test or twisting force may also reproduce the pain as well as compression of tibiofibular syndesmosis. The examination should also include assessment of limb length, alignment, and muscle tone.

The common differential diagnosis in the leg includes MTSS, CECS, tendinopathies, and neurovascular syndromes. It is also important to rule out malignancies, such as Ewing's sarcoma and osteosarcoma (Fayad et al. 2005).

31.3.3 Imaging

Plain radiographs are the first line of investigation because of availability and low cost. They have, however, a sensitivity of only 15 % in the first week, which is increased to up to 70 % at 3 weeks (Boden and Osbahr 2000). The x-ray may show direct evidence of the fracture with lucency or more commonly indirect evidence in the form of periosteal reaction, cortical changes with initial decreased density (gray cortex), and sometimes callus formation or endosteal thickening and sclerosis (Boden et al. 2001; Ohta-Fukushima et al. 2002).

CT scan has shown less sensitivity than bone scan or MRI and hence has been superseded by the latter for diagnosing stress fractures (Gaeta et al. 2005; Groves et al. 2005).

Triple-phase bone scintigraphy is a highly sensitive investigation to differentiate between MTSS and stress fracture (Gaeta et al. 2005). The former shows diffuse uptake in the delayed phase, while the latter shows localized tracer activity in all the three phases. However, scintigraphy can be falsely positive in cases of infection and bone tumor (Fayad et al. 2005).

More recently MRI has replaced scintigraphy as the investigation of choice despite cost and availability. It has sensitivity nearly equal to scintigraphy. The MRI usually shows bone edema at the site of fracture. MRI may also help in identifying reactive bone remodeling (interpreted as early stress injuries). MRI has the additional advantage of being able to evaluate surrounding soft tissues (Gaeta et al. 2005).

Although musculoskeletal ultrasound has shown much promise in soft tissue work, its use for the diagnosis of stress fracture is limited. One small study found that ultrasonography had a sensitivity of 83 %, specificity of 75 %, a positive predictive value of 58.8 %, and a negative predictive value of 91.7 % for metatarsal fractures (Banal et al. 2009). More investigation is required prior to routine adoption of ultrasound in the diagnosis of bony stress injury.

31.3.4 Treatment

Initial management of most stress fractures is nonoperative. The specific management depends on the nature and location of the fracture. Fibular and posteromedial tibia fractures are considered low risk and can be treated with less aggressive means. Anterior tibia and malleolar fractures are categorized as high risk and should be aggressively managed with casting, non-weight bearing, and use of bone stimulation (Mollon et al. 2008). The healing time can vary from 4 to 12 weeks or even longer dependent upon the location. The treatment begins with relative rest and non-weight bearing in high-risk injuries. Predisposing factors if present, such as suboptimal nutrition and hormonal imbalance, should be corrected. Analgesia with acetaminophen is recommended for pain control; however, NSAIDs should be avoided considering their negative effect on bone healing in animal studies (Wheeler and Batt 2005).

The use of crutches, pneumatic compression walking boots, or stirrup bracing is recommended (Rome et al. 2005). The use of shoe lifts, footwear changes, or orthotics may be necessary if limb malalignment is present.

The most common site for tibial fracture is on the posteromedial cortex. It is treated by relative rest followed by gradual resumption of graded activity. The fracture may take 2–4 months to heal. A pneumatic brace can decrease the time to return to full activity (Swenson et al. 1997). Anterior tibial cortical fractures are more troublesome. Since they are on the tension side of the bone, they are more likely to end up into delayed or nonunion. They may entail the use of cast treatment for up to 6 months (Boden and Osbahr 2000). If conservative measures fail, surgical fixation with drilling, osteosynthesis, or intramedullary rod may be required (Orava et al. 1991; Lassus et al. 2002).

31.3.5 Prevention

Preventative measures include modification of training intensity and formulation of individual training schedules for each athlete. Emphasis should be on proper nutrition maintenance and supplementation if required. Shock-absorbing insoles have been shown to be effective in decreasing lower extremity fractures in military recruits (Rome et al. 2005; Shaffer and Uhl 2006).

31.4 Chronic Exertional Compartment Syndrome

CECS is a less common cause of leg pain, but some studies of referral centers have reported an incidence as high as 27–33 % (Styf 1988; Clanton and Solcher 1994). It is defined as reversible ischemia occurring within a closed fibro-osseous space, which leads to decreased tissue perfusion and ischaemic pain. It is most commonly seen in runners but can also occur in sports requiring repetitive jumping and cutting such as basketball, soccer, and field hockey and basic military training. One of the first reports was described in 1956 by Mavor, when he described the case of a soccer player who was relieved with a fasciotomy (Mavor 1956). CECS most commonly occurs in the lower leg but has also been reported in the thigh and forearm (McDonald et al. 2006).

The anterior compartment is most commonly involved (45 %) followed by the deep posterior compartment (40 %). Infrequently affected are the lateral (10 %) and superficial posterior compartments (5 %) (Edwards and Myerson 1996). Symptoms are bilateral in 50–70 %, and both sexes are equally affected (Touliopolous and Hershman 1999; Glorioso and Wilkens 2001).

31.4.1 Etiology

The lower leg is divided into four compartments: anterior, lateral, superficial posterior, and deep posterior. The anterior compartment contains the anterior tibial vessels and the deep peroneal nerve, while the deep posterior compartment contains the posterior tibial nerve and posterior tibial artery. The remaining two compartments only have major nerves. The lateral compartment has the superficial peroneal nerve, and the superficial posterior compartment contains the sural nerve.

The pathophysiology of CECS is multifactorial. Broadly these factors can include normal muscle swelling that occurs with activity, constrains of a fixed muscular compartment, abnormally thickened fascia, muscle hypertrophy in response to resistance training, and dynamic contraction patterns during gait (Brennan and Kane 2003). With physical activity, the muscle volume increases up to 20 % due to increase in blood flow (Lundvall et al. 1972; Edwards and Myerson 1996; Glorioso and Wilkens 2001). If the fascia is noncompliant, the resultant volume expansion leads to an increase in the pressure within the compartment. After a certain threshold, the pressure becomes so much as to impede venous return and arterial blood flow. This results in focal ischemia and trapping of metabolic excretions within the compartment, leading to pain. This pain is only relieved when the compartment pressure decreases in the hours after the activity has been terminated.

Various anatomic variants also play an important role in the causation of CECS. These include conditions like fascial defects, preponderance of lower capillary density among predisposed individuals, and arterial regulations and blood flow (Fronek et al. 1987; Edmundsson et al. 2010). Creatine supplementation has also been postulated to contribute CECS (Glorioso and Wilkens 2001).

31.4.2 Clinical Presentation

Patients classically have pain during exercise or activity which is described as a dull, cramping, or burning sensation over the involved compartment which may persist even after the activity has ceased. There is almost always no rest pain. Typically the patient is a young runner who experiences recurrent pain after exercise at a reproducible point during exercise (Jones and James 1987). They may complain of numbness or weakness in the lower leg. As the chronicity of the condition increases, the period of time to onset of symptoms during exercise shortens.

High resting muscle tone and fascial herniations indicate that pressures during exercise may surpass pathological levels.

It is essential to provoke the patient's complaints with an exercise test. Zimmermann proposes a standardized treadmill running test with a pain scoring system that allows differentiation of several diagnoses per patient (Zimmermann 2012) (Fig. 31.1).

Repeat physical examination is warranted after a bout of provocative physical activity. One may find evidence of paresthesias, giving an indication as to which compartment is involved. Fascial herniations may be visualized. On palpation, the affected compartment will have increased tightness. In severe cases, muscle weakness and atrophy may be evident (George and Hutchinson 2012). In exceptional cases, CECS may progress into acute compartment syndrome if intensive sports participation is not stopped. Patients should be advised of this rare complication.

31.4.3 Diagnostic Investigation

Radiographs are unremarkable in patients with CECS. Compartment pressure testing is the gold standard for diagnosis. Post-exertional measures are required (Aweid et al. 2012). Pre-exertional measures may provide useful additional information (Paik et al. 2013). All four compartments should be routinely measured to prevent risk of recurrence and surgical failure. Many different methods have been described to measure the compartment pressure including slit catheter (Rorabeck et al. 1981), needle manometer (Whitesides et al. 1975), wick catheter (Mubarak et al. 1976), microcapillary infusion (Styf and Korner 1986), and microtip pressure method (McDermott et al. 1982). In a laboratory model, the arterial line manometer and Stryker devices (Fig. 31.2) are the most accurate (Boody and Wongworawat 2005). However, this has yet to be confirmed in vivo.

The criteria by Pedowitz are generally used in the diagnosis of CECS (Pedowitz et al. 1990). One of the following criteria must be present in addition to proper history and physical examination:

- Resting pressure ≥15 mmHg
- 1 min postexercise pressure ≥30 mmHg
- 5 min postexercise pressure ≥20 mmHg

Fig. 31.1 Lower leg pain profile, pain scores in 4 regions, Zimmermann (2012)

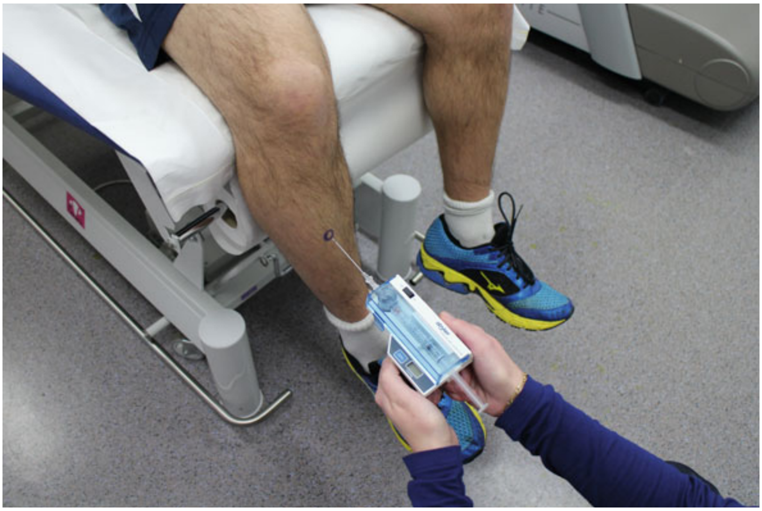

Fig. 31.2 Stryker intracompartmental pressure monitor

Whitesides proposed an alternate criterion, with a pressure increase within 20 mmHg of the diastolic blood pressure considered diagnostic (Whitesides and Heckman 1996).

Table 31.1 lists several other reported diagnostic criteria for CECS. It is important to note that intracompartmental pressure measurements are influenced by ankle

Table 31.1 Diagnostic criteria for chronic exertional compartment syndrome

Criteria	Pre-exercise	1 min postexercise	5 min postexercise
Pedowitz	≥15	≥30	≥20
Veith	>12	>30	>20
Hutchinson and Ireland	>10	–	>25
Verleisdonk	–	≥35	–

All measurements expressed in mmHg (Veith et al. 1980; Pedowitz et al. 1990; Hutchinson and Ireland 1994; Verleisdonk 2002)

and knee position and muscular tension (Gershuni et al. 1984). Clinicians are recommended to use a protocol with standardized catheter depth, exercise type, intensity and duration, footwear, and equipment. It may be wise to raise diagnostic thresholds to improve test specificity at the expense of sensitivity (Roberts and Franklyn-Miller 2012). Simultaneous intramuscular pressure and surface electromyography (EMG) measurement may prevent false diagnosis of CECS. The EMG detects remaining muscle contractions that elevate intracompartmental pressure (Zhang et al. 2011).

These are all invasive approaches, and recently interest has been drawn toward noninvasive pressure monitoring with the use of near-infrared spectroscopy and MRI. Near-infrared spectroscopy shows the deoxygenation of muscles during exercise and delayed reoxygenation postexercise in patients with CECS (Breit et al. 1997; Mohler et al. 1997; Zhang et al. 2001; van den Brand et al. 2004, Zhang et al 2012). MRI shows increased signal intensity in the involved compartment on T2-weighted sequence during exercise. If the compartment fails to return to baseline appearance within 25 min after exercise, it is considered diagnostic (Amendola et al. 1990; Verleisdonk et al. 2001). Other findings that could be seen on MRI are compartment bulging, effacement of fascial planes, convex deep fascial margins, and muscle herniation through fascial defects (Bresler et al. 2012). The usefulness of MRI for diagnosis has been called into question by Andreisek who found no difference in MRIs of healthy versus confirmed CECS patients at 3, 6, 9, 12, and 15 min postexercise (Andreisek et al. 2009).

31.4.4 Treatment

Nonsurgical management of CECS is frequently ineffective. Micheli et al. assessed multiple modalities including ice, rest, electrostimulation, and stretching and found that only prolonged rest and activity cessation were effective (Micheli et al. 1999). Recently, promising results have been reported with changing running technique in patients with CECS of the anterior compartment (Diebal et al. 2012). Anterior compartment pressures are significantly influenced by landing style (Kirby and McDermott 1983).

The use of compression sleeves (Fig. 31.3) is counterproductive, as they are not tolerated by patients with affirmed CECS. The sleeves increase already high

Fig. 31.3 Sport compression sleeves

intramuscular pressures and reduce the time of onset of complaints during exercise (Zimmermann 2013a).

Commonly, a fasciotomy of the involved compartment is required, which can be performed through an open subcutaneous manner or an endoscopic approach (Ota et al. 1999; Leversedge et al. 2002; Lohrer and Nauck 2007; Wittstein et al. 2010). Consistent results are usually obtained after release of the anterior and lateral compartment (80 %) but not after release of the superficial and deep posterior compartment (50 %) (Howard et al. 2000; van Zoest et al. 2008). Fasciotomy is not without its short-term and long-term complications, which include hematoma formation, infection, scarring, venous thromboembolism, nerve injury, inadequate release, unrecognized nerve impingement (George and Hutchinson 2012), and venous insufficiency. Surgery for CECS reduces pain, but patients should be counseled that they may not return to their preinjury level of exercise or remain pain-free (Slimmon et al. 2002).

31.5 Popliteal Artery Entrapment Syndrome

Popliteal artery entrapment syndrome (PAES) is a rare entity but can be of devastating consequence if unrecognized and left untreated. The syndrome occurs most commonly in young active men (Stager and Clement 1999). The reported incidence is 0.2–3.5 % (Anil et al. 2011).

31.5.1 Etiology

PAES commonly results from abnormal anatomic relationship between the popliteal artery and the surrounding musculofascial envelope (Lambert and Wilkins 1999; Stager and Clement 1999). Four types of PAES have been described and classified according to Whelan-Rich (Love and Whelan 1965; Rich et al. 1979). Type 1 occurs when the popliteal artery has a course medial to the medial head of the gastrocnemius muscle. In type 2, the arterial course is normal but the medial head of the gastrocnemius arises from abnormal lateral position. In type 3, there is an abnormal slip of the muscle that arises from the gastrocnemius and compresses the popliteal artery. In type 4, there is an abnormal fibrous band or the popliteus muscle itself compresses the popliteal artery. Type 5, though not originally reported by Whelan, refers to involvement of the popliteal vein. Type 6 is when the anatomy is normal, but there is hypertrophy of the surrounding musculature compressing the artery (functional PAES) (Turnipseed 2009). In addition to the above, repeated trauma to the artery can result in damage to the arterial wall resulting in atherosclerosis or possible thrombus formation. Moreover, there is a possibility of formation of aneurysm distal to the constriction with resultant embolization of the thrombi.

Other potential vascular causes in athletes of lower limb pain include intimal hyperplasia, popliteal artery aneurysm, peripheral arterial dissections, and cystic adventitial disease (Pham et al. 2007).

31.5.2 Clinical Presentation

The typical history is of claudication pain in a young athlete, which may be associated with paresthesias. The pain is brought on by activity at a predetermined distance and usually relieved with rest. Rarely, there may be discoloration of the foot or toes. There is no pain at rest.

Physical examination may reveal abnormal pulses, fullness from an aneurysm, or a normal exam. In the latter case, it may be prudent to palpate the dorsalis pedis and/or tibial arterial pulse and compare pulses when the ankle is in neutral position, maximal dorsiflexion, and maximal plantar flexion. In suspected cases, investigation for an abnormal ankle brachial pressure index could be pursued (normal >0.9).

31.5.3 Diagnostic Imaging

Direct angiography is the gold standard to diagnose PAES. Though angiography can successfully diagnose the arterial constriction, it can shed little light on the exact cause of the stenosis. This is where MR angiography supersedes conventional angiography in that abnormal muscle origin or accessory muscle head could be identified. Moreover, MRI can provide real-time images with the patient performing active dorsiflexion and plantar flexion. Contrast-enhanced MR is helpful in dealing with turbulence and flow patterns in an aneurysm and can successfully delineate the correct lumen of the artery (Elias et al. 2003). It is recommended that MR examinations should be done in a bilateral setting as bilateral involvement is seen in 30–60 % of the patients (Anil et al. 2011). Computed tomography angiography is advantageous as both extremities could be scanned simultaneously with a single bolus and it is faster than MR (Anil et al. 2011).

31.5.4 Treatment

The treatment is almost always surgical with the exact operation guided by the abnormality present. It could either take the form of surgical excision of the offending structure, venous bypass, or an interpositional graft. Other alternatives include endoluminal revascularization (Meier et al. 2010).

Conclusion

Lower leg pain is a common occurrence in athletics. To determine the true etiology, the astute clinician must perform a detailed history and physical examination. Adjunctive testing can assist in confirming the diagnosis. MTSS is the most common cause of exertional lower leg pain. The patient will have diffuse posterior medial tibial pain, whereas the discomfort of a stress fracture is more focal. CECS causes reproducible lower leg pain with tightness and associated neuropathic findings in the affected compartment. Exertional compartment testing is required for diagnosis. In contrast, popliteal artery entrapment syndrome results in exertional claudication and can be confirmed on functional MR angiography. The treatment for MTSS and stress fracture is typically conservative, while that of CECS and PAES often requires surgical intervention.

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Radiologic Imaging of Lower Leg Injuries

32

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Abbreviations

ABI	Ankle-brachial index
BMI	Body mass index = mass (kg)/(height (m))^2
CECS	Chronic exertional compartment syndrome
CT	Computed tomography
CTA	Computed tomographic arteriography
FS	Fat suppression
MIP	Maximal intensity multiplanar reconstruction
MPR	Multiplanar reconstruction
MRI	Magnetic resonance imaging
MTJ	Musculotendinous junction
MTSS	Medial tibial stress syndrome
ROM	Range of motion
SI	Signal intensity

32.1 Introduction

Lower leg injuries are a common problem in athletes. One-third of injuries in long-distance runners are lower leg injuries (Brewer and Gregory 2012). The spectrum of lower leg injuries in athletes contains a number of injuries with very similar presentations. In a retrospective review assessing 150 athletes with exercise-induced leg pain, 33 % had chronic compartment syndrome, 25 % had a stress fracture, 13 % had medial tibial stress syndrome and 10 % had a nerve entrapment syndrome (Clanton and Solcher 1994). Another study among 98 patients with recurrent lower leg pain reported medial tibial stress syndrome in 42 %, chronic compartment syndrome in 27 % and entrapment of the superficial peroneal nerve in 13 % of patients (Styf 1988). This chapter aims to offer a few key points that differentiate between these injuries both in clinical presentation and in imaging characteristics.

The differential diagnosis of (exercise-induced) lower leg pain (in athletes) includes the following disorders:

- Chronic exertional compartment syndrome (CECS)
- Stress fractures of the tibia or fibula
- Medial tibial stress syndrome (MTSS)
- Muscle strains
- Nerve entrapment syndromes
- Popliteal artery entrapment syndrome
- Fascial defects
- Referred pain from the hip or the knee
- Vascular claudication
- Lumbar disc herniation
- Tendinitis/tendinosis
- Effort-induced venous thrombosis
- Neoplasm
- Infection

The most common causes of lower leg pain in athletes and their preferred imaging techniques will be discussed more extensively in the paragraphs below.

32.2 Chronic Compartment Syndrome

32.2.1 Background

Chronic compartment syndrome is also known as chronic exertional compartment syndrome (CECS). The pathophysiology of chronic exertional compartment syndrome is multifactorial (Brewer and Gregory 2012). It is thought to differ from acute compartment syndrome in the sense that in CECS tissue pressures are elevated, but not to the extent that tissue ischaemia occurs, as is the case in acute compartment syndrome (Bong et al. 2005).

Some authors have postulated that in CECS increased compartmental pressure is caused by a combination of physiological factors such as increased blood flow, oedema and muscle volume during strenuous exercise, combined with decreased compliance of the fascia surrounding the compartment (Bong et al. 2005). It is still unclear, however, if pain in CECS is caused by subsequent decreased arterial blood supply and relative ischaemia or rather by periosteal nerve compression (Bong et al. 2005).

The lower leg is divided into multiple compartments containing muscles and other anatomic structures and separated by fascia. The contents of these compartments are described below:

- Anterior compartment: tibialis anterior, extensor hallucis longus, extensor digitorum longus and peroneus tertius muscles, anterior tibial artery and vein and deep branch of the common peroneal nerve.
- Lateral compartment: peroneus longus and peroneus brevis muscles and superficial branch of the common peroneal nerve.
- Superficial posterior compartment: soleus, plantaris and gastrocnemius muscles and the sural nerve.
- Deep posterior compartment: flexor digitorum longus, flexor hallucis longus and popliteus muscles, posterior tibial artery and vein and the tibial nerve.
- The tibialis posterior muscle has its own fascial enclosure and is sometimes considered a separate 'fifth compartment' (Davey et al. 1984).

The compartments that are most commonly involved are the anterior compartment, in 40–60 % of patients, and the deep posterior compartment, in 32–60 % of patients (Bong et al. 2005; Brewer and Gregory 2012).

32.2.2 Risk Factors

Apart from the main patient group of long-distance runners, chronic compartment syndrome is also common in athletes performing sports that require extensive running, such as soccer, football and basketball (Bong et al. 2005). Several studies have observed fascial defects in 20–60 % of patients with chronic compartment syndrome (Pedowitz and Gershuni 1995). These defects are commonly found in the fascia surrounding the lateral compartment (Edwards et al. 2005). Muscle tissue can herniate through a fascial defect, and some authors have considered such herniations to be an indicator of increased compartmental pressure (Blackman 2000).

However, fascial herniations have also been shown to occur in patients without chronic compartment syndrome (Bong et al. 2005).

32.2.3 Clinical Picture

Patients suffering from chronic compartment syndrome commonly present with a dull ache in the leg within the first thirty minutes of exercise. This is then followed by a cramping, burning or aching pain and tightness occurring with continuing exercise (Pedowitz and Gershuni 1995; Bong et al. 2005). Pain often increases during running and quickly disappears when exercise is ceased. Most often, pain is located over the involved compartment(s). In the vast majority of patients, symptoms are bilateral (Bong et al. 2005). Some patients may experience neurological symptoms as well, such as weakness or sensory abnormalities (Blackman 2000; Bong et al. 2005).

Physical examination at rest often reveals no signs of pathology. Palpation is usually not painful, but in some cases, exercising before physical examination can cause the affected muscles to feel tense and deep palpation or passive stretching to be painful (Blackman 2000; Bong et al. 2005).

32.2.4 Clinical Diagnostics

Compartment hydrostatic pressure testing is the gold standard for the diagnosis of chronic compartment syndrome, requiring pre-exertional and post-exertional measurements (Bong et al. 2005; Edwards 2005; Brewer and Gregory 2012). Exact methods and techniques and normal values of measuring pressure vary, but measurements should always be done in rest, followed by measurement after exercise similar to the level of exercise in the athlete's regular routine (Bong et al. 2005). Pedowitz et al. have described criteria for these pressure measurements to be applied in clinical practice (Pedowitz and Gershuni 1995). However, compartment pressure testing is an invasive diagnostic method, which explains why imaging modalities such as MRI and ultrasound also have a valuable role in the diagnosis of chronic compartment syndrome.

32.2.5 Radiologic Imaging

The additional value of radiologic imaging in CCS is limited.

32.2.5.1 Magnetic Resonance Imaging

In two studies, MRI has been shown to detect an increased T2-weighted signal in the affected compartment in patients with chronic anterior compartment syndrome, where in one study this increased signal disappeared after fasciotomy (Eskelin et al. 1998; Verleisdonk et al. 2001). One study describes significant post-exertional MRI findings in CCS at forearm muscles in motocross racers (Gielen et al. 2009). However, the interpretation of increased signal intensity (SI) should be interpreted carefully as increased muscle signal is also described in non-symptomatic racers. However, more research is necessary before MRI can be applied universally as a method for detecting increased compartmental pressure (Bong et al. 2005).

32.2.5.2 Ultrasound

The use of ultrasound in the diagnosis of chronic compartment syndrome has been evaluated on a small scale (Rajasekaran et al. 2013). The diagnosis is based on the anterior compartment thickness as measured on ultrasound images (Rajasekaran et al. 2013). Although ultrasound is a promising non-invasive diagnostic modality, general criteria do not yet exist for the diagnosis of chronic compartment syndrome.

32.2.5.3 Other Imaging Methods

Imaging methods other than MRI or ultrasound have not proved useful in the diagnosis of chronic compartment syndrome (Pedowitz and Gershuni 1995; Blackman 2000). Imaging modalities such as conventional radiographs or CT are mostly used to exclude other causes of chronic leg pain (Blackman 2000).

32.2.5.4 Treatment

The conservative treatment of chronic compartment syndrome consists of sport cessation or massage therapy, but these are not considered successful options

(Bong et al. 2005). A more effective treatment but invasive option is surgical fasciotomy of the involved compartments of the leg (Bong et al. 2005).

32.3 Lower Leg Stress Fractures

32.3.1 Background

In literature, various terms are used for describing stress fractures, such as insufficiency, fatigue, incremental, low-trauma and march fractures (Liong and Whitehouse 2012). The cause is thought to be excessive, prolonged or recurrent loading of the bone producing a misbalance between bone resorption and bone formation processes, which leads to stress injury (Lassus et al. 2002). If overuse with microtrauma is continued, eventually a stress fracture can develop (Lassus et al. 2002; Brewer and Gregory 2012). As much as 80–95 % of all stress fractures are located in the lower extremity, with the majority of these fractures involving the tibia and a minor part concerning the fibula (Brewer and Gregory 2012). Stress fractures of the tibia can be either transverse or longitudinal (Liong and Whitehouse 2012). Transverse fractures are more common, whereas longitudinal fractures are seen in only 10 % of tibial stress fractures. Tibial stress fractures usually affect the distal two-thirds of the posteromedial tibia, categorised as low-risk stress fractures, compared to anterior cortex stress fractures, which are considered high risk (Liong and Whitehouse 2012). Stress fracture of the fibula occurs most often in the lower third part of the fibula, just proximal to the attachment of the tibiofibular ligament (Fredericson et al. 2006).

32.3.2 Risk Factors

Stress fractures of the lower leg are common in military recruits, dancers and athletes, especially long-distance runners. Females have a four times higher risk of a stress injury in general (Lassus et al. 2002). Other risk factors for stress fractures include Caucasian race, irregular menses, eating disorders, osteoporosis or osteopenia, and previous stress fractures (Lassus et al. 2002; Edwards 2005). Additionally, multiple concurrent stress fractures are not unusual, as is seen in 10 % of runners and in 20 % of female athletes (Sullivan et al. 1984; Bennell and Brukner 1997).

32.3.3 Clinical Picture

At first, patients experience only pain during exercise, but later on pain is also present in rest and in some cases even at night (Lassus et al. 2002; Edwards 2005; Fredericson et al. 2006). Swelling of the surrounding soft tissues may be present (Lassus et al. 2002).

On physical examination, the leg commonly appears normal. Palpation or tapping at the site of fracture can produce tenderness if extensive bone marrow involvement is present (Fredericson et al. 1995). In a third of patients, the posterior part of the tibia can be painful (Fredericson et al. 2006). Pain can be accompanied by erythema or localised swelling of the leg (Edwards 2005). The bony tenderness can be more discrete than in chronic compartment syndrome or MTSS (Bong et al. 2005). Vibratory pain at the site/location of the stress fracture is thought to be able to confirm the diagnosis (Edwards 2005).

32.3.4 Clinical Diagnostics

Imaging has an important role in the diagnosis of lower leg stress fractures, especially because early identification of stress fractures is essential in order to prevent long-term complications.

In some cases, the diagnosis of stress fracture can be made exclusively based on patient history and physical examination. In inconclusive cases, however, imaging can provide additional information that is essential for the diagnosis. The imaging modalities used most commonly in the diagnostic workup of lower leg stress fractures are plain radiographs, CT, MRI and bone scintigraphy.

32.3.5 Radiologic Imaging

32.3.5.1 Conventional Radiography

In the diagnostic workup of (chronic) leg pain in athletes, plain radiographs are mainly used to rule out fatigue fractures (Bong et al. 2005). However, false negatives are not uncommon, and because of this low sensitivity, X-ray is not decisive in the diagnosis of fatigue fractures of the lower leg (Lassus et al. 2002; Beck et al. 2012). Especially in early fatigue fractures, plain radiographs are usually negative, and sensitivity can be as low as 10 % (Brewer and Gregory 2012). Additionally, radiographic signs only become visible after 2–12 weeks after the onset of symptoms, if at all (Lassus et al. 2002; Edwards 2005). Nevertheless, radiography is considered the imaging option of choice when suspecting a stress fracture of the lower leg to rule out other bony pathology.

The first sign of a stress fracture on radiography is the 'grey cortex sign', a grey-looking hypodense area seen in the bone cortex, which is thought to be related to the resorption phase of bone remodelling (Mulligan 1995) (Fig. 32.4a). Subsequently, new periosteal bone formation and endosteal bone thickening can be observed in this area (Lassus et al. 2002; Fredericson et al. 2006) (Fig. 32.1). A fracture line, if at all present, can be visible as a radiolucent line in compact cortical bone or as a sclerotic line in cancellous bone. Especially the midanterior cortex should be thoroughly evaluated for a subtle lucency, labelled 'the dreaded black line', which can indicate the presence of a midanterior cortex tibial stress fracture (Edwards 2005).

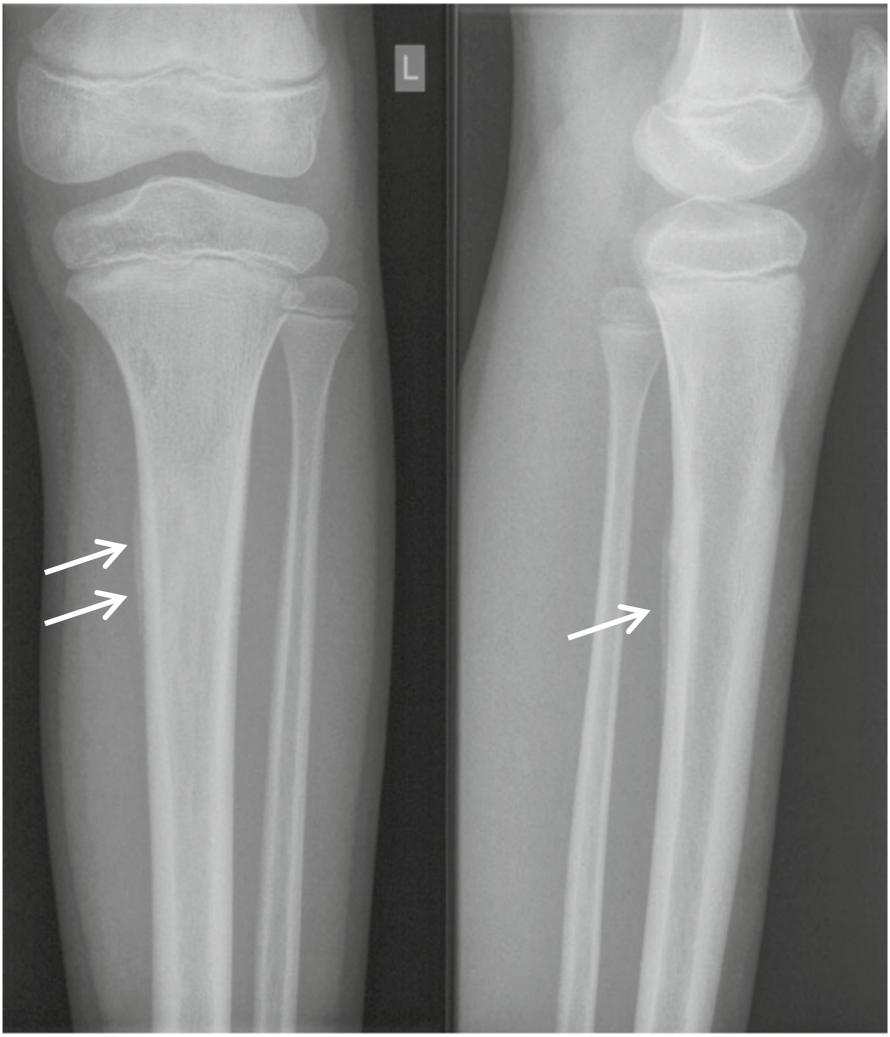

Fig. 32.1 A 9-year-old boy with exertion-related chronic tibia shaft pain at the left side. Radiograph demonstrates unilamellar calcified periosteal reaction at the medial and posterior aspect of the proximal third of the tibia diaphysis (*arrows*). No fracture signs are present

Other signs of stress fracture on conventional imaging include osteopenia, endosteal reaction, vague cortical margin and, in advanced stages, partial or complete fracture (Edwards 2005; Fredericson et al. 2006) (Fig. 32.2).

Transverse stress fractures of the tibia are identified as a transverse fracture line, perpendicular to the bone cortex, but in many cases no abnormalities are visible at all (Lassus et al. 2002). Longitudinal stress fractures of the tibia can be difficult to recognise on conventional radiographs because of the lengthwise fracture line orientation (Lassus et al. 2002). In fibular stress fractures, the first sign on radiographs

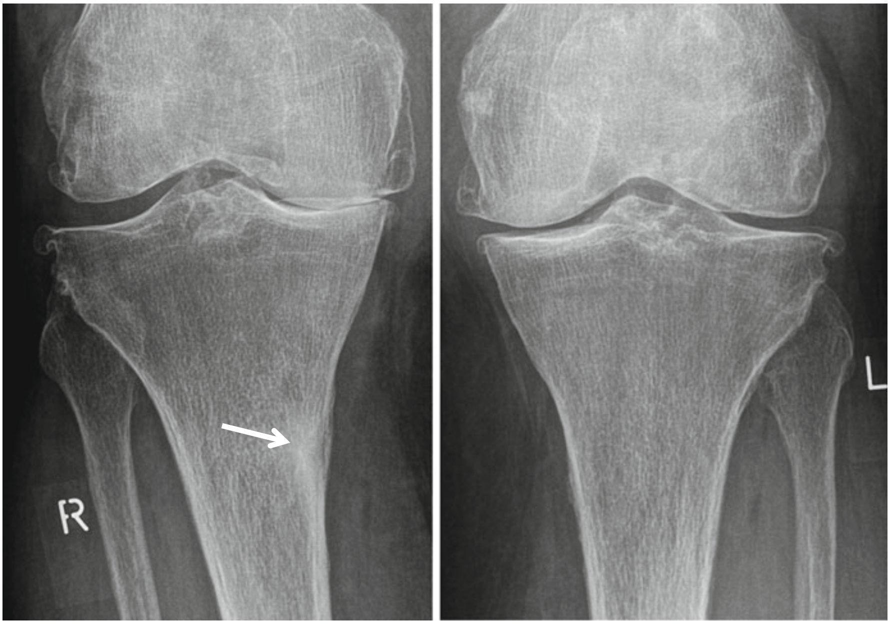

Fig. 32.2 A 69-year-old woman with stress fracture at the right proximal tibia diaphysis. Left side for comparison. Demonstration of cortical osteopenia, periosteal and endosteal reaction with sclerosis at the endosteal lining (*arrow*)

is a hazy periosteal reaction, which is followed by callus or a fracture line in persistent disease (Lassus et al. 2002).

32.3.5.2 Computed Tomography

Computed tomography (CT) is used less frequently than radiography in the diagnosis of lower leg stress fractures, but it is able to differentiate stress fractures from stress reactions. This can aid in the exclusion of other causes of stress reaction such as malignancy (Brewer and Gregory 2012). Although CT is considered less sensitive than X-ray, longitudinal and spiral fracture lines are better visible on CT than on conventional radiographs (Lassus et al. 2002). Additionally, CT is able to depict osteopenia as a first sign of fatigue damage of the cortical bone and can detect bone loss better than X-ray (Gaeta et al. 2005). This is particularly useful in the diagnosis of stress fractures, because osteopenia is the earliest sign of fatigue injury to bone cortex (Gaeta et al. 2005). In certain cases, CT can even distinguish fractures lines that are not visible on MRI (Lassus et al. 2002).

32.3.5.3 Magnetic Resonance Imaging

Several authors have found MRI with fat suppression to be useful or promising in the diagnosis and grading of lower leg stress fractures (Fredericson et al. 1995). MRI can often detect bone marrow oedema within days of the onset of symptoms and is more sensitive and specific than CT or bone scintigraphy in diagnosing stress

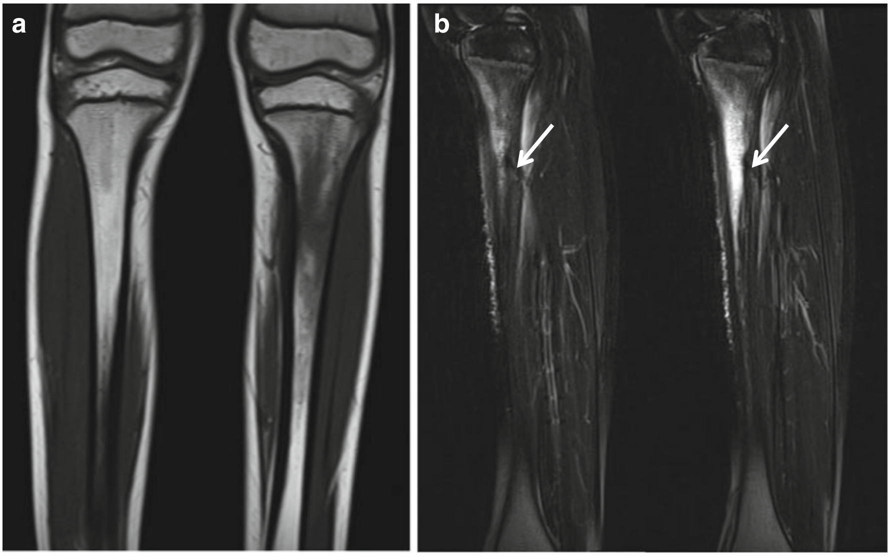

Fig. 32.3 MRI, same patient as 32.1. (**a**) coronal T1-WI left tibia with right tibia for comparison. Decreased SI at the medulla of the tibia diaphysis – proximal third at the left tibia – with thickening of the periosteum and cortical bone at the medial aspect. (**b**) Sagittal T2-WI with fat suppression. Increased SI at the medulla and posterior periosteum and periosseous soft tissues with demonstration of cortical fracture line with low SI (*arrows*). Thickening of the cortex related to ossified periosteal reaction

fractures of the tibia, with a reported sensitivity of 88 % and a specificity of 100 % (Fredericson et al. 1995; Ishibashi et al. 2002; Gaeta et al. 2005; Brewer and Gregory 2012). Because of these characteristics, MRI is increasingly popular in the workup of suspected lower leg stress fractures. However, this also implies that MRI is most useful during the first 3 weeks of symptoms, because the oedema disappears before signs of new bone formation appear (Lassus et al. 2002). Abnormalities on MRI have been correlated to a longer recovery period in bone stress injuries in general (Arendt et al. 2003).

Especially in cancellous bone stress injuries, bone marrow oedema is the primary sign of injury, which is not visible on conventional radiographs or CT (Gaeta et al. 2005). In both cancellous and cortical stress injuries, MRI with T2-weighted FS or STIR images is the imaging method of choice (Gaeta et al. 2005) (Figs. 32.3 and 32.4). The amount of bone marrow oedema is commonly more extensive than in medial tibial stress syndrome, and, in severe cases, a fracture line can be seen (Lassus et al. 2002). In fibular stress fractures, radiographs are usually positive, but MRI can show earlier abnormalities such as periosteal or bone marrow oedema and even fracture lines (Bergman and Fredericson 1999).

Despite these diagnostic advantages, MRI should still be interpreted with caution. A clear fracture line is confirmative of the diagnosis of stress fracture, but the presence of solely oedema in the absence of a fracture line does not rule out other

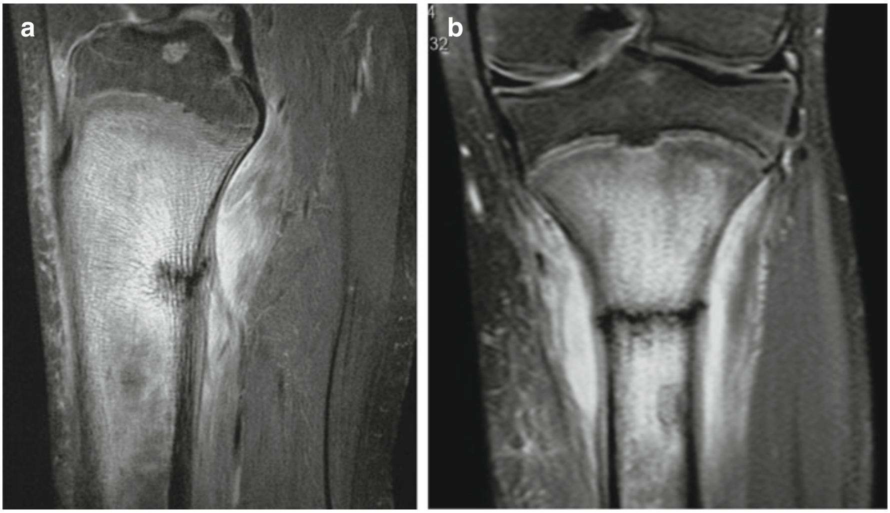

Fig. 32.4 Transverse fatigue fracture of the proximal right tibia. MRI of the right knee with sagittal (**a**) and coronal (**b**) T2-WI with FS demonstrating an extensive area with bone marrow oedema and hypointense fracture line with transverse orientation at the posterior third of the proximal tibia diaphysis. Periosteal new bone formation with multilamellar character is demonstrated at the posterior corticalis on sagittal image (**a**). Soft tissue oedema is surrounding the proximal metaphyseal and diaphyseal parts of the tibia

stress reaction of the bone (Lassus et al. 2002) (Fig. 32.3). In contradistinction with bone marrow oedema, fracture lines at the spongious bone are easier documented on T1-WI compared to T2-WI with FS (Fig. 32.5). Furthermore, in a study by Bergman et al., 43 % of 21 asymptomatic runners were found to have abnormalities suggesting stress reaction on MRI of the lower leg, while none developed a stress injury after 12 months (Bergman et al. 2004). This is interpreted as physiologic increased bone remodelling and production in line with Wolff's law, with adaption of the bone turnover of a healthy person to increased load resulting in increased strength and ability to resist higher loading. This is specifically the case in sports with increased activity or training. MRI findings should thus always be combined with the clinical picture.

Several studies have compared MRI with scintigraphy, concluding that both are useful imaging modalities for the early diagnosis of lower leg stress fractures (Fredericson et al. 1995). The sensitivity of MRI in diagnosing stress injuries is similar to that of bone scintigraphy, but the specificity is higher (Lassus et al. 2002).

32.3.5.4 Ultrasound

The value of ultrasound in the diagnosis of lower leg stress fractures is very limited. In some cases, periosteal or muscle oedema, a cortical fracture line or callus can be seen (Kiuru et al. 2004) (Fig. 32.6).

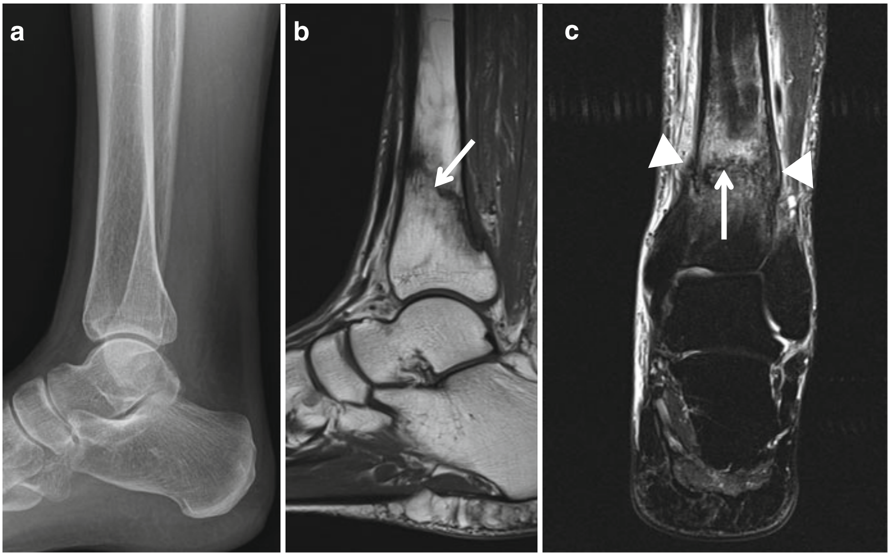

Fig. 32.5 Radiograph and MRI of a 54-year-old female with fatigue fracture at the left distal tibia meta- to diaphysis. No signs of stress fracture are observed on radiograph (**a**). MRI examination is performed 2 months later with sagittal T1-WI (**b**) and coronal T2-WI with fat suppression (**c**). Hypointense fracture line is easier documented on T1 compared to T2-WI (*arrow*). Complete fracture with medial translation over 5 mm is seen on the coronal image. Calcified periosteal reaction with low SI is demonstrated on the medial and lateral aspect of the fracture line (*arrowheads*). Non-calcified periosteal reaction and adjacent soft tissue oedema with increased SI on T2-WI FS are demonstrated. Discrimination of ossified and not ossified periosteal reaction is not possible on T1-WI

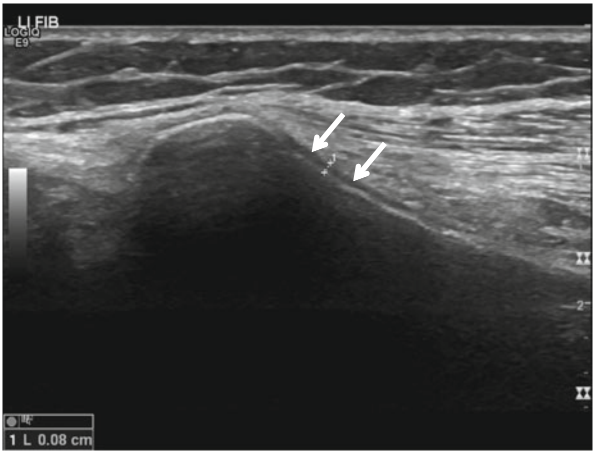

Fig. 32.6 A 20-year-old female basketball player with chronic exertional pain at the level of the posterolateral knee. Longitudinal ultrasound examination at the level of the proximal third of the left fibula metaphysis reveals hyposonant thickening of the periosteum (*arrow*) with regular cortical margin

32.3.5.5 Grading Systems

Based on conventional radiographs, CT, MRI and nuclear imaging methods, grading systems have been developed for the diagnosis and staging of stress fractures

Table 32.1 Imaging classification by Kaeding et al. (2013)

Grade	Radiograph findings	MRI findings
Normal	Normal	Normal
1	Normal	Positive STIR image
2	Normal	Positive STIR and positive T2-weighted image
3	Periosteal reaction	Positive T1-, T2-weighted and STIR without definite cortical break visualised
4	Injury or periosteal reaction	Positive injury line on T1- or T2-weighted scans

(Beck et al. 2012). In 1989, Jones et al. developed a radiological classification of bone stress injuries (Jones et al. 1989). Fredericson et al. developed a classification of bone stress injuries using MRI (Fredericson et al. 1995). Gaeta et al. described criteria for the diagnosis of early tibial stress injuries on CT and MRI (Gaeta et al. 2005). Recently, Kaeding et al. have introduced a classification of stress fractures (Kaeding and Miller 2013). Arendt et al. developed a grading system in 2003 (Arendt et al. 2003) (Table 32.1).

32.3.5.6 Treatment

Treatment is primarily focused on pain relief using relative unloading of the limb and NSAIDs and prevention of further injury with a period of rest, sometimes using a brace or cast (Lassus et al. 2002; Edwards 2005). Recovery times reportedly vary from 4 to 20 weeks, depending on the severity of the stress injury (Beck et al. 2012). In severe or persistent cases or when quick return-to-play is needed, surgical treatment can be considered, which consists of placement of an intramedullary nail (Edwards 2005).

32.4 MTSS

32.4.1 Background

Medial tibial stress syndrome (MTSS) is also known as ‘shin splints’ or soleus enthesopathy (Moen et al. 2009; Newman et al. 2013). This variation in nomenclature can be confusing. The reported incidence of MTSS varies from 4 to 35 % in various populations (Moen et al. 2009). Medial tibial stress syndrome comprises 6–16 % of all running injuries and up to 50 % of lower leg injuries in selected populations such as military recruits (Kortebein et al. 2000; Yates 2004).

Many hypotheses describe the possible aetiology of this syndrome, but little data are available on exact injury mechanisms (Newman et al. 2013). The most commonly accepted hypothesis describes periostitis, a stress reaction on the periosteal attachment to the bone without stress fracture, caused by repetitive pull of the soleus muscle on its posteromedial tibial insertion (Moen et al. 2012; Newman et al. 2013). Another theory is based on the concept of bone overload due to a complex of factors such as periostitis, tendinopathy and muscle dysfunction (Brewer and Gregory 2012; Moen et al. 2012).

As in tibial stress fractures, in MTSS usually the distal two-thirds of the posteromedial tibia are affected (Liong and Whitehouse 2012).

32.4.2 Risk Factors

MTSS is most common among military recruits and athletes performing sports that involve repetitive jumping and landing (Lassus et al. 2002; Moen et al. 2009). The highest incidence is found in long-distance running, but athletes involved in tennis, basketball, volleyball and rhythmic gymnastics can suffer from MTSS as well (Edwards 2005; Moen et al. 2009).

Factors associated with a higher risk of developing MTSS are female gender, a previous history of MTSS, fewer years of running experience, prior orthotics use, increased BMI, increased navicular drop and increased external rotation hip range of motion (ROM) in males (Brewer and Gregory 2012; Newman et al. 2013).

32.4.3 Clinical Picture

The symptoms of medial tibial stress syndrome are similar to those of a lower leg stress fracture. In MTSS, however, pain is more diffuse compared to stress fractures, where pain is more focal (Moen et al. 2009). Night pain and pain on percussion are usually not present in MTSS. Patients commonly present with exercise-induced leg pain along the posteromedial border of the middle or distal two-thirds of the tibia (Edwards 2005; Moen et al. 2009; Liong and Whitehouse 2012). Initially, pain starts with exercise but subsides with continued exercise and is absent in rest (Edwards 2005; Moen et al. 2009). In certain cases, pain will recur at the end of the activity, and in more advanced disease, pain continues to be present during activity and may not subside with rest (Edwards 2005; Moen et al. 2009). Especially forced pronation and plantar flexion during activity can cause exacerbation of pain (Edwards 2005).

On physical examination, diffuse posteromedial tenderness on palpation of the distal two-thirds of the posteromedial tibial border is most sensitive (Bong et al. 2005; Liong and Whitehouse 2012). Swelling or erythema is rare, and vascular and neurological examinations are usually normal (Edwards 2005).

32.4.4 Clinical Diagnostics

The diagnosis of MTSS can be made clinically (Moen et al. 2009). In the differential diagnosis of medial tibial stress syndrome, a stress fracture of the lower leg should always be considered. Imaging should thus be performed to rule out stress fracture. Both bone scan and MRI can be used to confirm the diagnosis in the diagnostic workup of medial tibial stress syndrome (Moen et al. 2009). Medial tibial stress syndrome is considered a clinical diagnosis. Nevertheless, when the diagnosis is unclear or symptoms persist despite conservative treatment, additional imaging can be of use (Moen et al. 2009). The clinical diagnosis of MTSS is often used as the gold standard in defining sensitivity and specificity of imaging techniques (Moen et al. 2009).

32.4.5 Radiologic Imaging

32.4.5.1 Conventional Radiography

In patients with medial tibial stress syndrome, radiographs may show mild postero-medial thickening of the cortex (Bong et al. 2005). More commonly, however, plain radiographs will not display any abnormalities at all (Anderson et al. 1997; Brukner 2000; Magnusson et al. 2001). X-ray imaging is thus mainly used to exclude other causes of lower leg pain, such as stress fractures or tumours (Edwards 2005; Moen et al. 2009).

32.4.5.2 Computed Tomography

Gaeta et al. showed osteopenic changes in the tibial cortex using high-resolution CT scan, with a 42 % sensitivity and a 100 % specificity (Gaeta et al. 2005). However, a large portion of asymptomatic runners showed osteopenic changes on CT as well (Gaeta et al. 2006).

32.4.5.3 Magnetic Resonance Imaging

MRI can be of use in determining the severity of tibial stress reaction (Fredericson et al. 1995). When MTSS is present, MRI can detect periosteal oedema and bone marrow oedema with a sensitivity of 79–88 % and a specificity of 35–100 % (Batt et al. 1998; Gaeta et al. 2005) (Fig. 32.7). Fredericson et al. composed a MRI classification system that includes periosteal oedema, bone marrow oedema and eventually true stress fracture (Fredericson et al. 1995). This grading system has been modified by Arendt et al. (Arendt et al. 2003).

In a prospective study, Moen et al. found signs of bone marrow oedema and periosteal oedema on MRI in 44 % of 104 symptomatic legs of patients with MTSS (Moen et al. 2012). However, several other studies have shown large numbers of asymptomatic legs with similar changes on MRI (Batt et al. 1998; Bergman et al. 2004). This suggests that bone marrow oedema and periosteal oedema are imaging characteristics that cannot be attributed exclusively to MTSS. In a small prospective study, STIR images have been found valuable in the detection of periosteal oedema in patients with medial tibial pain (Mattila et al. 1999).

Apart from its diagnostic value, MRI is thought to be useful in determining the prognosis of medial tibial stress syndrome as well. Arendt et al. found that MRI can be of use in estimating the time to return to sport in MTSS (Arendt et al. 2003). Moen et al. concluded that the absence of abnormalities such as bone marrow oedema or periosteal oedema on MRI in patients with MTSS was associated with a longer recovery time (Moen et al. 2012). Anderson et al. reported a relationship between the absence of signs of MTSS on MRI and longer duration of medial tibial stress symptoms (Anderson et al. 1997).

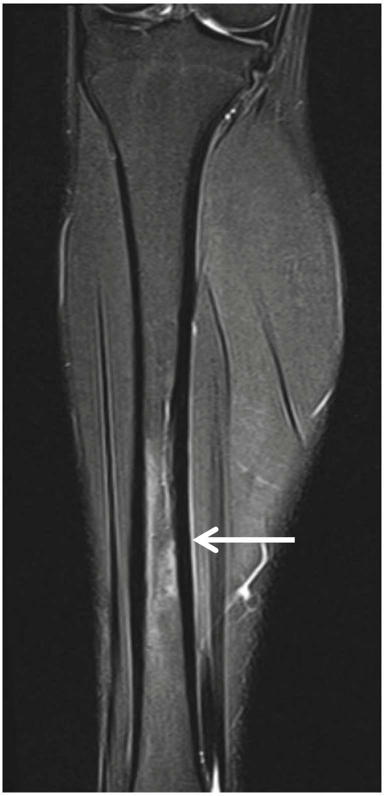

Fig. 32.7 A 17-year-old male ballet dancer with clinical complaints of MTSS. Endosteal and periosteal (*arrow*) minor oedema at the middle third of the diaphysis

32.4.6 Treatment

The treatment of medial tibial stress syndrome is conservative, and pain usually resolves with relative unloading of the limb, ice and NSAIDs (Edwards 2005). Recovery times are usually long. In a study among 74 athletes, the return to level of presymptomatic running performance took 6–10 months in the majority of patients (Moen et al. 2012).

32.5 Popliteal Artery Entrapment Syndrome and Endofibrosis

32.5.1 Background

Compression of the popliteal artery by surrounding musculotendinous structures as it exits the popliteal fossa is commonly known as popliteal artery entrapment syndrome (Edwards 2005; Brewer and Gregory 2012). Usually, this syndrome is caused by an accessory medial head of the gastrocnemius passing posterior to the popliteal artery, but other less common causes such as fibrous bands of the gastrocnemius or popliteus muscles or aberrant popliteal artery have been described as well (Ehsan et al. 2004). Endofibrosis is a condition firstly described in cyclists at the external iliac artery related to an extremely high blood flow with repetitive flexion of the artery, with kinking of the artery leading to build-up of fibrous tissue on the inside of the artery; it is rarely described at the popliteal artery (Peach et al. 2012).

32.5.2 Risk Factors

Popliteal artery entrapment syndrome is more common among males and especially those performing sports that require excessive dorsiflexion and plantar flexion of the ankle, such as football, basketball, soccer and running (Edwards 2005). Endofibrosis is described in cyclists, rowers and triathletes in endurance sports with repetitive flexion of arterial segments.

32.5.3 Clinical Picture

Patients with popliteal artery entrapment syndrome and/or endofibrosis present with symptoms of intermittent exertion-related claudication, such as pain and cramping in the calf, coldness of the affected leg and sometimes even paraesthesias in the foot (Fredericson et al. 2006). Symptoms are typically present unilaterally and in the posterior part of the leg (Edwards 2005).

On physical examination, the leg can feel cool. Reduced pulses on palpation are considered a pathognomonic sign of popliteal artery entrapment syndrome (Edwards 2005).

32.5.4 Clinical Diagnostics

The diagnostic workup of popliteal artery entrapment syndrome and endofibrosis is similar to that of any other arterial occlusion in the leg. An initial screening is done by ankle-brachial index (ABI) before vascular studies of the lower extremity are performed (Brewer and Gregory 2012). It is recommended to perform the ABI with the foot in different positions to test for possible functional causes of artery entrapment (Brewer and Gregory 2012). An ABI below 0.9 is considered abnormal. Sensitivity of the ABI is 90 % and specificity is 98 % in patients with a stenosis of more than 50 % in a major leg artery.

32.5.5 Radiologic Imaging

When the ankle-brachial index is below 0.9 indicating possible stenosis, Doppler ultrasound studies and comparative blood pressure measurements can be performed in order to detect any vascular abnormalities (Bong et al. 2005).

Computed tomography angiography (CTA) or magnetic resonance angiography (MRA) can be performed to confirm the diagnosis and depict the exact localisation of the arterial compression or tapering due to endofibrosis and occlusion in case of complication with thrombosis (Toorop et al. 2004). The major differential diagnosis in younger patients is a popliteal adventitial cyst and atheromatosis in older patients. Ultrasound is a good technique to exclude the presence of a popliteal adventitial cyst (Fig. 32.8). In endofibrosis a typical finding is tapering of the

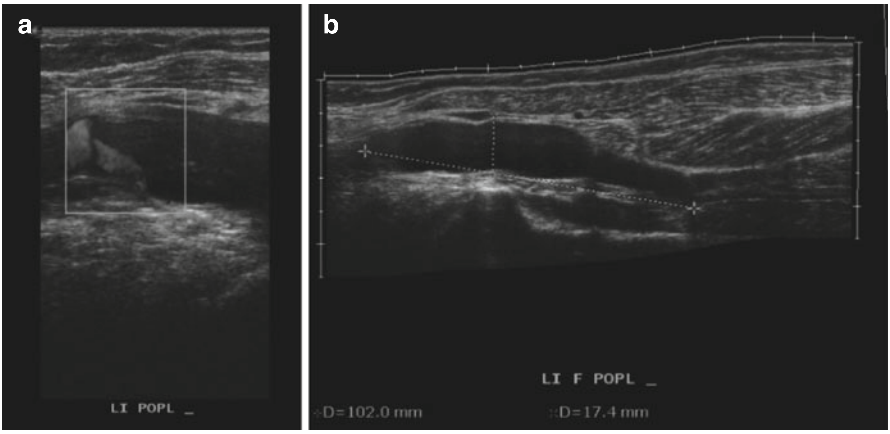

Fig. 32.8 A 49-year-old male presents with progressive claudication of the left calf during and after short walks. He has no right-sided symptoms. The patient takes no medication, he is a non-smoker and there are no obvious other anamnestic risk factors for atherosclerosis. Physical examination shows mild muscle atrophy of the left calf and no signs of venous insufficiency. Popliteal pulses were absent and pedal pulses weak. (**a**) Ultrasound of the left knee in sagittal-longitudinal view of the popliteal artery. Image plane sagittal and longitudinal to the popliteal artery (left = proximal). Power Doppler box at the level of the popliteal artery. A well-delineated cystic lesion (anechoic tubular mass lesion without intralesional power Doppler activity) is present at the right half of the power Doppler box. The lesion has a close correlation to the popliteal artery and tapers its lumen. Power Doppler activity is present at the popliteal artery at the left half of the power Doppler box and stops at the level of its tapering. There are no signs of atherosclerosis (no wall thickening, neither calcifications) at the popliteal artery. (**b**) Ultrasound of the left knee, panoramic view with image plane sagittal and longitudinal to the popliteal artery (left = proximal). Longitudinal overview of the cyst. Maximal craniocaudal dimension 10 cm, maximal anteroposterior dimension 1.7 cm. (**c**) First-pass contrast-enhanced CT angiography (MD-CT, 64-slice GE), axial MPR of both knees at the level of the fossa poplitea. Normal opacification of the right popliteal artery (*arrowhead*). Sharply demarcated, hypodense cystic lesion at the left side, without opacification of the popliteal artery (*arrow*). (**d**) First-pass contrast-enhanced CT angiography (MD-CT, 64-slice GE), sagittal MPR at the left fossa poplitea region. Demonstrates the secondary compression and tapering of the popliteal artery at its proximal part (*arrow*). (**e**) First-pass contrast-enhanced CT angiography (MD-CT, 64-slice GE), thick slab MIP reconstruction of the popliteal regions. Tapering and occlusion of the left proximal popliteal artery (*arrow*). Development of collateral circulation with reinjection at the distal truncus tibiofibularis and proximal anterior tibial artery. Normal findings at the right side

Fig. 32.8 (continued)

artery (Fig. 32.9). Both radiological techniques are useful and less invasive methods than direct digital (subtraction) angiography, which is the gold standard for the diagnosis of popliteal artery entrapment syndrome and endofibrosis (Edwards 2005; Brewer and Gregory 2012). Imaging during dorsiflexion of the foot is mandatory to demonstrate the compression of the artery in popliteal entrapment syndrome. MRI is the best technique to discriminate the origin of the arterial compression, i.e. muscle hypertrophy, accessory medial head of the gastrocnemius, fibrous bands of the gastrocnemius or popliteus muscles or aberrant popliteal artery (Fig. 32.9).

32.5.6 Treatment

The preferred treatment of popliteal artery entrapment is surgical popliteal artery release, resulting in restored blood flow in the artery (Edwards 2005). In patients with endofibrosis and no signs of arterial damage, the release of the artery can also be achieved by myotomy and consequent cleaving of the fibrous band (Edwards 2005). In more severe cases, endarterectomy and vein patch angioplasty or even saphenous vein bypass grafting can be necessary to preserve arterial blood flow (Edwards 2005; Brewer and Gregory 2012).

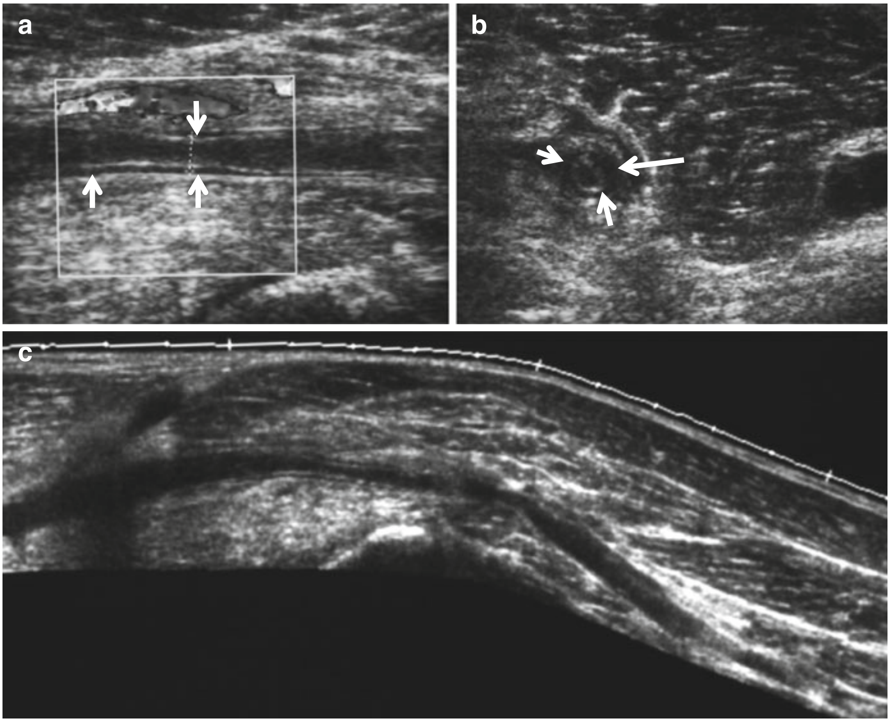

Fig. 32.9 Endofibrosis at the left popliteal artery in a 45-year-old male patient with a history of intermittent claudication at the left lower leg, developed during alpine ski and increased over several years. He looked for medical assistance with acute claudication at the left lower leg. Ultrasound (**a**–**c**) and digital subtraction angiography were performed (**d**, **e**). Ultrasound with sagittal Doppler registration (**a**), axial (**b**) and panoramic sagittal imaging of the left popliteal artery demonstrates gradual thinning (tapering) of the popliteal artery lumen with circular hyposonant thickening of the subintimal layer of the tunica media (*arrows*) and regular lining of the reflective intima. Absence of flow related to acute thrombosis is documented on Doppler registration (**a**). Digital subtraction angiography (**d**, **e**) of the left and right knee demonstrates the occlusion of the left popliteal artery

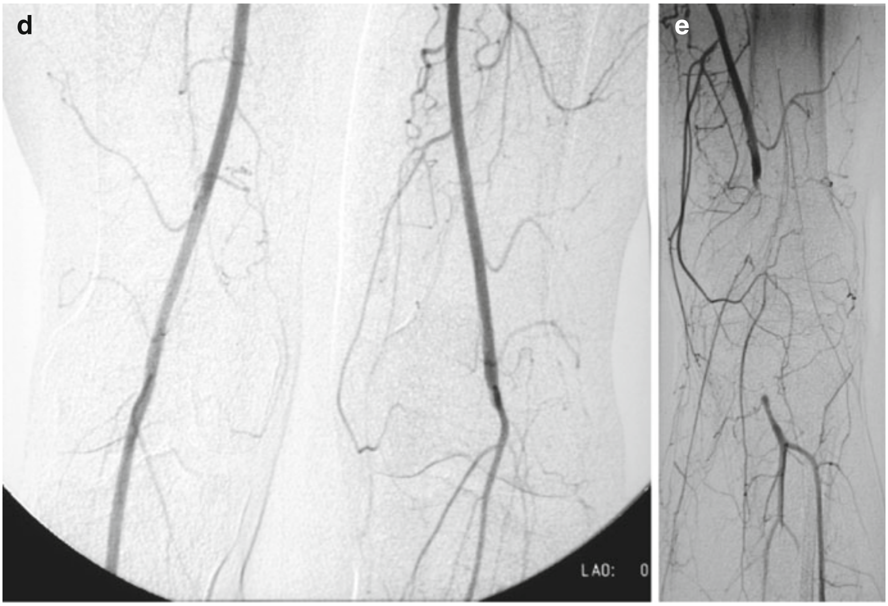

Fig. 32.9 (continued)

32.6 Nerve Entrapment

32.6.1 Background

In peripheral nerve entrapment of the lower leg, the common peroneal nerve, superficial peroneal nerve and saphenous nerve are affected most commonly (Edwards 2005; Brewer and Gregory 2012). The primary cause of nerve entrapment in the lower leg is trauma (Edwards 2005).

32.6.2 Clinical Picture

Patients complain of a burning pain in the region where the nerve is compressed, radiating to the area innervated by the affected nerve (Edwards 2005). Pain starts on activity and exacerbates if exercise is continued, sometimes accompanied by regional motor or sensory symptoms (Edwards 2005; Brewer and Gregory 2012). At physical examination, the area of nerve compression can be tender on palpation (Edwards 2005). Swelling can be present, but more localised than seen in chronic exertional compartment syndrome (Edwards 2005). Compression or percussion of the nerve can elicit a tingling sensation suggestive for nerve entrapment.

32.6.3 Clinical Diagnostics

Confirmation of peripheral nerve entrapment is achieved through electromyography and nerve conduction studies. However, the condition needs to present for at least 3–4 weeks for conduction abnormalities to become visible.

32.6.4 Radiological Diagnosis

In the diagnosis of nerve entrapment in the lower leg, imaging techniques are of limited value. Conventional radiographs are used in some cases, mainly to rule out other causes of nerve compression, such as bony abnormalities, stress fractures or tumours (Edwards 2005). MRI and ultrasound can be of additional value to demonstrate variant muscle and tendon anatomy, secondary wallerian degeneration of the nerve and neuromas or neurinomas.

32.7 Acute Muscle Trauma

Acute muscle trauma can be either indirect, i.e. related to muscle elongation with or without muscle tearing, or direct due to a blow on the muscle against the bone or fascia; the former is referred to as muscle strain, the latter as muscle contusion. Muscle contusion is more commonly encountered at the thigh at the level of the vastus intermedius and lateralis of the quadriceps femoris muscle. It is typically related to haemorrhagic infiltration and haematoma and will not be discussed in this chapter. If shear stress is applied on the skin, the subcutaneous tissue and superficial muscle fascia or bone may become separated. This type of lesion is referred to as Morel-Lavallée lesion; it is well known at the lateral aspect of the knee and lower leg.

32.7.1 Muscle Strain

Muscle strain in the lower leg occurs most frequently at the medial gastrocnemius distal myotendinous junction (49 %) (Koulouris et al. 2007). The second most frequent location of muscle strain at the lower leg is the soleus (46 %). The plantaris (5 %) and lateral gastrocnemius (2.5 %) are rarely involved. Dual muscle involvement is frequently encountered, with a combination of the medial gastrocnemius and soleus muscle in 60 %, a combination of the soleus and tibialis posterior muscle in 15 % and the soleus and flexor hallucis longus muscle in 5 % (Koulouris et al. 2007). Many authors use the term tennis leg to describe all acute muscle injuries in the superficial calf (Pacheco and Stock 2013).

32.7.1.1 Background and Risk Factors

The increased risk at the medial gastrocnemius is related to its two joints crossing with increased vulnerability during eccentric muscle activity and increased fast-twitch fibres in contrast with slow-twitch soleus muscle (Boden 2000). Previous muscle injury increases the risk of reinjury of the medial gastrocnemius; dual muscle injury is probably related to muscle fibrosis and fibrotic thickening of the aponeurosis with sticking of the medial gastrocnemius to the soleus muscle. Frank haematoma is rarely found in muscle strain. Serosanguinous collections are located at the rupture area and may evolve extramuscularly if the superficial muscle fascia is involved and/or in unipennate muscle architecture, e.g. the medial head of the gastrocnemius muscle. Intermuscular serosanguinous seroma between the aponeuroses of the medial gastrocnemius and soleus muscles may separate the muscle bellies up to the popliteal fossa of the knee. This condition poses a special risk to the development of intermuscular fibrosis with both muscles sticking together.

32.7.1.2 Clinical Picture

The typical patient is a middle-aged recreational athlete with a history of sharp pain in the middle third of the calf during explosive sprinting or jumping activities with simultaneous knee extension and ankle extension. Pain, tenderness, swelling and ecchymosis are typically located at the middle third of the medial aspect of the calf with tracking down to the ankle of the ecchymosis.

32.7.1.3 Clinical Diagnostics

History is usually sufficient to make a proper diagnosis, but grading based on clinical examination and history is incomplete. Occasionally bone or soft tissue neoplasms will masquerade as sports injuries, and prompt imaging will prevent delayed diagnosis (Lewis and Reilly 1987).

32.7.1.4 Radiological Diagnosis

Imaging can provide a specific diagnosis in clinically problematic cases. MRI or ultrasound can help to identify the involved muscle(s), grade the muscle tear and identify late sequels such as seroma and fibrosis. Stretch-induced or indirect muscle trauma is almost uniformly occurring at the muscular side of the myotendinous junction (MTJ). In parallel muscle fibre organisation, the MTJ is a small well-defined area, whereas in featherlike organisation the MTJ is an elongated area that may comprise the complete muscle length; it is centrally located in circumpennate muscle architecture and superficially located in unipennate (e.g. medial gastrocnemius muscle) and bipennate muscle organisation. Muscle lesions are graded: grade III is defined as a complete tear, grade II a partial muscle tear involving 5–95 % of muscle mass and grade I is defined as elongation or discrete disruption of fibres involving less than 5 % of the muscle mass.

MRI

Although MRI is not routinely recommended for evaluation of musculotendinous injuries to the calf, it can be helpful in problem-solving and indicate whether surgical intervention is required as in the case of Achilles rupture (Deutsch and Mink 1989; Anouchi et al. 1987). Muscle contusion, partial tear and complete tear can be differentiated (Jacobson 1989). Axial SE T1-WI imaging is combined with TSE T2(-FS)

Fig. 32.10 MRI of grade I medial gastrocnemius strain in a 37-year-old male with an episode of acute pain at medial half of the right calf suggestive for tennis leg. Coronal T2-WI of the right and left calf performed 3 days after the injury. A small area with increased SI with infiltration between muscle fibres is depicted (*arrow*). Symmetric low SI of the intermuscular aponeurosis between the soleus and medial head of the gastrocnemius is obvious (*arrowheads*). No thickening and/or serous fluid in the intermuscular aponeurosis is documented

series in the three orthogonal planes. Acute traumatic lesions are characterised with increased SI on T2-WI related to oedema and serosanguinous infiltration in the muscle and extramuscular tissues if the superficial muscle fascia is involved. In grade I muscle strain MRI may be normal, or a small intramuscular area with feathery appearance and increased T2 time is detected (Figs. 32.9 and 32.10). In grade II lesions fibre discontinuity without or with muscle fascia involvement is depicted by the presence of high SI fluid in the gap that also may be palpated, and retraced muscle may present as a mass on US/MRI as well as on palpation (Fig. 32.11). In grade III the muscle fascia is invariably involved with muscle retraction. Late findings are muscle seroma or encapsulated fluid collection as well as a defined area with homogeneous increased SI or fibrosis at the muscle or the intermuscular area presenting as an area with decreased SI on T2- and T1-WI (Fig. 32.11b). The plantaris muscle is a small parallelly organised muscle at the popliteal fossa with a very thin tendon that is not likely to be imaged in normal persons. The diagnosis of a ruptured plantaris tendon or grade III muscle strain relies on the presence of a 'mass' which is isointense to the muscle between the gastrocnemius and soleus muscles.

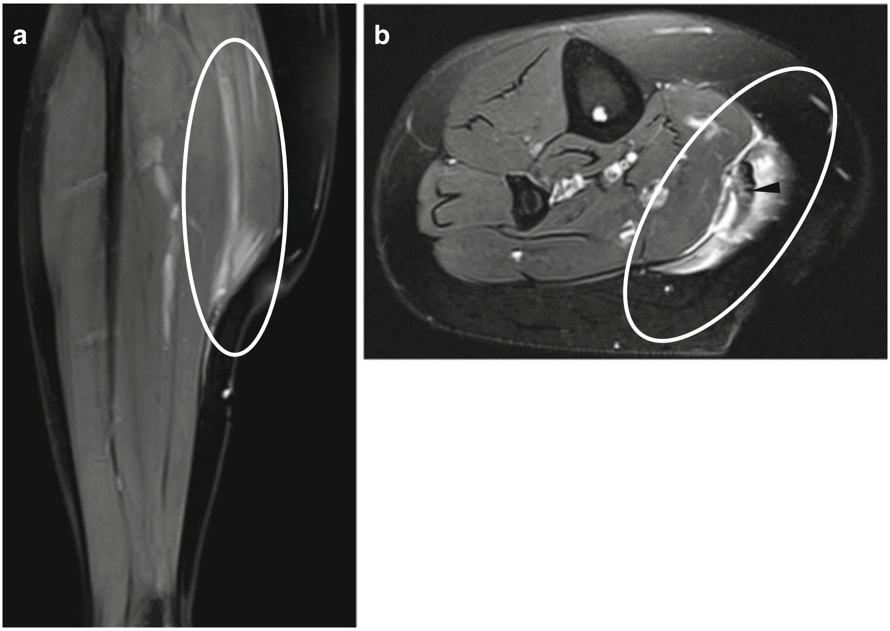

Fig. 32.11 Male, 27 years old, with clinical recurrence of right tennis leg. Coronal (**a**) and axial (**b**) TSE T2-WI FS images of the right calf. Feathery infiltration at the distal MTJ of the right medial gastrocnemius with some retraction is obvious on the coronal image (*oval*); thickening and increased SI of the aponeurosis and intermuscular area with partial separation of soleus muscle and medial gastrocnemius muscle are obvious on coronal and axial images (*oval*). Central area with low SI on the axial image represents fibrosis as sequel of previous muscle tear (*arrowhead*)

Ultrasound

Ultrasound is less expensive but more operator dependent than MRI. Muscle fibre tears are evident by alteration in the normal linear echogenic muscle fascia (epimysium) between different muscles and/or alteration of the normal intramuscular organisation of the contractile components (fibres and fascicles) that are surrounded by reflective endomysium and perimysium. This intramuscular architecture is evident on US but not on MRI. The conspicuity of discontinuity of the contractile apparatus is enhanced during US procedures with active contraction of the muscle: this is a major advantage of US procedures over MRI. In grade I muscle strain or elongation, the ultrasound examination may be normal, or small hypoechoic areas may be present without or with minor fibre discontinuity. Thus, normal ultrasound examination with typical clinical presentation of muscle strain is diagnostic for grade I muscle strain and implies a good prognosis with restitution ad integrum within 2 weeks. Fluid collections present as areas of diminished echoes. By comparison with an asymptomatic extremity, subtle abnormalities can also be noted. In grade II muscle strain direct US demonstration of fibre discontinuity and retraction is obvious, and at the retracted area some hypoechoic fluid is documented (Fig. 32.12b). The retracted muscle fibres are mobile on compression with the

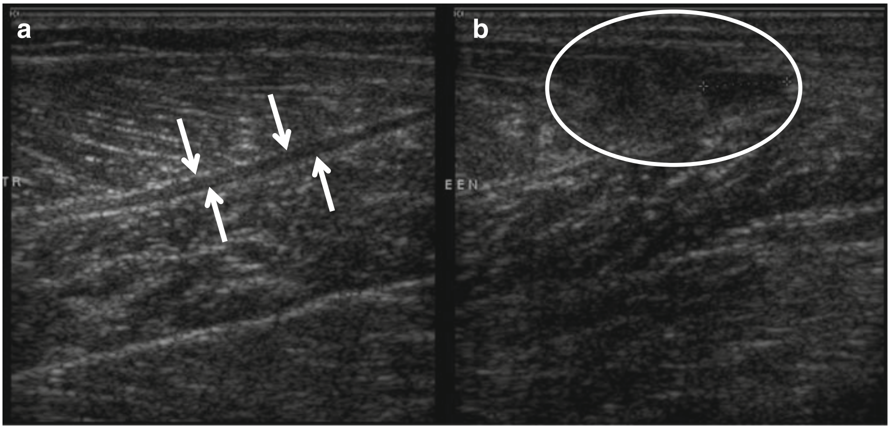

Fig. 32.12 Male, 48 years old, with clinical right tennis leg. Longitudinal ultrasound of the left normal (**a**) and right pathologic (**b**) medial gastrocnemius distal MTJ. Normal unipennate fibre organisation with hyposonant contractile apparatus and reflective endomysium is depicted (**a**). The thin and regular reflective aponeurosis or the medial gastrocnemius and soleus (*arrows*) are separated by a narrow bandlike hyporeflective area of loose connective tissue. At the pathologic right side (**b**) fibre disorganisation and retraction with and poor definition of the medial gastrocnemius distal aponeurosis are documented proximal to a small assonant fluid area (*oval*)

ultrasound probe; this sign is known as the 'bell clapper sign'. Old scar tissue (up to 6 weeks of age) is characterised by hyposonant star-shaped areas with muscle fibre attraction at the muscle contractile apparatus or oval more regularly shaped areas located at the surface of the muscle (Fig. 32.13). Seromas are characterised by well-defined hyposonant areas with a change in shape during external compression (Fig. 32.14). A normal plantaris tendon is readily documented on US examinations (Fig. 32.15). Whereas ultrasound is more frequently used in the initial evaluation of suspected deep venous thrombosis, musculoskeletal injuries can mimic this diagnosis. Ultrasound might be considered a comprehensive modality for the evaluation of leg or calf pain.

32.7.2 Morel-Lavallée Lesion

32.7.2.1 Background and Risk Factors

A Morel-Lavallée lesion represents a closed degloving injury associated with shear injury. This typically occurs as a result of shear force on the skin with subcutaneous fatty tissue abruptly separating from the underlying muscle fascia. The separation causes disruption of the segmental perforating blood and lymph capillaries filling the space created superficial to the fascia by fluid of variable composition, ranging from serous fluid to blood. The fluid collection may then spontaneously resolve or become pseudo-encapsulated and refractory. Once the lesion becomes pseudo-encapsulated, conservative management with compression bandages is rarely

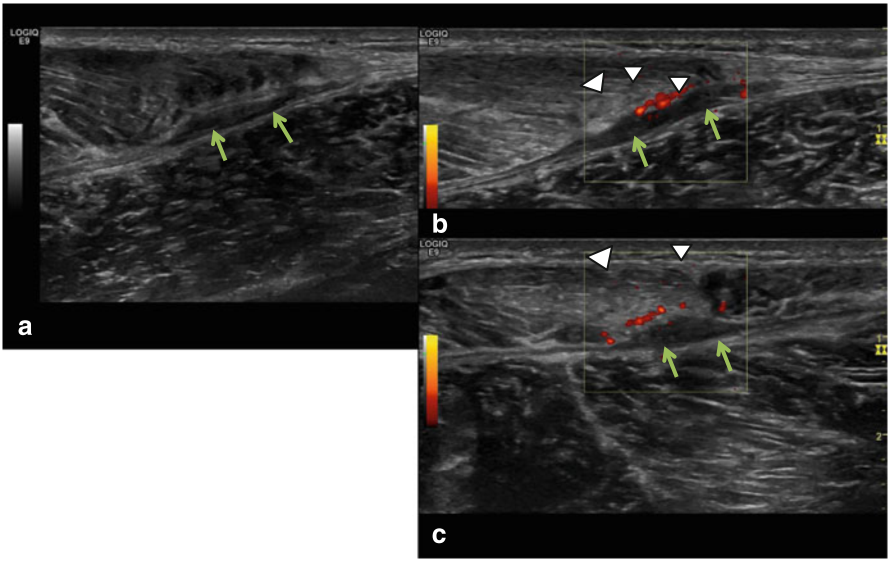

Fig. 32.13 US examination of a 39-year-old patient with a 2.5-week-old recurrence of tennis leg. Longitudinal view without (**a**) and with (**b**) power Doppler registration and axial view with power Doppler registration (**c**). Old hyporeflective scar at the interaponeurotic area between the medial gastrocnemius and soleus muscles (*arrows*). This scar is differentiated from serous collection by its constant shape during compression. Hyperreflective area at the distal MTJ of the medial gastrocnemius with fibre disorganisation and increased power Doppler activity represents the area of recent grade II strain with muscle regeneration (*arrowheads*)

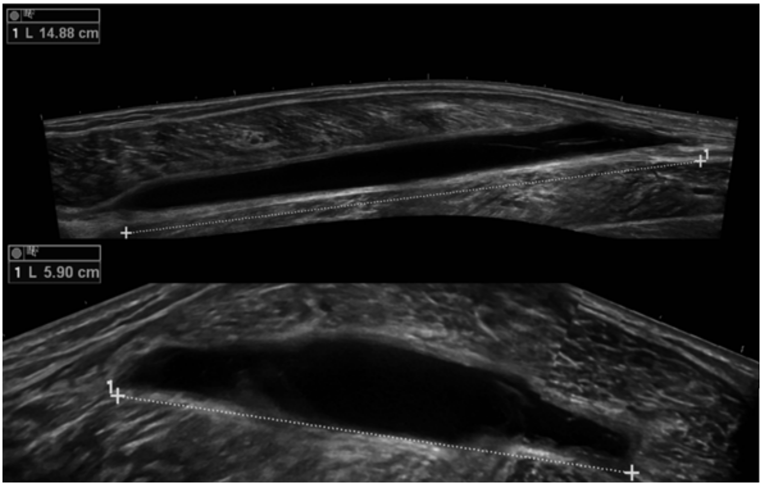

Fig. 32.14 US examination of a 63-year-old male patient with a 6-week-old tennis leg. Panoramic longitudinal (*top*) and axial view demonstrating a large well-defined hyposonant seroma interspersed between the medial gastrocnemius and soleus. Longitudinal maximal distance 15 cm and transverse maximal distance 6 cm. This area changed shape on compression by the ultrasound probe. The cranial part climbed up to the popliteal fossa

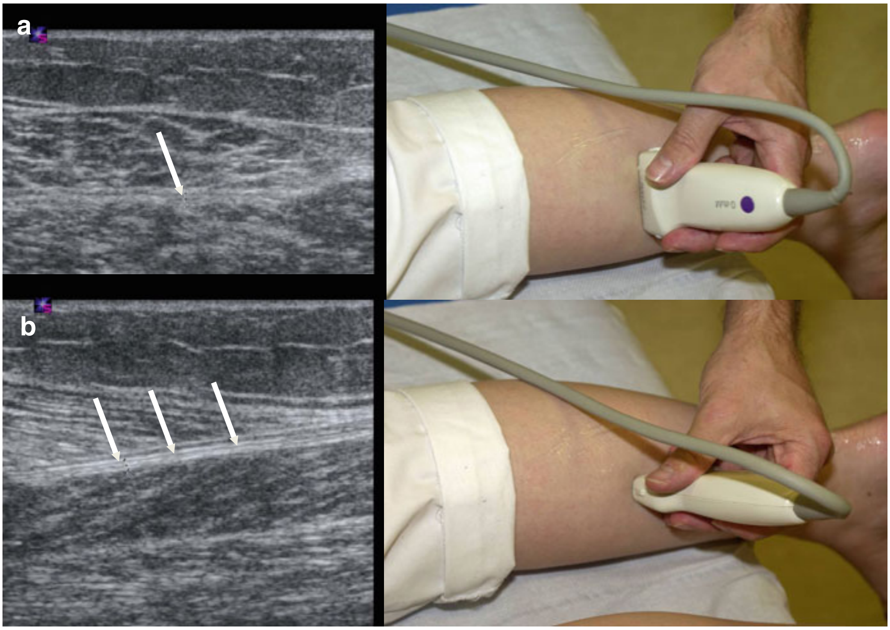

Fig. 32.15 US examination with probe position of plantaris tendon in axial (**a**) and longitudinal (**b**) imaging plane. The plantaris tendon is the third reflective line interspersed with the aponeurosis of the medial gastrocnemius and the soleus (**b**, *arrows*) and is the small oval area on axial view (**a** *arrow*)

successful. In this stage, to prevent reaccumulation, surgical drainage is sometimes to be completed with pseudocapsule resection (Tejwani et al. 2007 and Morel-Lavallée 1863).

32.7.2.2 Clinical Picture

Deglovements present clinically as often impressive and very soft masses with variable skin coloration. In the chronic situation with encapsulated collection, the pain subsides with major burden aesthetic complaints.

32.7.2.3 Diagnostics

Clinical presentation is often specific. MRI or ultrasound can be used to stage the lesion. Ultrasound-guided evacuation with associated compression bandage is an elegant treatment option.

32.7.2.4 Radiological Diagnosis

MRI shows signs of fluid infiltration adjacent and superficial to the muscle fascia without involvement of the fascia. The fluid infiltrates between fat lobules and changes shape or disappears during ultrasound probe compression (Fig. 32.16). In the chronic stage the fluid may become encapsulated and well defined (Neal et al. 2008). The collection has most often characteristics of fluid with high SI on T2 and low SI on T1-WI; rarely, blood degradation products are found with characteristics of methaemoglobin or haemosiderin depending on the age of the lesion.

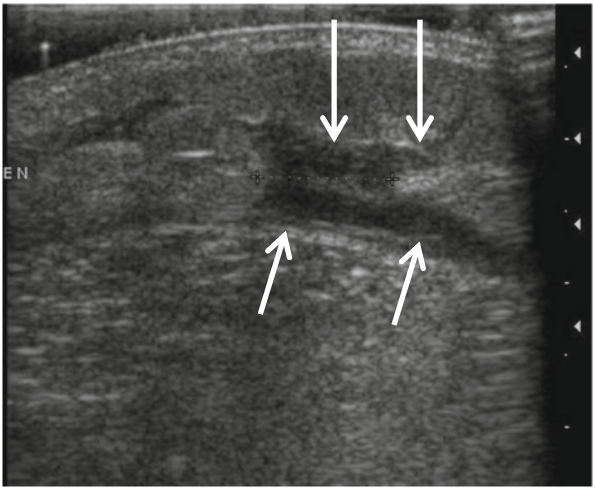

Fig. 32.16 Morel-Lavallée lesion at the left lower leg in a 64-year-old female. Ultrasound examination demonstrating hyposonant separation of reflective subcutaneous fat lobules and distention superficial to the muscle fascia (*arrows*)

32.8 Fascial Defects and Muscle Herniation

Fascial defects are most frequently seen over the anterolateral aspect of the leg (Bong et al. 2005). The most common location for these defects is in the distal third of the lower leg, where the superficial peroneal nerve perforates the fascia of the lateral compartment (Bong et al. 2005; Edwards 2005). The presence of a fascial defect is thought to be related to elevated hydrostatic pressure within the compartment surrounded by that fascia (Blackman 2000). Herniation of muscle through such a defect can compress the superficial peroneal nerve, causing pain radiating to the dorsal side of the foot. Muscle herniation can be evident on physical examination (Blackman 2000). In case of ischaemia of the herniated muscle tissue, local tenderness can be seen on palpation of the location of the defect (Bong et al. 2005). Fascial defects in the compartments of the leg have been thought to be related to the development of chronic compartment syndrome, but their presence has also been reported in asymptomatic athletes (Bong et al. 2005). Radiological imaging (US or MRI) demonstrates the muscle herniation into the subcutaneous tissue (Fig. 32.17a, b). The herniated muscle presents with identical muscle ultrasound characteristics and disappears during compression with the probe. Dynamic ultrasound examination during muscle contraction and/or examination in the upright position is more sensitive. In case of impingement of herniated muscle, increased SI on T2-WI can be found.

32.9 Other Causes of Lower Leg Pain

Apart from causes located in the lower leg itself, the origin of lower leg pain can in some cases be found elsewhere. Referred pain from the hip or the knee and lumbar disc herniation can cause lower leg pain and should be considered when no local pathology explaining the pain can be found in the lower leg.

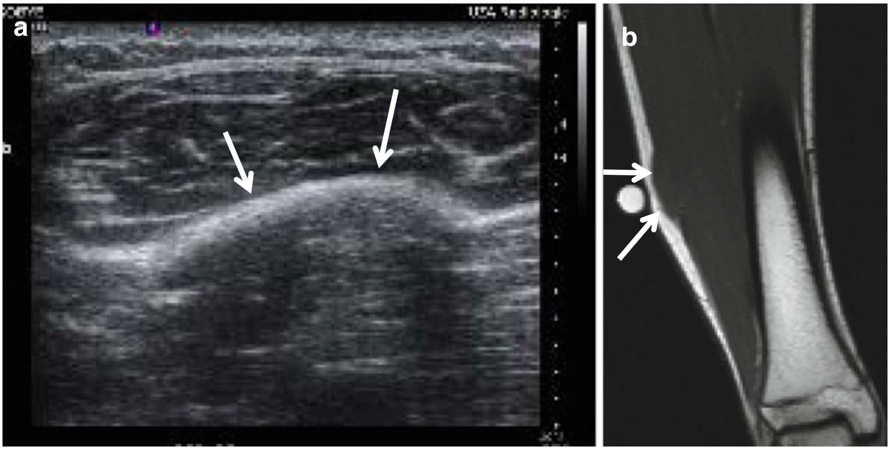

Fig. 32.17 US and MRI (SE T1-WI) of the same female patient with mass (*arrows*) at the lower leg. Extension of the muscle tissue to the subcutaneous tissue on ultrasound (**a**) and MRI (**b**) with identical muscle reflectivity and signal intensity, respectively

Other causes of lower leg pain include tendinopathy or tenovaginitis-paratenonitis, intermittent claudication (by arterial occlusion or arterial obstructive disease), neoplasm and infection. In the relatively healthy population of athletes, these pathologies are much less common than the syndromes described above. However, the clinician should always keep them in mind.

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Nuclear Medicine Imaging of Lower Leg Injuries

33

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Contents

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Abstract

This chapter deals with sports injuries of the lower leg that have been addressed with nuclear medicine imaging techniques. Medial tibial stress syndrome, stress fractures of the lower leg, chronic exertional compartment syndrome, and miscellaneous conditions showing abnormalities on scintigraphy are reviewed. Emphasis is placed on the position of the nuclear imaging technique in the diagnostic workup, as well as interpretative criteria of scintigraphies, including SPECT/CT.

Abbreviations

CECS	Chronic exertional compartment syndrome
CT	Computerized tomography
ICP	Intramuscular compartment pressure
MBq	Mega Becquerel
min.	Minutes
MRI	Magnetic resonance imaging
MTSS	Medial tibial stress syndrome
p.i.	Post injection
SPECT	Single-photon emission computerized tomography
Tc	Technetium
Th	Thallium

33.1 Introduction

The lower leg is frequently involved in sports-related injuries. These injuries are almost always the result of chronic overexertion of the musculoskeletal system. This is most seen in both professional and recreational long-distance runners. In fact, 9–32 % of all sports injuries have been reported to originate from the lower legs (van Gent et al. 2007). Indeed, during running, forces that are five to ten times the magnitude of everyday activities are transferred to tendons, periost, bone, joints, and ligaments as a consequence of repeated and prolonged muscle contraction.

Progressive, chronic exertional pain of the lower legs during sports is most often related to any of four pathologies: medial tibial stress syndrome, stress fracture of the tibia/fibula, chronic exertional compartment syndrome, or a tendinopathy of the plantar flexors (Hartgens and Hoogeveen 2008). Of the first three mentioned conditions, nuclear medicine techniques have been used to provide diagnostic information. Tendinopathy is discussed in the respective chapters of the knee and ankle. Acute trauma, which frequently occurs during sports activities, is not further discussed as this is beyond the scope of nuclear medicine techniques. Table 33.1 also lists some rare causes of lower leg complaints during sports activities that can be

Table 33.1 Lower leg sports injuries associated with nuclear medicine abnormalities

Common causes
Medial tibial stress syndrome
Stress fracture
Compartment syndrome
Rare causes
Muscle overuse: strain, rhabdomyolysis
Trauma: interosseous membrane, syndesmosis
Osteomyelitis
Benign and malignant tumors
Metabolic insufficiency fractures

associated with nuclear medicine abnormalities. These are discussed under miscellaneous conditions (Van der Wall et al. 2010).

33.2 Medial Tibial Stress Syndrome (MTSS)

33.2.1 Introduction

Medial tibial stress syndrome (MTSS) has been a common name in the nuclear medicine literature used for a cortically localized hyperactivity on bone scintigraphy associated with exercise-induced lower extremity pain, following the first description by Holder and Michael (Holder and Michael 1984). Recently, Yates and White redefined MTSS as "pain along the posteromedial border of the tibia that occurs during exercise, excluding pain from ischemic origin and signs of stress fracture, and with diffuse painful palpation over a length of at least 5 cm" (Yates and White 2004). This definition was an update from the more commonly used clinical term "shin splints" which was introduced in 1966 by the American Medical Association as "pain and discomfort in the leg from repetitive running on a hard surface or forcible, excessive use of foot flexors." Because excessive muscular traction and stimulation of osteoblasts in Sharpey's fibers crossing the periosteum has been implicated in the pathophysiology along with cortical thickening seen on radiographs, "periostitis" has also been a popular name in clinical and radiological literature. The lack of official definition and terminology has somewhat hampered comparison between studies (Moen et al. 2009).

In fact, MTSS is one of the most frequent forms of exercise-induced leg pain, with incidences ranging from 4 to 35 % (Clanton and Solcher 1994), and has been reported in military personnel, runners, jumping athletes, rhythmic gymnasts, and dancers. It is an unresolved question whether MTSS and stress fracture are both part of the same continuum in which MTSS, if left untreated, could lead to a full stress fracture or that these should rather be regarded as two separate entities that may co-exist (Beck 1998).

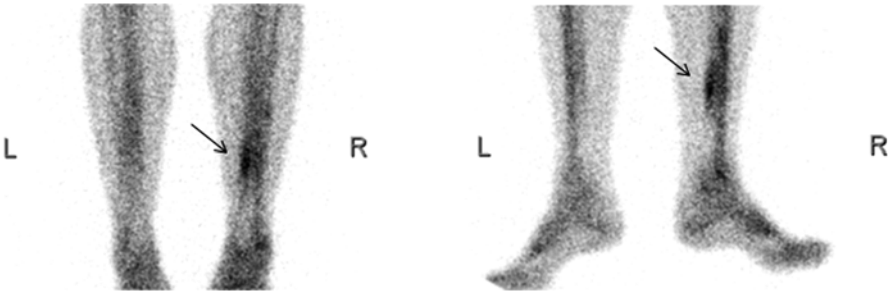

Fig. 33.1 Images of a 25-year-old male with lower leg pain after exercise. Anterior (*left*) and lateral (*right*) planar bone scan of the lower legs, showing the typical aspect of MTSS in the left tibia (*arrows*)

33.2.2 Examination Techniques

Three-phase bisphosphonate bone scintigraphy: (1) dynamic angiographic phase, (2) static anterior and lateral blood pool phase images, and (3) delayed bone phase images with anterior, posterior, medial, and lateral views of the lower legs, preferably from the knee to the ankle (large view camera).

33.2.3 Image Interpretation

Holder and Michael were the first to describe bone scan abnormalities in MTSS, demonstrating an abnormal uptake of the posterior cortex of 1/3 of the tibia in the delayed bone phase (Holder and Michael 1984). This has been typically described as a line-shaped aspect; located at the posteromedial or anteromedial border, either proximal, midshaft, or distal; of lower-grade intensity; and without alterations in blood flow appearing in the early first or second phase (Fig. 33.1). Localization can be unilateral, although often bilateral with a degree of asymmetry. The time to recover from MTSS has been reported to be between 4 and 20 weeks.

33.2.4 Comparative Literature Results

Batt et al. (1998) and Gaeta et al. (2005) prospectively compared bone scintigraphy with MRI and found a similar sensitivity and specificity for the diagnosis of MTSS in symptomatic persons, i.e., 74–84 % and 33 % for bone scanning and 79–88 % and 33–100 % for MRI. Both studies used clinical parameters as gold standard. In the study of Batt, this was exercise-induced lower leg pain of less than 3 months duration associated with palpable tenderness along at least 5 cm. of the posteromedial tibia, without clinical evidence of compartment syndrome or stress fracture. In the study of Gaeta, inclusion criteria were a history of lower leg pain of less than 1 month without trauma or abnormalities on radiographs. Batt studied asymptomatic persons with both imaging modalities and found a high number of similar abnormal findings on bone scan as well as MRI, hence low specificity, while Gaeta found 100 % specificity on the basis of normal MRI findings in 10 asymptomatic persons. Beck et al. (2012) in a prospective study on 40 patients found equal reliability for all image modalities except radiography but found no significant relationship between clinical healing time and severity scores for any imaging modality.

In the study of Gaeta et al. (2005) high-resolution CT scan showed osteopenia changes in the tibial cortex with a sensitivity of only 42 % but specificity of 100 %. This high specificity could be interesting for the accuracy of SPECT combined with high-resolution CT in an integrated SPECT/CT scanner, but information from studies comparing MRI with SPECT/CT is currently not available. In this respect, it should be considered that MRI is more desirable from the perspective of avoidance of radiation exposure, especially in young persons.

33.2.5 Conclusion

Three-phase bone scintigraphy can support the clinical diagnosis of MTSS in a patient with lower leg pain and differentiate with a stress fracture. However, similar abnormalities on bone scan may also be seen in asymptomatic persons.

33.3 Stress Fracture of the Lower Legs

33.3.1 Introduction

Most stress fractures in sports medicine occur in the tibia, accounting for 24 %, followed by the tarsus (18 %), metatarsus (16 %), fibula (16 %), femur (7 %), pelvis (2 %), and spine (1 %) (Patel et al. 2011). Repetitive and excessive stress and bending on the bone occurs, leading to acceleration of normal bone remodeling with bone resorption outpacing bone formation in the tibial cortex, causing microfractures and eventually a full stress fracture. Stress fractures have traditionally been reported in military recruits, but today athletes at all competition levels of sports and an increasing number of "recreational" athletes with repetitive, high-intensity training may be affected, especially in long-distance walking, running, jumping, and dancing and in female athlete triad.

33.3.2 Examination Techniques

Three-phase bisphosphonate bone scintigraphy. Dynamic angiographic phase followed by static blood pool phase and delayed bone phase images of anterior, posterior, medial, and lateral views of the lower legs.

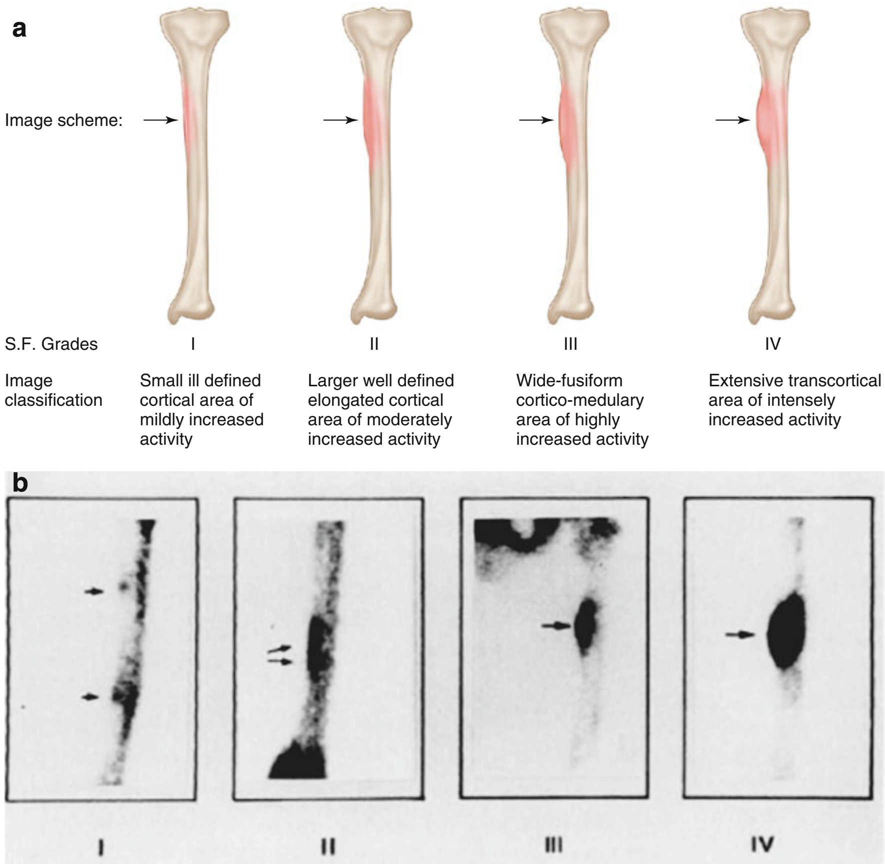

Fig. 33.2 Zwas classification of stress fractures. Four grades (*I–IV*) of stress fracture evolution as seen on bone scintigraphy are presented schematically (**a**) and in actual bone scintigraphies (**b**) (Reprinted by permission of the Society of Nuclear Medicine from Zwas et al. (1987). Figure 1)

33.3.3 Image Interpretation

Examination with nuclear techniques was described from the 1970s. Zwas et al. established a classification system of the severity of stress fractures in the tibia (Fig. 33.2) (Zwas et al. 1987). Today, this system is still widely used for the diagnosis as well as to distinguish between stress fracture and MTSS on the basis of the characteristics of the static, delayed bone phase scan. In this *grade I* consists of a small, ill-defined lesion with mildly increased activity; *grade II* is larger than grade I, with a well-defined, elongated lesion with moderately increased activity in the cortical region; *grade III* is a wide, fusiform lesion with highly increased activity in the corticomedullary region; and *grade IV* is a wide, extensive lesion with intensely increased activity in the transcorticomedullary region. Figure 33.3 is an example of a small grade I stress fracture of the tibia. According to Holder and others, stress

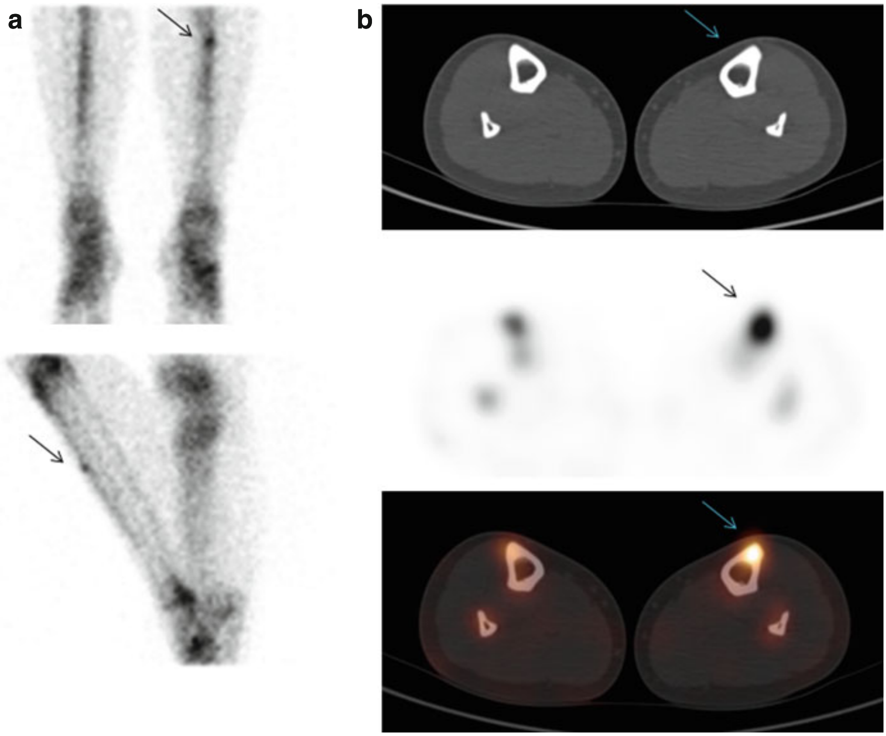

Fig. 33.3 Images of a 22-year-old active recreational runner with pain in the left lower leg. Planar bone scan (**a** *upper left*) shows focal uptake (*arrow*) in the left tibia. Corresponding SPECT/CT slices (**b** *upper right*) show an unequivocal hotspot in the left tibial cortex, consistent with a grade I stress fracture

fractures in the tibia and/or fibula usually have increased vascularity in the blood flow and/or blood pool during the acute and subacute phases, i.e., first weeks after onset of symptoms. This hypervascularity is spatially in accordance with the hot spot on the delayed bone phase. Mohan et al. (2011) recommended lateral blood pool images as an optimal method for evaluating vascularity.

Approximately 17 % of fractures will be bilateral (Courtenay and Bowers 1990). In long-distance runners, the most common site is the distal third of the tibia. The posterior aspect of the upper third is the most common site in children and elderly (Van der Wall et al. 2010). The vast majority of fibula fractures are in the distal third. Positive delayed bone phase usually returns to normal in 2–3 months for stage I and II lesions but can persist for more than 6 months in stage IV.

33.3.4 Comparative Literature Results

Three-phase bone scintigraphy has been the confirmation test for stress fractures in most previous studies because of its high sensitivity of 74–100 % (Gaeta et al. 2005;

Fredericson et al. 1995). Negative bone scans exclude a significant stress fracture lesion. Ishibashi et al. compared bone scan and MRI in 31 patients, in whom the diagnosis was made by clinical findings and conventional radiographs with or without MRI. They concluded that MRI and bone scan showed an equivalence for early diagnosis and grading, but MRI was preferable as it provided more diagnostic information on the surrounding soft tissue, had a higher specificity (Ishibashi et al. 2002), was superior for detection of early stress injury (Gaeta et al. 2005), and was the imaging modality with the closest relation to time to healing (Beck et al. 2012).

Presently, there are no published prospective studies examining tomographic SPECT/CT for evaluation of stress fractures in the lower leg. Groves et al. (2005) compared CT with bone scanning and found the detection rate of CT much less than scintigraphy. Interestingly, these authors pointed to the potential use of quantification at fracture sites.

33.3.5 Conclusion

Bone scintigraphy has a high sensitivity for the diagnosis of stress fracture of the lower legs, while differentiating from other causes of exercise-induced lower leg pain.

33.4 Chronic Exertional Compartment Syndrome (CECS)

33.4.1 Introduction

Chronic exertional compartment syndrome (CECS) is clinically defined as a condition of exercise-induced pain in any of the muscle groups below the knee, associated with sensations of tightness and firm palpation, and is provoked by resisted dorsiflexion (*anterior compartment*), walking/running (*anterior and/or posterior compartment*), or hops, jumps, and calf raises (*posterior compartment*). It is especially seen in young active individuals and athletes, running sports, and military personnel, which is distinct from the elderly patient group in whom atherosclerosis may underlie ischemia-induced exertional lower leg pain. Definite diagnosis of CECS is made by dynamic measurement of the intramuscular compartment pressure (ICP) by intramuscular needle or catheter (Aweid et al. 2012).

33.4.2 Examination Techniques

The radiopharmaceuticals that have been investigated for diagnosing CESC are the same used for myocardial perfusion scintigraphy: thallium-201 (^{201}Th) (Trease et al. 2001; Hayes et al. 1995; Takebayashi et al. 1997) or the technetium-99m (^{99m}Tc)-based radiopharmaceuticals ^{99m}Tc-tetrofosmin (Oturai et al. 2006) and $^{99m\text{Tc-sestamibi}}$ (Edwards et al. 1999). Uptake of these radiopharmaceuticals in the muscle is proportional to blood flow, cellular integrity, and mitochondrial function.

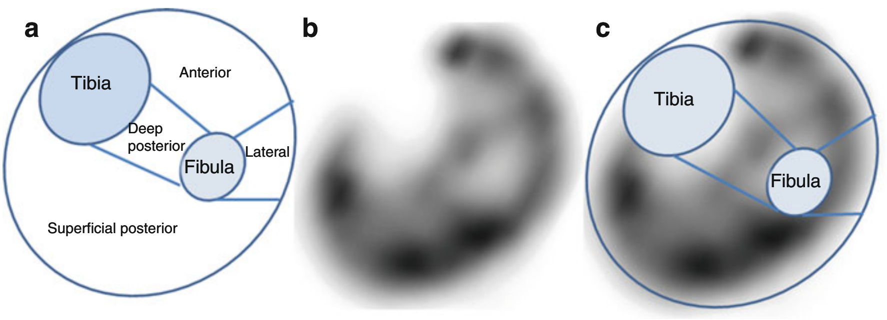

Fig. 33.4 Schematic transverse representation of the muscle compartments in the lower leg (**a** *left*); corresponding midcalf transversal ^{99m}Tc-sestamibi SPECT slice (**b** *center*); and combined image as used for quantification of separate compartments (**c** *right*)

In the protocol with ^{201}Th, an activity of 74–100 MBq (Hayes et al. 1995; Takebayashi et al. 1997) or 0.8 MBq/kg of body weight capped at 80 MBq (Trease et al. 2001) has been intravenously injected following treadmill, patient-specific, or compartment-specific exercise. Post-exercise SPECT scanning was done 5 min. post injection (p.i.) and compared with images in rest, 3–4 h p.i. following redistribution of the tracer. With ^{99m}Tc tracers, generally a 2-day protocol has been used with separate stress and rest SPECT scans, following an injection of 300–420 MBq at each occasion.

33.4.3 Image Interpretation

Visual (Trease et al. 2001; Oturai et al. 2006; Edwards et al. 1999) or quantitative (Hayes et al. 1995; Takebayashi et al. 1997) techniques have been used to evaluate rest and stress SPECT scans.

Semiquantitative analysis was used to grade each compartment in the stress images as very, moderately, or mildly hypoperfused, equally perfused, or hyperperfused in relation to the other components in the same leg (Trease et al. 2001), while rest (in the case of technetium-99 m tracers) or redistribution (in the case of thallium-201) images were graded as showing marked, moderate, or no/mild reversibility (Oturai et al. 2006).

In quantitative techniques, a transversal slice through midcalf has generally been analyzed with compartmental regions of interest (Fig. 33.4) using the change in normalized mean pixel counts and/or activity profiles expressed as uptake percentage or area under the curve, between stress and rest images. These results have been compared to that of asymptomatic, nonsmoking control cases (Hayes et al. 1995; Takebayashi et al. 1997).

It has been emphasized that an interval of days or weeks may be desirable to be sure that needle insertion and possible trauma by ICP does not affect SPECT results (Oturai et al. 2006). Also, in some patients undergoing the rest study the day after the stress study, the affected muscle compartment demonstrated supernormal uptake of sestamibi. This was likely to indicate a reactive hyperemia following the ischemic episode induced by exercise (Edwards et al. 1999).

33.4.4 Comparative Literature Results

A few articles have been published over the years about nuclear techniques to diagnose CECS. Two earlier studies by Hayes et al. (1995) and Takebayashi et al. (1997) showed promising results in quantified, controlled data using thallium-201 but were of small patient number. A first study with ^{99m}Tc-sestamibi was published by Edwards et al. (1999) in a larger patient group of 46. Interestingly, these authors related the perfusion result to the outcome after surgery or conservative treatment rather than ICP. Their results suggested surgery with clinical improvement in ^{99m}Tc-sestamibi-*positive* cases and conservative treatment with improvement in ^{99m}Tc-sestamibi-*negative* cases, demonstrating good positive (89 %) and negative (94 %) predictive values. However, subjective imaging criteria consisted of a "visually detectable decrease in ^{99m}Tc-sestamibi uptake in one or more compartments by experienced consultants in nuclear medicine." Recently, two prospective studies have been performed by Trease et al. (2001) and Oturai et al. (2006), showing no correlation between hypoperfusion on SPECT stress images and increased ICP. These authors suggested that there was no significant hypoperfusion in CECS subjects and muscle ischemia may not be present in CECS. These studies did not rely on visual interpretation with an asymptomatic control group, nor did they relate their findings to surgical outcome data.

33.4.5 Conclusion

Methodological shortcomings in all published studies hamper firm conclusion about the role of scintigraphy. Some studies have questioned the presence of muscle ischemia in the pathogenesis and diagnosis of CECS and hence usefulness of scintigraphy. Others have found good correlation with surgical outcome. Scintigraphy can provide noninvasive, simultaneous, and quantitative registration of perfusion in separate compartments.

33.5 Miscellaneous Conditions Showing Abnormalities on Scintigraphy

It has been found that extreme muscle exertion causing muscle damage or necrosis can demonstrate profound abnormalities on bone scintigraphy. Cases and small series that have been reported on this in the past have shown an acute, diffusely increased uptake in the involved muscles, which can be very

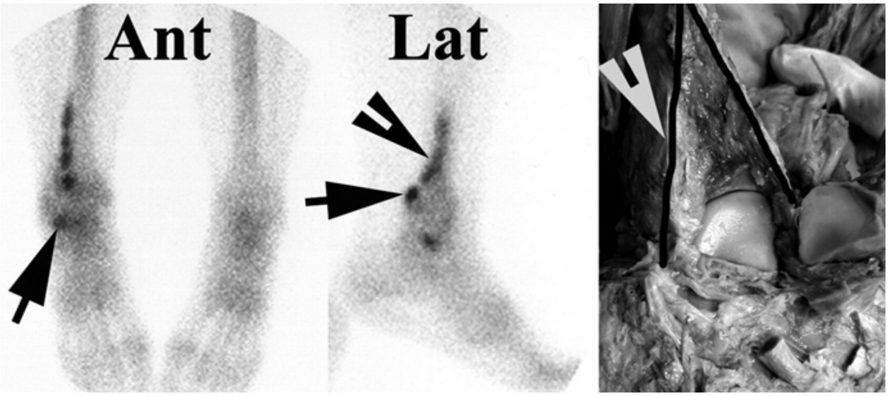

Fig. 33.5 Anterior (*Ant*) and lateral (*Lat*) images of a soccer player who sustained a complex injury to the ankle. Focal uptake at the posterior aspect of the ankle and tip of the lateral malleolus (*arrows*) in keeping with injuries to the ligaments. Additionally, there is intense uptake extending posteriorly and cranially through the ultradistal tibiofibular syndesmosis into the interosseous membrane (*arrowhead*). The picture on the *left* shows the anatomic dissection of the syndesmosis (*boundaries in solid lines*) (Reprinted from Van der Wall et al. (2010, with permission from Elsevier)

intense and occurs within hours of the injury, reaching a maximum within 24–48 h and returning to normal after approximately 1 week (Roland et al. 1997; Matin 1988).

The membrana interossea cruris is a membranous band connecting the inner side edges of the tibia and fibula. Significant trauma of the interosseous membrane clearly shows on bone scintigraphy but this is not so well known in the literature. Nevertheless, it has been shown that in 5 % of cases of ankle sprains, the interosseous membrane suffers significant injury that can show abnormally increase uptake on bone scan (Van der Wall et al. 2010). Figure 33.5 shows an example of such a case. Another case in Fig. 33.6 shows the activity of a tibiofibular synostosis. A synostosis, or rather dysostosis if pathological, at this level generally develops after an eversion (high) ankle sprain with disruption of the interosseous membrane. It usually develops 6–12 months after the trauma. Increased bone scan activity at this site is related to rupture of the membrane, ligaments, and/or fractures. The recognition and determination of such lesions is important to avoid distention of the ankle fork, instability, and premature arthrosis of the upper ankle joint. As Fig. 33.6 shows, SPECT/CT can be particularly valuable in the evaluation of the complex structure of the distal lower leg/ankle.

One consideration that should always be kept in mind in evaluating sports activity is the possibility that the presenting condition is not the consequence of excessive sports activity but rather aggravated by it and in fact related to another, underlying pathology coincidently coming to light. It is not exceptional that an underlying tumor or osteomyelitis focus is found by imaging as a result of exercise-induced lower leg pain.

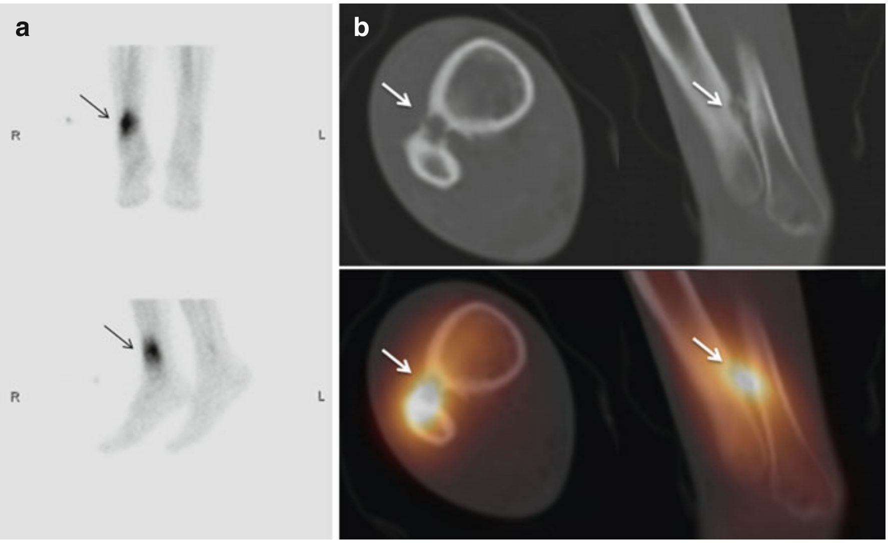

Fig. 33.6 Images of a 63-year-old male with unexplained lower leg pain for 2 years. Images of a synostosis of the interosseous ligament (*arrows*). Planar bone scan images (**a** *left*) show intense uptake distally in the lower leg (*black arrows*). Fused SPECT/CT images (**b** *right*) show a partially calcified and intensely active synostotic connection between tibia and fibula (*white arrows*)

Conclusion

Nuclear medicine studies can be useful in helping to differentiate causes of exercise-induced pain of the lower legs, discriminating increased musculoskeletal stress, skeletal injury, significant arthropathy, or the absence of major abnormalities. Its relation to function as well as quantification makes it particularly suitable for evaluation of management and outcome of sports-related injuries.

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Part XI

The Musculoskeletal System Topographically: The Ankle

Sports Injuries of the Ankle

34

J.L. Tol, P. D'Hooghe, and G.M. Kerkhoffs

Contents

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Abstract

The ankle is one of the most frequently injured joints in sports. Acute ligament injuries can be differentiated in lateral ligaments, medial ligaments and syndesmotic injuries. These acute injuries might lead to chronic articular injuries like anterior and posterior impingement, osteochondral defects of the talus and sinus tarsi syndrome.

Acute and chronic tendon injuries can be differentiated to posteromedial injuries (flexor hallucis longus, plantaris tendon and tibial posterior tendon injuries) and posterolateral injuries of the peroneal tendons. The most frequently posteriorly located injury is however the centrally located Achilles tendon. Understanding of the anatomy, injury mechanism is essential to provide optimal clinical, diagnostic and therapeutic care.

Abbreviations

AP	Anteroposterior
CAI	Chronic ankle instability
CGRP	Calcitonin gene-related peptide
FHL	Flexor hallucis longus
GAGs	Glycosaminoglycans
MI	Mechanical instability
OLT	Osteochondral lesion of the talus
RICE	Rest, ice, compression and elevation
ROM	Range of motion

34.1 Introduction

The burden of ankle injuries, particularly ankle sprains, is high in sports like football, soccer, handball, basketball and volleyball (Fong et al. 2007). Using the time loss injury definition, the ankle is one of the most common locations, which implies that these injuries force players to suspend sports activity.

Recent research in elite athletes reveals that an increased level of play is associated with a higher incidence and increased risk of injury (Langevoort et al. 2007). A substantial part of the acute ankle injuries will lead to chronic injuries. Knowledge of aetiology, diagnosis and optimal treatment of acute injuries and early recognition of delayed recovery are therefore essential to prevent chronic injuries.

34.2 Tendinopathies

The majority of tendon injuries around the ankle are posteromedial (flexor tendons), mid-posterior (Achilles tendon) or posterolateral (peroneal tendons) located.

34.2.1 Epidemiology

Most tendon disorders are common in middle-aged active people. With increasing sports participation in the general population, the number of overuse injuries has increased· Tendon disorders comprise 30–50 % of all sports-related injuries, and there is a lifetime risk of 52 % in elite long-distance runners of suffering from an Achilles tendon injury (Kujala et al. 2005). Despite the high prevalence, there is still a lack of knowledge about the aetiology and pathogenesis of these injuries.

The terminology used to describe chronic tendon disorders has changed in the past few decades. For many years, this condition was persistently defined as 'tendinitis', denoting an inflammation of the tendon (Cook and Purdam 2008; Maffulli et al. 1998). Several researchers proposed abandoning this term, as there were no signs of inflammation in chronic painful tendons analysed after biopsy or with microdialysis. To redress this confusing terminology, the term 'tendinopathy' was introduced to describe the clinical condition of pain, swelling and impaired performance. Histopathological studies showed that tendinopathy is frequently characterised by degeneration of the tendon tissue, also referred to as 'tendinosis'. The term tendinosis is based on histopathological characteristics and should only be used after histopathological confirmation (Maffulli et al. 1998).

The balance between the peroneal and posterior tibial tendon is crucial for a normal biomechanical hind foot function. Posttraumatic dysfunction of the posterior tibial tendon is associated with a (relative) flat foot and will negatively affect the biomechanics.

34.2.2 Achilles Tendon

Achilles tendinopathy is a clinical diagnosis characterised by pain, swelling and impaired load-bearing capacity. On history, pain is typically felt in the tendon midportion (Alfredson 2005; de Vos et al. 2007). A common training error that is associated with tendinopathy is a rapid increase in activity. The phrase 'too much, too soon' is frequently heard in the patient's history (Kujala et al. 2005). Initially pain is only present during the warming-up period or after activity. Interestingly, recent reports demonstrate that the condition is also more and more seen in completely nonactive individuals, making the aetiology ever more difficult to speculate about (Alfredson 2005). Rest may initially decrease the symptoms among active individuals, but frequently symptoms will return with an increase in activity. In a later stage, the tendon may become painful during rest and activities of daily living.

On clinical examination, the swelling in the tendon midportion may be obvious. Achilles tendon pain is usually localised to the tendon itself, mainly ventral-deep side, and does not refer to other regions. In the presence of swelling with pain on palpation, there is a high probability that histology will show features of tendinosis.

34.2.3 Plantaris Tendon

34.2.3.1 Functional Anatomy

The plantaris tendon originally is a knee and ankle flexor. In primates, it attaches to the plantar aspect of the proximal interphalangeal joints of the toes in primates, explaining its functionality for grasping with their feet. Darwinists suggest that through evolution in humans, the plantaris tendon is rudimental since human beings do not grasp with feet nor swing from trees any longer. Absence in 7–20 % human lower limbs has been reported (Danforth 1924; Freeman et al. 2008; van Sterkenburg and van Dijk 2011).

In humans, the plantaris muscle is triangularly shaped and lies posterior to the knee joint, originating from the inferior part of the lateral supracondylar line of the femur. Its tendon travels inferomedially, posterior to the soleus muscle and anterior to the medial gastrocnemius muscle. The tendon crosses the calf relatively proximal, running medial from and parallel with the Achilles tendon from the midportion of the calf, in the majority of cases ultimately inserting medially onto the calcaneus (Harvey et al. 1983; van Sterkenburg and van Dijk 2011). The plantaris muscle-tendon complex nowadays is a weak ankle and knee flexor and ankle inverter.

The medial portion of the Achilles tendon consists solely of the soleus tendon, since at about the level where the soleus contributes fibres to the Achilles tendon (3–11 cm), rotation of the tendon begins and becomes more marked in the distal 5–6 cm. The soleus is biarticular (ankle and subtalar joints). The plantaris tendon runs anteromedial to it.

Medial to the Achilles tendon, the plantaris tendon is located, originating from the lateral femoral condyle and inserting onto the medial calcaneus. The Achilles tendon is involved in plantar flexion, whereas – according to its anatomical course – the triarticular plantaris tendon (also) contributes to ankle inversion. The Achilles and plantaris tendon are collectively surrounded by a paratenon, which lies on an inner layer of endotenon and exists on a layer of mesotenon and an outer layer of epitenon.

34.2.3.2 Aetiology and Injury Mechanism

The aetiology of the pain in an athlete with midportion Achilles tendinopathy has not yet been entirely clarified. Pain was believed to be caused by expansion of the

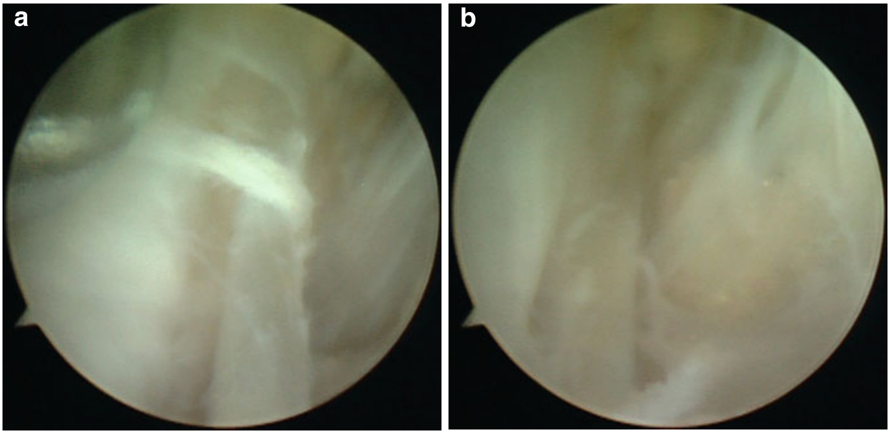

Fig. 34.1 Plantaris. In patients with a painful nodular thickening in the Achilles tendon, the pain is often most prominent on the medial side of the midportion Achilles tendon. At this level, the plantaris tendon runs closely with and parallel to the Achilles tendon and can have circular adhesions as seen in this endoscopic image (**a** before release, **b** after adhesiolysis).

Achilles tendon proper due to increased ground substance and an increased concentration of glycosaminoglycans (GAGs). A few years ago, the presence of neovascularisation around symptomatic tendons was raised as the cause of pain. Nowadays, accompanying nerves with high concentrations of nociceptive substances [glutamate, substance P, calcitonin gene-related peptide (CGRP)] are also supposed to play a role (Alfredson et al. 2001; Andersson et al. 2007; van Sterkenburg and van Dijk 2011).

It is believed that in a healthy situation, the plantaris tendon can move freely in relation to the Achilles tendon. Adhesions between plantaris and Achilles tendon (Fig. 34.1) can be the result of an inflammatory response of the paratenon, which is located around the Achilles and plantaris tendons.

The plantaris muscle-tendon complex not only causes flexion but also inversion, whereas the triceps surae is a flexor only. Adhesions between both tendons obstruct the opposite forces of these two bi- and triarticular muscle groups. Although the movement between the two will be limited, traction onto the surrounding paratenon will take place with every step with a mean of 5,000–12,500 steps/day in people with a low active to active lifestyle (Tudor-Locke and Bassett 2004; Tudor-Locke et al. 2008). Chronic painful tendons have been shown to exhibit new ingrowth of sensory nerve fibres from the paratenon (Schubert et al. 2005). Repetitive traction onto this richly innervated area might contribute to the medially located pain and stiffness during and after walking.

34.2.3.3 Clinical Presentation and Evaluation

It is hypothesised that the main cause of the pain in patients with symptomatic midportion Achilles tendinopathy does not arise from the tendon proper but is generated by its surrounding tissues.

Symptoms of a patient with midportion Achilles tendinopathy include painful swelling typically 2–7 cm proximal to the insertion and stiffness especially when getting up after a period of rest. Pain is the main symptom in Achilles tendinopathy that leads a patient to seek medical help. It is often most prominent 2–7 cm from the insertion onto the calcaneus on the medial side (Segesser et al. 1995; van Sterkenburg and van Dijk 2011). Tendinopathy and paratendinopathy often coexist (Saxena 1995; van Sterkenburg and van Dijk 2011). Intratendinous changes most often remain asymptomatic (Kannus and Józsa 1991). In these cases, a painless swelling at 2–7 cm proximal to the insertion is the only finding. In isolated paratendinopathy, there is local thickening of the paratenon. The area of swelling does not move with dorsiflexion and plantar flexion of the ankle, where it does in isolated tendinopathy (Steenstra and van Dijk 2006; van Sterkenburg and van Dijk 2011). Paratendinopathy can be acute or chronic. Acute isolated paratendinopathy manifests itself as painful peritendinous crepitus as the tendon glides within the inflamed covering. Areas of increased erythema, local heat and asymptomatic palpable tendon nodules or defects may also be present at clinical examination. In chronic paratendinopathy, exercise-induced pain is the main symptom while crepitation and swelling diminish.

It has been described that the location of the pain in patients with Achilles tendinopathy is most often located on the medial side (Segesser et al. 1995; Steenstra and van Dijk 2006; van Sterkenburg and van Dijk 2011). During Achilles tendoscopy in patients with Achilles tendinopathy, it has been observed that at the level of complaints, the plantaris tendon is affixed onto the Achilles tendon on the medial side (19) (Fig. 34.1). Some authors describe a higher medial stress onto the Achilles tendon due to hyperpronation. This is supported by the finding that most ultrasonographic midportion disorders (91 %) are found in the posteromedial segment of the tendon (Gibbon et al. 2000; de Jonge et al. 2011a).

34.2.4 Flexor Hallucis Longus Tendon

Flexor hallucis longus (FHL) tendinopathy is a typical injury in ballet dancers. It is characterised by posteromedial located pain, especially at relevée and grand plié. During active or passive flexion movements of the first toe with the ankle in 10–20° plantar flexion, the moving FHL can be palpated posterior to the medial malleolus. With tendinopathy there is pain on palpation and active resistance testing. Crepitus might be present and is suggestive for FHL tenosynovitis. Flexor hallucis longus tendinopathy is frequently seen together with the posterior ankle impingement syndrome.

34.2.5 Peroneus Tendon

This is the most common cause of posterolateral ankle pain in athletes. Most athletes will present with a history of ankle sprains. Posterolateral-located clicking sensations are suggestive for peroneal tendon luxations. Athletes with a varus hindfoot and/or restricted range of motion (ROM) of the subtalar joint are more prone to peroneal tendon overload. Pain on palpation is found just posterior to the lateral malleolus and can extent more distally. Swelling and slightly increased skin temperature might be present and should be compared to the contralateral site. Peroneal luxations should be tested by active resisted eversion. The tendon will luxate laterally and anteriorly.

34.2.6 Tibialis Posterior Tendon

Athletes with a clear pes planovalgus or with a forefoot abduction are prone to place greater strain on the muscle (Rabbito et al. 2011). Posteromedial palpation will reveal tenderness, discrete swelling and occasionally crepitus. Resisted supinations provoke the pain.

34.3 Achilles Tendon Ruptures

34.3.1 Epidemiology

Achilles tendon rupture occurs relatively common (de Jonge et al. 2011b). Although it is the thickest and strongest tendon in the human body, it remains susceptible to injury. During the last decades, the incidence of spontaneous ruptures has been rising, which may be due to the increasing keep-fit culture. Ruptures occur most frequently in patients between the age of 30 and 50 years old, with a male predominance. Approximately 75 % of Achilles tendon ruptures occur during sports activities, especially racket games, soccer and handball. Diagnosis is clinical. However, there is still a lack of consensus on the best management of the Achilles tendon rupture. Generally, open operative management is used, although over the past few years, percutaneous techniques are performed more commonly. Conservative management seems to be a good alternative for those with great co-morbidity or patients who do not wish to have surgery. Recent systematic reviews have concluded that operative management has a lower re-rupture rate but must be balanced by the risks associated with surgery (Khan and Carey Smith 2010).

34.3.2 Functional Anatomy

The Achilles tendon consists of the fibres of two muscle units in the superficial compartment of the posterior leg: the gastrocnemius muscle (medial and lateral head) and the soleus muscle. At about the level where the soleus contributes fibres to the Achilles tendon, rotation of the tendon begins and becomes more marked in the distal 5–6 cm. This rotation results in a relatively hypovascular area. The Achilles tendon inserts crescent-shaped halfway the posterior tuberosity of the calcaneus (Lohrer et al. 2008). The blood supply to the tendon is poor, and there is decrease in its nutrition with advancing age. Unlike other tendons in the leg, the Achilles tendon is a type 1 tendon that lacks a synovial sheath. Instead, it has a paratenon, which is an array of thin connective tissue containing blood vessels (Saxena and Bareither 2001). Together with the bone-tendon and the muscle-tendon junction, the paratenon forms the sole vascular supply of the Achilles tendon. A recurrent branch of the posterior peroneal artery mostly supplies the paratenon, whereas the peroneal artery makes small contributions.

The sural nerve is located to the lateral border of the Achilles tendon at its midportion, but many variations have been described (Apaydin et al. 2009). It is especially vulnerable to iatrogenic damage, most often Achilles tendon surgery, resulting in hypo- or hyperaesthesia of the lateral side of the affected foot.

34.3.3 Aetiology and Injury Mechanism

There is little agreement on the aetiology of spontaneous Achilles tendon ruptures. Several hypotheses have been proposed, such as poor tendon vascularity, the adverse effect of the use of corticosteroids and fluoroquinolones and exercise-induced hyperthermia in a relatively avascular tendon. Mechanical factors such as overpronation of the foot on heel strike, training errors, malfunction or suppression of propriocepsis of skeletal muscle have also been suggested. Histologically, spontaneously ruptured Achilles tendons might show degeneration of the fibres near the rupture site. There is a decrease in the maximum diameter and density of collagen fibrils. However, there is little evidence of a failed healing response. Aetiology is probably multifactorial.

The mechanism of injury includes a sudden pushing off from the weight-bearing forefoot with the knee in extension, unexpected ankle dorsiflexion and violent dorsiflexion of a plantar-flexed foot (Arner and Lindholm 1959).

34.3.3.1 Clinical Presentation and Evaluation

Achilles tendon rupture is a clinical diagnosis. Patients report sudden intense pain in the midportion of the Achilles tendon, often stating that someone might have struck their heel. On clinical examination, a positive calf squeeze test, the so-called Thompson test, and a gap in the Achilles tendon are consistently found. If any diagnostic doubt still exists, the next step is to perform ultrasonography of the tendon and its insertion.

34.4 Ligament Injuries

34.4.1 Acute Lateral Ankle Ligament Injuries

34.4.1.1 Epidemiology

Injury to the lateral ligament complex of the ankle is a common problem in the emergency department. It is estimated that 1 ankle sprain occurs per 10,000 people per day. Overall, injuries of the lateral ligament complex of the ankle form a quarter of all sports injuries. Some sports (e.g. basketball, soccer and volleyball) have a particularly high incidence of ankle injuries (Lindenfeld et al. 1994; Luidinga and Rogmans 1985). The treatment of inversion injuries is performed by emergency and primary health-care physicians as well as by orthopaedic and trauma surgeons (Kannus and Renström 1991). The total annual cost to society for ankle injuries has been estimated to be approximately 40 million Euro per 1 million people.

34.4.1.2 Functional Anatomy

Together, the anterior talofibular, calcaneofibular and posterior talofibular form the lateral ligament complex of the ankle. The anterior and posterior talofibular ligaments run horizontally from the lateral malleolus to the talus and are capsular ligaments that represent discrete thickenings of the ankle joint capsule. The calcaneofibular ligament runs from the fibula down- and backwards directly to the calcaneus and is extracapsular, and in close approximation to the inferior sheath of the peroneal tendons, it is regarded a stabiliser of the ankle (talocrural) and subtalar joints.

Relevant nerves for the ankle originate from the lower lumbar and higher sacral spinal roots (L4–S2). Efferent fibres of the deep peroneal nerve innervate the anterior muscles of the leg, the superficial peroneal nerve innervates the peroneal muscles on the lateral side and the tibial nerve innervates the muscles on the posterior side of the leg. The afferent path consists of all nerves that send proprioceptive information from mechanoreceptors around the ankle to the central nervous system.

34.4.1.3 Aetiology and Injury Mechanism

There are predisposing factors for sustaining an acute lateral ligament injury. A high longitudinal arch, greater foot width, cavovarus deformity, gait on the lateral side of the foot and congenital joint hypermobility have been described.

The most common mechanism of injury is supination and adduction (usually referred to as inversion) of the plantar-flexed foot (Lauge-Hansen 1949). In sports involving jumping, a major cause of lateral ligament injury is a player landing on the foot of an opponent; in contact sports, most injuries occur during tackling where the opponent hits the medial side of the lower leg, causing outward rotation of the knee and forcing the ankle into an inverted position. It is known that the anterior talofibular ligament is the first ligament to crack and is torn in 97 % of cases (Broström 1965; Steenstra and van Dijk 2006; Verhagen et al. 1995). The subsequent ligament to crack is the calcaneofibular ligament; indeed isolated rupture of the calcaneofibular ligament occurs in only 3 %. Brostrom found that combined ruptures of the anterior talofibular ligament and the calcaneofibular ligament occurred in 20 % of the cases (Broström 1965). The last ligament to crack is the posterior talofibular ligament which is usually uninjured unless there is a frank dislocation of the ankle.

34.4.1.4 Clinical Presentation and Evaluation

On presentation, patients mostly recall the accident as a twisting injury to their ankle and present with pain and swelling. Differentiation between an ankle fracture and a lateral ligament rupture is not always easy. The Ottawa ankle decision rules are helpful in saving unnecessary radiographic investigation in about 30 % of cases, using bony tenderness and inability to bear weight as positive indicators for radiography (Stiell et al. 1993). When no osseous injury is present, the degree of injury can traditionally be graded I to III (Bernett and Schirmann 1979). Grade I is a mild stretching of the ligament without instability, grade II is a partial rupture with mild instability of the joint (such as isolated rupture of the anterior talofibular ligament) and grade III involves complete rupture of the ligaments with instability of the joint. Due to the strong character of pain and swelling, the patient will contract the muscles around the ankle, which hinder reliable anterior drawer testing. It has become a common practice to wait a few days; to advice the patient according to the rest, ice, compression and elevation (RICE) protocol; and to perform a delayed physical examination after 5–7 days. Swelling, local tenderness, a positive anterior drawer test and hematoma indicate the presence of a lateral ligament rupture.

34.4.2 Chronic Lateral Ankle Ligament Injuries/Instability

Although surgical treatment for acute injuries of the lateral ankle ligaments probably gives slightly better functional results than conservative treatment, it is unclear whether this compensates for a higher risk of complications, higher costs and required operation time (Kerkhoffs et al. 2007; Pijnenburg et al. 2000). Conservative treatment leads to full functional recovery in most people. However, up to 20 % continue to suffer from lateral ankle instability, characterised by recurrent ankle sprains or a feeling of apprehension in the ankle (giving way). If this persists for longer than 6 months, the term ‘chronic (lateral) ankle instability’ (CAI) is used (Karlsson et al. 1996).

34.4.2.1 Aetiology and Injury Mechanism

Prior to the 1960s, it was assumed that chronic ankle instability was mechanical in origin, resulting from structural laxity of the injured ankle ligaments. This ‘mechanical instability’ (MI) can be assessed by physical and radiological examination, using the anterior drawer test and the ankle inversion test (Karlsson et al. 1996). However, it is now clear that chronic ankle instability may occur with or without increased ligament laxity. Increased ligament laxity does not always result in symptomatic instability. These observations have led to the concept that functional instability (FI) resulting from a neuromuscular deficit is implicated along with mechanical instability in people with symptoms of chronic ankle instability (Halasi et al. 2005; Hertel 2002; Hubbard et al. 2007).

34.4.2.2 Clinical Presentation and Evaluation

The diagnosis is based on the patient’s history. Pure lateral instability is characterised by recurrent inversion sprains or giving way as the main symptom. Pain and swelling may accompany an episode of recurrent spraining but is not present in between. The location of pain gives an indication of what structure is affected. Deep ankle pain on weight-bearing fits the diagnosis of an osteochondral defect. In long-standing ankle instability, there are signs of posttraumatic osteoarthritis of the talocrural joint. Duration of symptoms should be evaluated, as 6 months is more or less the time for rehabilitation of an acute lateral ligament injury. It is important to clarify the type of physiotherapy a patient has had, e.g. whether instability training has been performed. The use of ankle supports gives an idea of the severity of the instability. Furthermore, level of sports and work should be assessed, as compared to pre-injury levels.

Gait and stance examination may show a lateral gait or a cavovarus foot that predisposes for inversion injuries. General swelling indicates intra-articular pathology or recent injury. Range of motion of the ankle and subtalar joints should be assessed for pain, crepitus, restrictions and locking. The ankle region should be carefully palpated for tenderness. Increased laxity of the lateral ligaments is best tested with the anterior drawer test, comparing it to the contralateral side.

For lateral ankle ligament instability, plain ankle radiographs (AP, lateral and mortise) are usually sufficient to rule out displaced fractures; it is important to recognise that in 30 % of cases, occult fractures, i.e. not visible on radiographs, are described in literature. Ankle stress radiographs may help to confirm mechanical instability but have a low sensitivity and positive predictive value. Stress radiographs are mostly used in research, to quantify the effect of a (surgical) treatment. The clinical application remains questionable. Additional investigation is usually not part of clinical practice.

34.4.3 Acute Medial Ankle Ligament Injuries

34.4.3.1 Functional Anatomy

The deltoid ligament inserts from the medial malleolus and attaches to the medial talus, calcaneus and navicular bone. It can be differentiated into the anterior tibiotalar ligament, the tibiocalcaneal ligament, the posterior tibiotalar ligament and the tibionavicular ligament. The deltoid ligament is a strong ligament and less frequently injured than the lateral ligaments.

34.4.3.2 Aetiology and Injury Mechanism

The classical injury mechanism of a deltoid ligament lesion is forced eversion of the foot, such as a direct trauma to the lateral aspect of the foot and ankle (Hintermann et al. 2006). It is relatively uncommon that an inversion trauma induces combined lateral ligament injury and deltoid lesions.

34.4.3.3 Clinical Presentation and Evaluation

Physical examination reveals swelling and pain on palpation of the medial ligament with signs of talar subluxation in complete lesions. Standard radiographs are frequently normal. The sensitivity of MRI to detect deltoid lesions is high (Schneck et al. 1992). However, there is a risk of overdiagnosing deltoid ligament lesions – deltoid ligament abnormalities after a classical inversion trauma (with lateral ligaments injuries) are reported to be present in 60 % of the cases, but this frequently does not align with the clinical findings.

The therapy of deltoid lesions is dependent on associated injuries, such as syndesmotic injuries and ankle fractures. Combined lateral and deltoid ligament injuries can frequently be treated in the same manner as a lateral ligament injury. Simple isolated deltoid sprains can be treated with functional treatment. Isolated deltoid ruptures are mostly treated conservatively by 4–6 weeks of immobilisation and progressive rehabilitation; however, high-level athletes can be advised to consider a surgical option.

34.4.4 Syndesmotic Injury

34.4.4.1 Epidemiology

Injuries to the distal tibiofibular syndesmosis can range from stable minor sprains to significant fractures of the distal fibula with combined syndesmotic disruption; they are typically related to eversion-type ankle injury. When compared with its clinical disability, a syndesmotic injury presents worse than a typical lateral ankle sprain. When patients present with a classic ankle sprain, it is noted that up to 18 % of them also suffer from a syndesmotic lesion.

34.4.4.2 Functional Anatomy

The syndesmosis consists of the anterior and posterior inferior tibiofibular ligament and the interosseous tibiofibular ligament. The inferior transverse tibiofibular ligament is sometimes considered as a fourth ligament, but it is not a separate structure, since it is really a continuation of the distal aspect of the posterior inferior tibiofibular ligament. In almost 75 % of the cases, there are contact facets with articular cartilage jointing the distal tibia and fibula, forming a true synovial joint.

The posterior inferior tibiofibular ligament provides approximately 40 % of the resistance towards lateral displacement, the anterior inferior tibiofibular ligament 35 % and the interosseous ligament 22 %. The remaining stability is provided by the interosseous membrane.

34.4.4.3 Aetiology and Injury Mechanism

The mechanism of injury in a syndesmotic sprain can be an isolated hyperdorsiflexion force, but it occurs most commonly due to an external rotation injury, in combination with axial loading of the ankle. However, in patients with a combined deltoid injury or medial malleolar fracture, an abduction force is mainly the cause of the associated syndesmotic lesion.

Isolated total ruptures are relatively infrequent, and acute syndesmotic injuries have been reported especially in football and skiing.

34.4.4.4 Clinical Presentation and Evaluation

Direct palpation pain onto the syndesmosis and more proximally is the key to a good clinical assessment. It is also important to check the entire fibula up to the knee for any suspected syndesmotic injury. Swelling is much less noted in a syndesmotic injury when compared with a traditional ankle sprain, and the ecchymosis is usually more proximal to the ankle joint compared with a usually more distally localised ecchymosis in a lateral ankle sprain (Kerkhoffs et al. 2012; McCollum et al. 2013).

The test is performed by stabilising the leg with the knee flexed at 90° and then rotating the foot externally. When acutely injured, this test will elicit pain at the syndesmosis. Other tests to determine the integrity of the syndesmotic ligaments are the squeeze test, the cotton test and the fibular translation test. The cotton test and the fibular translation tests are more useful for chronic syndesmotic lesions (McCollum et al. 2013).

During a squeeze test, the examiner grasps the supine patient's middle part of the tibia and fibula and applies compression and release motion. A positive test is considered if the patient experiences pain in the syndesmotic area. The cotton test can be performed by steadying the distal leg with one hand while grasping the plantar heel with the opposite hand and moving the heel directly from side to side.

Any lateral translation during this test indicates potential syndesmotic instability. The fibular translation manoeuvre tests anteroposterior pain and stability of the distal fibula.

During physical examination, it is important to palpate the medial ankle in addition to determine the integrity of the deltoid ligament, since it can highlight a more significant unstable syndesmotic injury.

Imaging

A mortise or AP and lateral weight-bearing radiograph should be used to evaluate the tibiofibular clear space and to rule out any ankle fracture. Also stress radiographs are recommended. With these 'conventional' diagnostics, still syndesmotic ligament injuries easily can be missed. For this reason, magnetic resonance imaging (MRI) is recommended, which has been reported to have a sensitivity and specificity of, respectively, 95 and 90%.

When performing a mortise view, 1 mm overlap or more is predictive of an intact syndesmosis.

The use of stress radiographs, compared with the contralateral side, is essential when plain radiographs are equivocal. Imaging modalities with advanced ultrasound of the anterior tibiofibular ligament, bone scan and arthrography have been used in the assessment of syndesmotic injuries, but magnetic resonance imaging provides a more accurate evaluation of the ligamentous anatomy of the syndesmosis, since MRI demonstrates also the posterior inferior tibiofibular ligament and can nicely elucidate associated injuries such as deltoid ligament injuries, bone bruises, fractures and osteochondral injuries. Arthrography has demonstrated a high sensitivity of 90 % with a specificity of 67 % when performed within 48 h after trauma. However, arthrography has – in most instances – been replaced by MRI since it is expected to have a similar high sensitivity and specificity, and MRI has the advantage of being a non-invasive technique.

In summary, distal syndesmotic sprains are related to eversion-type ankle injury and are less frequent than typical lateral ankle sprains that are related to inversion-type ankle injury, but they are easily recognised when associated with a fracture of the fibula at the level of the distal metaphysic or diaphysis.

Increased awareness and a thorough history, clinical examination and detailed radiographic evaluation including the whole length of the diaphysis and distal syndesmotic sprains – not associated with a fracture – can be astutely diagnosed following the appropriate above-mentioned reasonable guidelines.

34.5 Ankle Impingement Syndromes

34.5.1 Anterior Ankle Impingement

34.5.1.1 Epidemiology

One of the most common causes of chronic anterior ankle pain in athletes is the anterior ankle impingement syndrome. The anterior ankle impingement syndrome is typically characterised by anteriorly located ankle pain, which increases by forced hyperdorsiflexion.

It can be differentiated in soft tissue and bony impingement.

34.5.1.2 Aetiology and Injury Mechanism

Contrary to other joints, osteophytic formation of articular cartilage can typically develop in athletes without pathologic changes of the weight-bearing articular cartilage and should therefore be differentiated from osteophytes in degenerative osteoarthritis. It is questionable if the osteophytes develop due to repetitive capsular traction during hyper-plantar flexion movements. Post-ankle trauma cartilage damage and subsequently recurrent instability are supposed to enhance the osteophytic formation. In football and soccer players, the osteophytes are a manifestation of anterior medial ankle contact trauma in combination with recurrent kicking of the ball (Tol and van Dijk 2004; Tol et al. 2002).

The cause of pain is hypothesised to be due not to the osteophyte itself, but it is the inflamed soft tissue impingement that occurs between the osteophytes (Cheng and Ferkel 1998; McMurray 1950). During forced dorsiflexion movements, this soft tissue component gets squeezed between the anterior distal tibia and the talus. Recurrent trauma to this soft tissue component may lead to hypertrophy of the synovial layer, subsynovial fibrotic tissue formation and infiltration of inflammatory cells. In theory, arthroscopic excision of the soft tissue could relieve pain. Talar and tibial osteophytes, however, decline the anterior space, and compression of this soft tissue component is more likely to occur (van Dijk et al. 1997; Tol et al. 2001).

34.5.1.3 Clinical Presentation and Evaluation

Most patients present with a history of ankle sprain. Their major complaint is persistent anterior-located ankle pain with dorsiflexion, exercise-induced swelling and limitation of ankle dorsiflexion (Cheng and Ferkel 1998; van Dijk et al. 1997; Scranton and McDermott 1992). The pain does not necessarily lead to complete withdraw from sports activities, but often to reduced training intensity.

On physical examination, there is a recognisable local pain on palpation along the anterolateral and/or anteromedial joint line. In plantar flexion, the joint capsule stretches over the osteophytes, which makes it difficult to palpate the osteophytes. Neutral or slightly dorsiflexion position is advised to palpate the tibial or talar osteophytes.

A differentiation can be made between anteromedial and anterolateral impingement (van Dijk et al. 1997). On palpation of the anterior joint line, the patient is asked if the test recreates his or her pain. Since the middle section is covered by neurovascular structures and tendons, this part of the joint is difficult to access by palpation. If a patient with a clinical anterior impingement syndrome experiences pain predominantly located in section I when palpated, the diagnosis is anteromedial impingement. If pain on palpation is predominantly located in section III, the diagnosis is anterolateral impingement (van Dijk et al. 1997). This impingement is located at the anterolateral tibiofibular groove and is caused by vascularised meniscoid tissue that is pinched between the ligaments (anterior inferior tibiofibular or anterior talofibular ligament) and the talus. Forced hyperdorsiflexion can provoke the pain, but this movement is often not positive when examining the patient.

34.5.1.4 Clinical Differentiation Between Anteromedial and Anterolateral Impingement

At the anterior joint line, the tibialis anterior muscle and the extensor digitorum longus muscle divide the anterior ankle joint in a medial section (section I), middle section (section II) and lateral section (section III). If pain on palpation in a patient with a clinical anterior impingement syndrome is predominantly located in the medial section (section I), the diagnosis is anteromedial impingement. In patients with an anterolateral impingement, the pain is predominantly located in the lateral section (section III).

34.6 Posterior Ankle Impingement Syndrome

34.6.1 Aetiology and Injury Mechanism

The most common cause of posterior ankle pain is the posterior ankle impingement syndrome (Callanan et al. 1998; van Dijk et al. 1995, 2000; Hamilton et al. 1996). It is a clinical pain syndrome, which can be provoked by forced hyper-plantar flexion movements. During plantar flexion, the posterior ankle capsule and soft tissue pinch between the distal tibia and posterosuperior calcaneal bone. It can be differentiated in soft tissue and bony impingement. Bony impingement can be caused by a prominent posterior process of the calcaneal bone or a prominent os trigonum. An os trigonum is present in about 7 % of the normal population and is not necessarily associated with the posterior ankle impingement syndrome.

The posterior ankle impingement syndrome is caused by repetitive overload due to microtrauma or has an acute traumatic origin. The classical example of repetitive overload is seen in ballet dancers, but is not exclusively related to ballet. Forced plantar flexion during 'en pointe' and 'demi pointe' might induce repetitive impingement of the posterior-located soft tissue components (van Dijk et al. 1995).

Acute forced hyper-plantar flexion might also lead to the posterior ankle syndrome. This traumatic and acute origin is typically found during a blocked kicking action in football. Compression of the os trigonum between the distal tibia and calcaneal bone can lead to the displacement of the os trigonum and fractures of the processus posterior tali or distal tibia.

34.6.2 Clinical Presentation and Evaluation

The major complaint is persistent posterior-located ankle pain with (forced) plantar flexion movements. On physical examination, there is a recognisable local pain on palpation along the posterior aspect of the talus. Posteromedial palpation of the talus might be difficult due to the neurovascular structures and flexor tendons. Posterolateral palpation reveals recognisable pain. The posterior ankle impingement test is essential for making the diagnosis. With this test, the ankle is passively and quickly forced from neutral to hyper-plantar flexion position. Recognisable posterior pain is decisive for the diagnosis. With plantar flexion, slightly external rotation and eversion, the posterolateral structures are compressed. For medial compression, slightly inversion and internal rotation are required.

34.7 Sinus Tarsi Syndrome

Sinus tarsi syndrome reflects a clinical entity that demonstrates an abnormal tarsal sinus and tarsal canal. Due to increased physical activity and induced by inversion trauma, the lateral part of the ankle becomes chronically painful. Tenderness over the sinus tarsi in clinical examination is disclosed during palpation and is increased by inversion and eversion joint movement of the hindfoot.

This condition frequently shows normal plain radiographic examination, and no diagnostic reference standard exists. Imaging modalities such as a subtalar arthrography show a complete disappearance of the microrecesses along the interosseous ligament in this condition.

MRI demonstrates soft tissue pathology into the sinus tarsi, together with a close relationship of injury to the lateral ligaments of the ankle. Pathology of the fat pad and the anterior annular ligament are considered important contributors to the pain syndrome. Recent literature also reveals an increased frequency of calcaneofibular ligament (i.e. a stabiliser of the ankle joint but also of the subtalar joints) injury in patients with sinus tarsi syndrome. Detection of calcaneofibular ligament injury thus has increased prognostic value compared to anterior talofibular ligament injury; the latter is found in the majority of patients with inversion trauma that present at emergency departments.

34.7.1 Functional Anatomy

The tarsal sinus and the tarsal canal form a boundary between the anteriorly located talocalcaneal-navicular joint and the posterior subtalar joint, and they course from posteromedial to anterolateral. In 1944, Wood Jones emphasised the difference between the more superficially localised sinus tarsi and the tarsal canal, being the portion that extends to the medial aspect of the foot posterior to the sustentaculum tali. The cone-shaped tarsal sinus widens laterally and contains its ligaments, nerves and blood vessels within its fibro-fatty tissue.

The superficial layer of the inferior extensor retinaculum is consistently found to be a thick, strong, well-defined layer that is readily accessible for repairs of lateral ankle instability (Gould 1983). However, it cannot be a major mechanical stabiliser of the hindfoot since it is a superficial layer, is easily distensible and contains a large proportion of elastic fibres. The suggested main stabilisers of the hindfoot are the interosseous talocalcaneal ligaments and the cervical ligament, which are thick and strong (Kjaersgaard-Andersen et al. 1989). These two ligaments consist primarily of collagen fibres, and both connect the talus and the calcaneus deep in the sinus tarsi and the tarsal canal. Although biomechanics shows that an isolated lesion of the cervical or interosseous ligament results in minor movement increase of the total hindfoot joint complex, the resultant instability is considerable when these increments in movement are compared with the total range of motion, especially at the talocalcaneal joint. Therefore, it is suggested that the minor instability appearance of these lesions still might have a clinical role in sinus tarsi syndrome.

34.7.2 Clinical Presentation and Evaluation

Sinus tarsi syndrome is induced by a supination trauma of the hindfoot. Its clinical presentation includes localised pain over the sinus tarsi itself and is increased by hindfoot motions, supination or pronation. Although there are no established diagnostic criteria for posttraumatic sinus tarsi syndrome, it's a well-defined entity of foot pathology. Local pain is increased during physical activity such as walking or running, especially on uneven ground. Although there are normally no clinical mechanical signs of laxity or instability, the patient often describes a sensation of 'giving way' in the ankle. Around 70 % of the reported sinus tarsi syndrome cases in literature are caused by inversion injury of the ankle. Consequently, there is a close association between tarsal sinus and canal ligament tears with tears of the lateral collateral ligaments; especially the calcaneofibular ligament covers both the ankle and subtalar joints.

The association between inversion injury of the ankle and pathology of the talar and subtalar capsule-ligamentous structures has been stressed by Meyer and co-workers (Meyer and Lagier 1977; Meyer et al. 1988). In summary, although the patient's major complaint is frequently the sensation of hindfoot instability, they rarely present with objective hindfoot instability.

34.7.2.1 Imaging

Since sinus tarsi syndrome is a soft tissue injury in the majority of cases. Therefore, plain radiographs are only helpful in the setting of excluding displaced fractures. The early phase of a triphasic bone scan may demonstrate focal increased perfusion but is non-specific. When patients present with chronic pain and normal plain radiography, a computed tomography or MRI is used to exclude occult fractures such as those of the lateral process of the talus and posterior body of the talus. When a sinus tarsi syndrome is confirmed, arthrography of the subtalar joint demonstrates a sac-like anterior bulge of the capsule.

In the past decade, patients with a sinus tarsi syndrome have been investigated with detailed normal anatomical, cadaveric and MRI-based studies.

34.8 Osteochondral Injuries

34.8.1 Epidemiology

An osteochondral lesion of the talus (OLT) is one of the most important causes of residual pain after an ankle sprain. It is defined as the separation of a fragment of articular cartilage, with or without subchondral bone. Its incidence after an ankle sprain, which has been reported as up to 6.5 %, is probably underestimated because these lesions often remain undetected (Flick and Gould 1985).

34.8.2 Functional Anatomy

Three essential components form the functional anatomy of the ankle joint. They consist of the complex relationship between the bony anatomy, the ligamentous anatomy and the tendinous anatomy. Articular cartilage is a tissue of mesenchymal origin that covers the articular surfaces of bone and is capable of maintaining its properties for decades.

Adult articular cartilage has different functions: it spreads the applied load onto the subchondral bone, it provides the articular surfaces with low friction and lubrication and it is responsible for the mechanism of shock absorption. Cartilage is an avascular, aneural and alymphatic tissue that is composed of water, type 2 collagen, proteoglycans, glycoproteins and cells.

In adult cartilage, cells represent less than 10 % of the total volume, and the chondrocytes receive nutrients by diffusion from the synovial tissue. The complex network, formed by proteoglycans and type 2 collagen, provides the articular cartilage with two characteristics: the resistance to a compressive stress and the high elasticity.

Hyaline cartilage can be subjected to different types of lesions, which may lead to different repair responses. Generally, cartilage lesions can be divided into superficial lesions, blunt traumas and combined subchondral bone or osteochondral lesions injuries.

Subchondral bone is the life partner of cartilage. What affects one influences the other.

Cartilage provides the low-friction surface that disseminates shear forces and allows a joint to convert bending forces into axial loads, sustained by the skeleton.

Subchondral bone must be sufficiently flexible as if too stiff it becomes an anvil on which cartilage can be injured.

34.8.3 Aetiology and Injury Mechanism

An osteochondral lesion is defined as a type of damage that consists of a full-thickness cartilage defect extending into the underlying subchondral bone. Articular cartilage is a metabolic active tissue, but it has a poor intrinsic healing potential when damaged. Traumatic lesions and degenerative diseases strongly affect joint function, as the reparative process of articular cartilage frequently results in fibrous tissue and the native cartilage around the damaged area is often necrotic and remains inert without any remodelling phenomena.

The healing process of the osteochondral lesions is influenced by different factors: the size and the location of the damaged area and also the age of the patient. In fact, extensive defects or lesions in the weight-bearing areas have minor chances to the successful healing. On the other hand, young patients with an osteochondral lesion show a more effective synthesis of macromolecules, allowing a better cellular response to injury.

34.8.4 Clinical Presentation and Evaluation

34.8.4.1 Imaging

Due to the many possible variations in their presentation, imaging and treatment options, several classifications have been described and are being used when talking about osteochondral lesions of the ankle. The lesions are typically located at the talus and known as osteochondral lesion of the talus (OLT).

The first is a revised Berndt and Harty radiographic classification of osteochondral lesions by Loomer et al. (1993).

Stage	Characteristics
I	Compression of subchondral bone
II	Partially fractured but undisplaced
III	Completely fractured but undisplaced, also called ‘in situ’ fragment
IV	Displaced fracture
V	Radiolucent (fibrous defect)

The CT-based classification of osteochondral lesions by Ferkel and Fasulo (1994)

Stage	Characteristics
I	Cystic lesion with dome of talus, intact roof on all views
IIA	Cystic lesion with communication to talar dome surface
IIB	Open articular surface lesion with overlying no displaced fragment
III	Undisplaced lesion with lucency
IV	Displaced fragment

The MRI classification of osteochondral lesions by Anderson et al. (1989)

Stage	Characteristics
I	Subchondral trabecular compression. Plain radiograph normal, positive bone scan, marrow oedema on MRI
II	Incomplete separation of fragment
IIA	Formation of subchondral cyst
III	Unattached, undisplaced fragment with the presence of synovial fluid around ligament
IV	Displaced fragment

The biochemical composition and the morphological organisation of the articular cartilage are fundamental for the biomechanical function of this tissue. In physiological conditions, the extracellular matrix and the joint environment allow the cartilage tissue for a biomechanical response with practically no tissue consumption and degradation. However, when a lesion occurs, the remaining cells are not able to organise an adequate regenerative response, or – in the case of an osteochondral lesion – the infiltrating cells fail in the attempt of organising the newly formed tissue into a biomechanically functional matrix. Therefore, especially in large lesions involving weight-bearing areas in adult patients, this leads to a long-term failure of the reparative tissue, making the defect of the articular cartilage one of the most problematic and challenging issues for the orthopaedic surgeon nowadays.

34.9 Stress Fractures

Overuse-type stress fractures occur mainly in athletes and runners and more frequently in skeletally mature patients in the age of 20–40 years. Although stress fractures have been described in nearly every bone, they are more common in the weight-bearing lower extremities. Metatarsal insufficiency-type stress fractures can occur in older osteoporotic patients with reduced bone mineral density, but medial malleolar stress fractures rarely do. The incidence of medial malleolar overuse-type stress fractures varies from 0.6 to 4.1 % of all stress fractures. Medial malleolar stress fractures account for only 10 % of all stress fractures of the foot and ankle. Approximately 10 % of stress fractures of the lower leg occur in the fibula, most commonly in the distal third, less frequently in the proximal third (Sobczyk et al. 2008). Stress fractures of the fibula are caused by, for example, tibiofibular synostoses and bowing of the lower extremity in children. Literature on the subject is scarce.

34.9.1 Aetiology and Injury Mechanism

Overuse stress fractures occur as a result of repetitive and excessive impact on normal mineralised bone of forces exceeding bone resistance when the body's repair abilities are insufficient so that the forces exceed the intrinsic ability of the bone to repair itself in a specific period of time (Sobczyk et al. 2008). Medial malleolus stress fractures are caused by abnormal weight transmission and torsional forces (Okada et al. 1995). Muscular forces are believed to be no relevant on the medial side of the ankle. The fracture line is vertical or oblique, arising from the junction of the medial malleolus and the tibial plafond (Orava et al. 1995; Shelbourne et al. 1988). Shelbourne et al. believed that closed chain loading of the foot results in a series of obligatory events that can result in injury to the medial malleolus (Shelbourne et al. 1988). When the forefoot pronates during the stance phase of gait, the navicular bone abducts, causing internal rotation of the talus. This rotation is then transmitted to the tibia through the medial malleolus, causing the characteristic stress fracture orientation. Okada et al. believed that an abnormally small angle between the tibial shaft and plafond increases stress transmission to the medial malleolus (varus alignment) (Okada et al. 1995). Tibia vara can lead to increased force transmission across the ankle joint by escalating the varus moment between the talus and the medial malleolus (Kor et al. 2003). Other series report no relationship between malalignment and the incidence of medial malleolar stress fractures (Okada et al. 1995; Orava et al. 1995).

34.9.2 Clinical Presentation and Evaluation

A specific and accurate diagnosis is the key to proper treatment. A key to diagnosis is a high index of suspicion in the appropriate setting. Diagnosis of a medial malleolus stress fracture may be difficult because of vague symptoms and slow onset. The anterior medial impingement syndrome, intra-osseous cyst formation in the medial malleolus as a result of osteochondritis dissecans in the tibial plafond or cartilage damage in this area is the most important in the differential diagnosis.

The patients' history is important to prevent delay in diagnosis and prolonged absence from competition. Patients with medial malleolus stress fractures usually have a history of high physical activity, a period of raised training intensity or the addition of adjunctive training activities. There is usually no history of acute trauma. It is important to know training habits or a change of habits, footwear, orthotics and previous (stress) injuries. Conditions such as osteoporosis, use of tobacco, hyperthyroidism, excessive alcohol intake, weight loss, menstrual disorders or eating disorders should also be considered in insufficiency stress fractures (Shelbourne et al. 1988). Male endurance athletes are also predisposed to insufficiency stress fractures as a result of abnormally low testosterone levels.

Symptoms are aggravated with activity and relieved with rest. The pain is generally localised over the medial malleolus, does not radiate and is often accompanied with some swelling and stiffness in this region. Physical examination should be carried out with the patient in sitting position without floor contact as well as with the patient standing and should include both foot and ankles. Physical examination of the patient with medial malleolus stress fracture normally reveals a normal range of motion of the tibiotalar and subtalar joint and the normal strength of the ankle muscles. Pain on palpation and percussion over the medial malleolus is mostly observed. The physical examination also confirms pain on palpation of the bony medial malleolus rather than along the surrounding tendons. Focal pitting or doughy oedema may be present. Sometimes there is effusion of the ankle joint. As discussed earlier, it is important to look at malalignment and gait pattern. Sometimes the patient will be unable to hop on the affected extremity because of pain.

Although a medial malleolus stress fracture is usually suspected on the basis of the patients' history and findings from a thorough physical examination, imaging modalities may be helpful in confirming the diagnosis or providing more information. Standard radiographs are the first step in evaluating the athlete suspected of having a medial malleolus stress fracture. These radiographs are initially negative in a maximum of 70 % of the cases and may not show evidence of stress fractures for 2–4 weeks after initiation of symptoms (Okada et al. 1995). In more advanced cases, cortical or medullary fracture lines may be seen extending vertically or obliquely upwards at the junction of the medial malleolus and tibial plafond. Other signs that may be noted are regional osteopenia, sclerosis and callus formation. Because of the high incidence of false-negative radiographs early in the course of medial malleolus stress fractures, additional diagnostic investigations are often indicated. Three-phase radionuclide bone scanning has been the first choice in additional imaging, but MRI has more and more replaced it. An increased uptake observed on the bone scan correlates with increased bone activity and may confirm the diagnosis of medial malleolus stress fracture or stress reaction (Schils et al. 1992). In contrast to MRI, it might be challenging to exactly localise the fracture with bone scanning. Advantages of MRI are precise differentiation between various tissues, with evaluation of surrounding ligaments, tendons and articular cartilage. The early changes of a stress reaction representing oedema and haemorrhage can be seen as an increased signal on short tau inversion recovery sequences within stress fracture demonstration of the hypointense fracture line in late stages of the disease. CT scans, especially in new-generation multidetector scanners with thin sections (2 mm), provide better bony detail for localisation of the stress fracture. Often well-circumscribed, small, lytic areas in addition to the fracture line can be seen on CT scans. This is believed to be the result of an earlier microfracture with subsequent resorption. CT scanning is also important for preoperative planning.

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Radiological Imaging of Ankle Injuries

35

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Abstract

Ankle sprains are common, but fortunately, the symptoms often resolve spontaneously. Many clinicians use the Ottawa rules to determine who should undergo radiographic examination to detect fracture. However, radiographs alone may overlook occult and sometimes highly significant fractures. In problem cases especially where there is persisting pain or disability, additional imaging is indicated. This might be CT or MR if there is evidence of an ankle joint effusion or ultrasound or MR if a ligament or tendon injury is suspected. Ultrasound examination is more accurate in detecting the nature of soft tissue injury, but MR is more comprehensive as it will cover bones and the deeper parts of the bone. The more complex imaging has a potential use in planning rehabilitation in the athlete.

Abbreviations

CT	Computed tomography
MRI	Magnetic resonance imaging
US	Ultrasound examination

35.1 Introduction

Injuries to the ankle are perhaps the most common problem for athletes. They range from minor sprains that recover in days with minimal treatment to career-threatening events. The conventional approach is to follow a management algorithm that uses conservative management as its mainstay, reserving more aggressive or invasive therapy when problems arise. There is now an increasing desire amongst clinicians and athletes to be more proactive by attempting to predict outcome, enabling a rehabilitation programme to commence early after the injury. Imaging inevitably takes a major role in this process. In this chapter, we will discuss the mechanisms of injury, the fracture patterns, ligament injuries and tendon injuries. We will describe where imaging may fit into the management process both in the occasional athlete and for professional sports persons whose career may be threatened. Finally, we will debate which areas have particular importance in future research.

35.2 Mechanisms of Injury

Those taking part in running, field sports, racket sports, jumping activities, gymnastics and martial arts are particularly at risk of an ankle injury. However, almost all athletes are at risk and, with few exceptions, will find their activities significantly curtailed by an ankle injury.

There are two major groups: the acute violent episode and those resulting from overuse or repetitive injury.

Twisting, inversion or eversion events may lead in sequence to sprain, ligament tears, fractures and osteochondral injury. The athlete often remembers the event sufficiently to aid in diagnosis. Whether there was a snap or popping sensation at the time assists the clinical review. Swelling and bruising patterns may point to a particular injury depending on their locations, but they may also be so extensive that they can impede diagnosis. However, point tenderness is a guide, and it is especially important to examine for bone tenderness. The "Ottawa Rules" state that if there is no bone tenderness, then fracture is unlikely. These rules are used to select sprained ankle patients for radiographic examination (Bachmann and ter Riet 2004).

Acute injuries to the Achilles tendon lead to a particular history; the athlete will describe a sudden severe pain in the back of the ankle and they assume another person has kicked them. Indeed, some unwarranted altercations on the pitch or track have resulted in this particular injury.

Chronic repetitive injury is usually gradual and occult in its onset. However, as there must be a threshold of awareness to the symptoms, the athlete may attribute the onset to a particular race or training session. Observation of signs of an established or long-standing lesion is useful in these circumstances.

There may be a history of previous acute injury that predisposes itself to repetitive causation. For example, an old healed fracture with malalignment may lead to localised premature osteoarthritis.

35.3 Predisposition to Injury

Biomechanical overload of the joint, ligament or tendon may result from deformity that is either congenital or acquired. In the ankle, the former includes subtalar coalition, pes cavus (high arch foot) and pes planus (flat foot). A bump on the posterior superior calcaneus (Haglund deformity) may lead to an abnormal load on the Achilles tendon, although there is debate as to whether this deformity is the result of remodelling of bone secondary to Achilles overload (Kang et al. 2012).

Previous fractures, especially those that involve joint surfaces, increase the risk of premature osteoarthritis. The abnormal gait that ensues may in turn overload tendons, enthesis and ligaments. The causative old injury or fracture may be remote, for example, in the opposite leg or spine. Previous surgery including arthroplasty of other joints may increase the risk of ankle injury.

Patients with metabolic or congenital bone disease may present with an ankle injury sometimes with relatively minor injury. The ankle is not a typical site for spontaneous osteoporotic insufficiency fractures, but this common condition may increase the risk sufficiently enough to lead to fractures after minimal trauma. Therefore, age, gender, diabetes, treatment with anticoagulants, steroids, antiepileptic drugs and antacids (malabsorption) are factors to consider.

35.4 Acute Injuries

35.4.1 Fractures

A useful approach to analysing fractures of the three malleoli is to consider them as either "pull-off" or "push-off" fractures. If the force applied pulls at the bone by the ligament or tendon attachments, a fragment may be avulsed. This will have a contour that is rounded or relatively flat at the fracture surface and a typical transverse fracture orientation. In younger patients, the tendon or ligament tends to be strong and bone of apophysis may give way. In the older patient, a rupture of a tendon or ligament is more likely, but both types of traction injury occur in all ages. Avulsion fractures of the lateral and medial malleoli tend to be at the tip of the bone, and it is uncommon for them to extend above the joint line.

On the other hand, impaction of the talus against the malleoli may push off a portion of the bone. Here, the fracture line will propagate proximally, commonly above the joint line. The contour may be oblique, spiral or twisted.

The nature of any fracture can be used to predict other injuries. The force causing the break will be dissipated across the limb. For example, an isolated spiral fracture of the fibula extending above the joint indicates a push-off injury with rotation. The force will have extended through the ankle joint and across the medial ligament where there will have been distraction. Therefore, a medial collateral (deltoid) ligament tear is likely.

Joint effusion has a high association with intra-articular extension of a fracture (Clark et al. 1996). If no fracture is apparent on conventional radiographs but there are soft tissue signs of a joint effusion, then the chance of osteochondral or chondral injury is increased. Some would argue that this is an indication for urgent CT or MR examination. Joint effusions can be detected on ultrasound (Fig 35.1).

The conventional radiograph is still the main stay in initial trauma imaging. There are several classification methods: in common use are the Weber classification, the Lauge-Hansen classification and the AO system (Fig 35.2). These are of particular value in research projects. Some will use the classification to assist in determining the best treatment pathway. Their use and application depend on local practice.

35.4.2 Ligament Tears

Ligaments may tear in their mid-substance or avulse from their bone insertions. Sometimes, a fragment of bone is pulled away with the ligament. The mildest type of injury is a sprain where some fibres are torn internally without complete separation. This may include cases where the ligament is stretched and not split.

Given the complex three-dimensional structure of some of the ligaments (spring and deltoid), the tears may be partial or complete. Rupture of part of a ligament is worse than a simple sprain where there is no macroscopic or imaging disruption of fibres.

Fig. 35.1 (**a**) Radiograph showing an ankle effusion. (**b**) Ultrasound showing an ankle joint effusion

It has been argued that less severe ligament injuries may lead to scar tissue and adhesion to adjacent structures and that the long-term symptoms exceed the apparent damage using imaging. This may be particularly important where tendon sheaths abut ligaments (e.g. medial and lateral tunnels). Ligament tears can be detected by ultrasound and MRI (Perrich et al. 2009; Peetrons et al. 2004) (Figs. 35.3 and 35.4). Neovascularisation may be seen at the site of ligament damage with Ultrasound.

35.4.3 Tendon Injuries

Tendons and their insertions are at risk from partial or complete rupture due to sudden overload in their direction of action. An outside force or excessive muscle contraction may be the cause. Chronic tendinopathy may increase the risk but age is also a major factor.

Fig. 35.2 A radiograph of a Weber type B ankle fracture

Dysfunction, pain and abnormal physical signs are important diagnostic features. However, the clinical signs may be misleading especially in patients with concomitant diseases such as arthropathy or adjacent fractures. On occasion, overlap of function of intact tendons may prevent adequate clinical examination. An intact plantaris muscle, which is a variant or vestigial structure, may mislead the examiner to consider a completely ruptured Achilles tendon to be intact.

Complete rupture normally leads to retraction of the tendon ends, sometimes by a considerable distance.

When a tendon tears, blood and fluid may fill the vacant tendon sheath. However, this fluid will resolve with time, and the empty tendon sheath or paratenon will fill the gap. Care should be taken not to confuse this with an intact tendon. Here, dynamic imaging is especially useful using both the patient's efforts to move the limb and passive motion applied by the examiner. Ultrasound is therefore the best way of imaging as dynamic movement can be performed whilst imaging. With

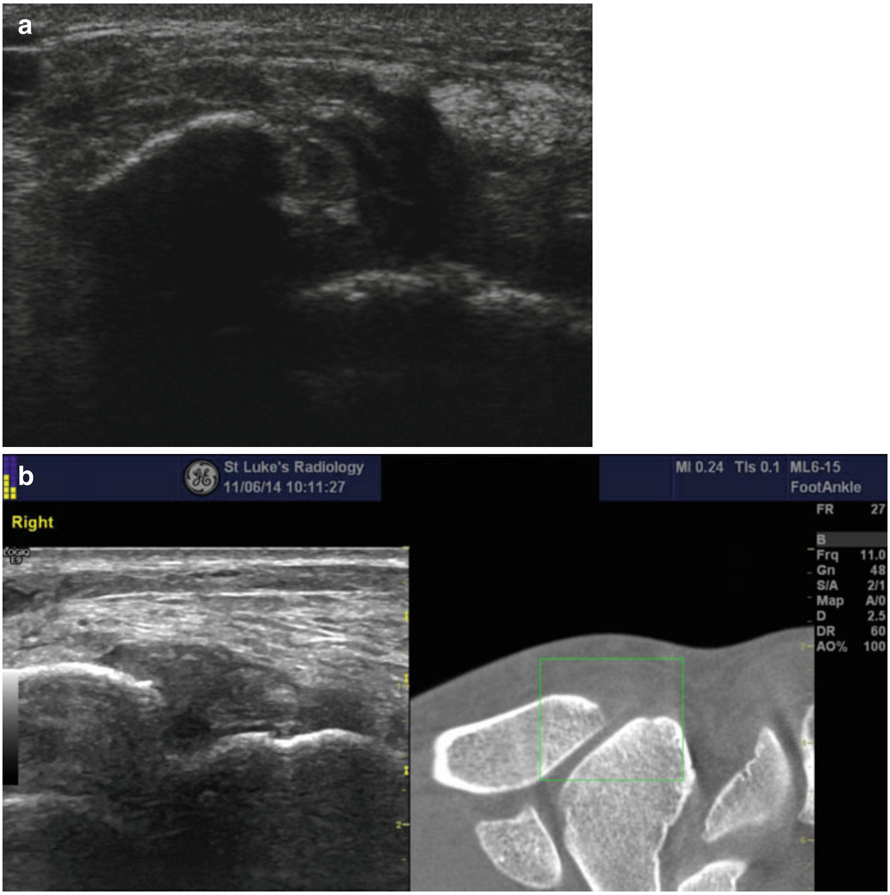

Fig. 35.3 Anterior talofibular ligament rupture. (**a**) An ultrasound of a ruptured anterior talofibular ligament. There is discontinuity of the ligament fibres. (**b**) Cone-beam CT with ultrasound fusion imaging showing the anterior talofibular ligament tear on the ultrasound with a tiny periosteal lift of the distal fibula seen on the CT and ultrasound images

extended field-of-view imaging, the precise location of the tendon tear can be demonstrated in a manner that may be easier for the observer reviewing the images to appreciate (Fig 35.5).

In children, the tendons are strong, and the bone or enthesis are weaker. Avulsion injuries are more common. Epiphyseal plates are especially weak and tend to break before the tendon does. The role of imaging is to detect the avulsion and assess the size of the separated bone fragment. This will help when considering the efficacy and potential outcome of surgical reattachment.

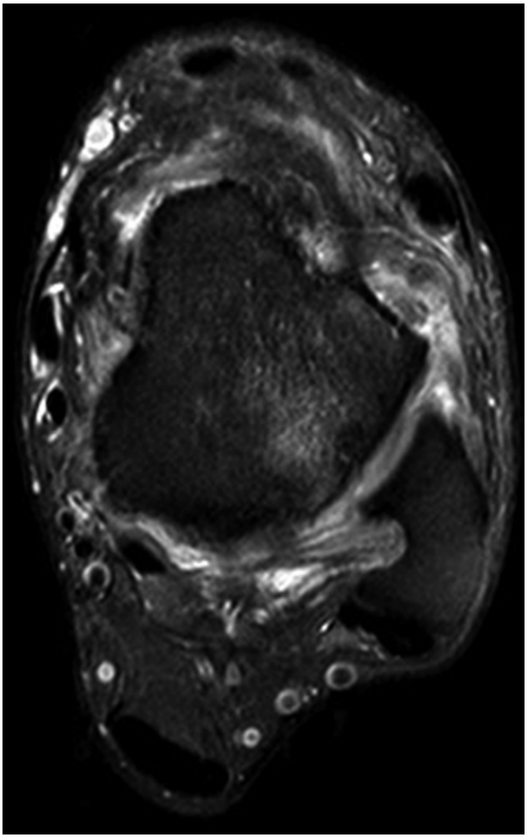

Fig. 35.4 An MRI of a ruptured anterior talofibular ligament. There is discontinuity of the ligament fibres and a gap where the ligament should be

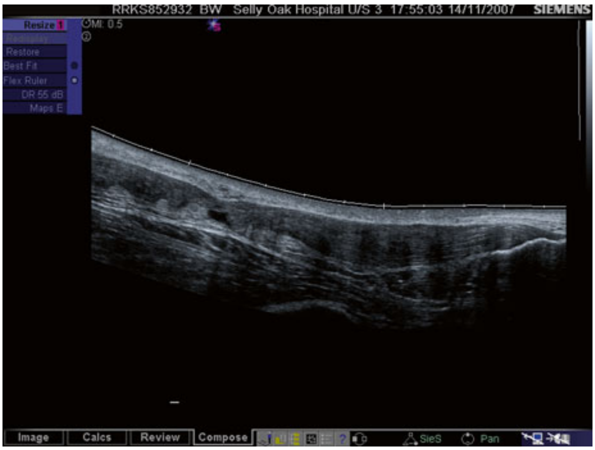

Fig. 35.5 Extended field-of-view ultrasound image of a complete Achilles tendon tear

35.5 Chronic Injuries

35.5.1 Stress Injuries

The bone remodels in response to load surprisingly quickly. In a matter of weeks, the bone and ligament or tendon insertions will strengthen whatever the age of the patient. This remodelling makes the bone fit for purpose and is why a skeleton gives clues to the lifestyle and activity of the person. Overload occurs when the bone is diseased or does not have time to respond to the load. Stress injuries result. In the first instance, the bone reacts with local oedema in the marrow and sometimes with an increased blood supply and a thin layer of oedema in the periosteum. If the load continues, trabeculae give way, and the microfractures start to repair. This gives more local bone oedema but also will show linear oedema and then sclerotic repair. This is best seen using MRI when the STIR sequence will show the bone stress response as high signal, and the fracture if present will be of low signal on a T1 SE sequence (Figs. 35.6 and 35.7). A break in the cortex with periosteal oedema can also be identified by ultrasound examination (Fig 35.8). Continued load leads to a true fracture that separates one and then both cortices.

Fig. 35.6 MRI coronal STIR showing a stress fracture of the distal fibula

Fig. 35.7 MRI coronal T1SE showing a stress fracture of the distal fibula which has become a complete fracture

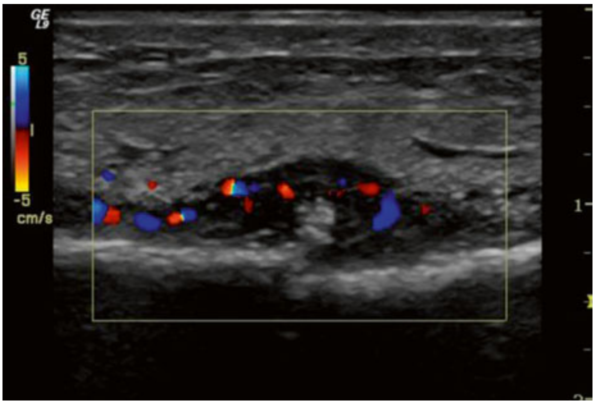

Fig. 35.8 Ultrasound with colour Doppler showing a stress fracture of the distal fibula

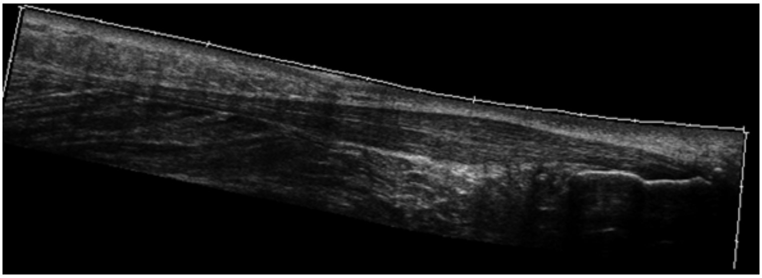

Fig. 35.9 Extended field-of-view of the Achilles tendon showing a fusiform swelling in keeping with chronic tendinosis

Although more common in the foot, stress fractures may be seen in the distal tibia or fibula in the transverse plane and in the calcaneus in the coronal plane (Teh et al. 2011; Sijbrandij et al. 2002).

35.5.2 Tendinopathy

Overuse of a tendon due to repetitive activity especially when this is unaccustomed may lead to tendinopathy. There is a degenerative element to this disorder that is more evident in older patients. Early signs are pain and dysfunction with tenderness and swelling. Symptoms will be exacerbated by the causative activity, but the worsening may be delayed by hours or even a day. Imaging will reveal fluid in the tendon sheaths in type II tendons, oedema in the paratenon and adjacent soft tissues in type I tendons with increased vascular supply. Continued overuse will lead to internal tendon degeneration and delamination. The tendon may thicken due to repetitive small injuries and fibrotic repair processes. Areas of fibrosis and calcification may become permanent features. When impingement of bony spurs or implanted metal is the cause, then rupture may ensue. The tendon will show fluid in the tendon sheath and mucoid degeneration. This is visible using both ultrasound and MRI. The ultrasound will also show neovascularisation which is a sign of tendon degeneration and also often correlates with the amount of pain the patient is experiencing (Reiter et al. 2004; Calleja and Connell 2010) (Figs 35.9 and 35.10).

35.5.3 Enthesiopathy

Enthesiopathy is a traction injury of the tendon insertion and adjacent bone due to repetitive load, the tendon thickens locally, and there will be neovascularisation in the tendon and adjacent tissues. There will be focal bone oedema and some soft tissue swelling also with increased local blood supply. The bony enthesis may distort due to minor partial avulsion and repair. The enthesis may enlarge with bony overgrowth as a result. This is often seen in distal insertion Achilles tendinosis but can

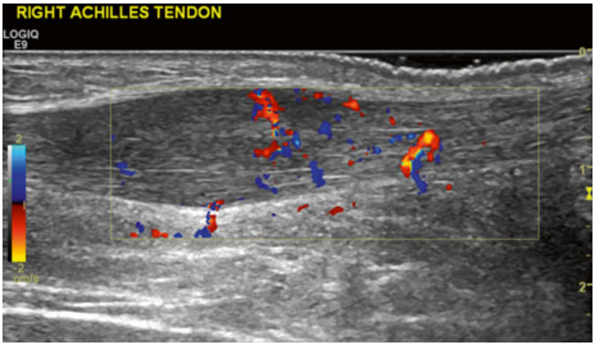

Fig. 35.10 Ultrasound with colour Doppler showing an Achilles tendinosis

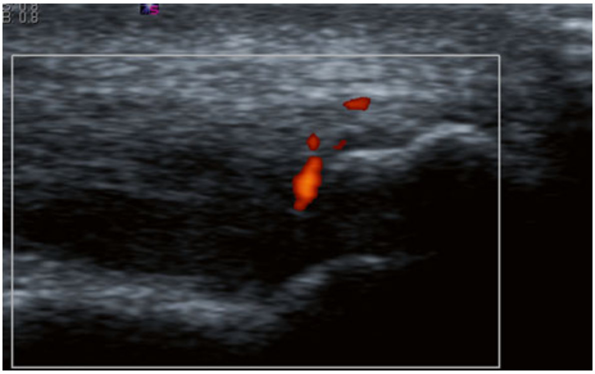

Fig. 35.11 Ultrasound with colour Doppler showing an insertional Achilles tendinosis with enthesiopathy

sometimes also be associated with an underlying inflammatory arthropathy in the athlete (Fig 35.11). A common example in the ankle is plantar fascia insertion enthesiopathy; not strictly a tendon, but the signs are the same.

35.5.4 Instability

Long-term instability affects around 10 % of patients with ankle injuries. There is no clear means of predicting who will suffer this problem, and current practice is to wait and see if the patient comes back with persisting problems. It may be that severe ligament injury, especially those to the calcaneofibular ligament related to instability at the subtalar joints, may predict subsequent problems, but there is no evidence regarding the best early management. Many ankle ligament tears damage proprioception, and an active rehabilitation programme with balance exercises will be helpful in many cases.

Diastasis of the tibiofibular syndesmosis is especially difficult to detect. It is commonly associated with tibiofibular ligament tears but may be hard to detect using conventional radiographs, CT or MRI. Standing views may assist by showing

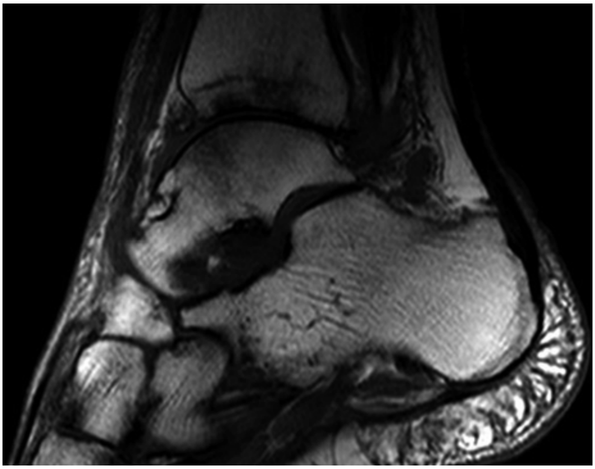

Fig. 35.12 MRI sagittal T1SE showing a sinus tarsi syndrome with oedema (low signal) within the sinus tarsi

widening of the syndesmosis, and newer extremity CT in a standing position shows promise. Dynamic assessment using ultrasound may show abnormal movement.

35.5.5 Sinus Tarsi Syndrome

It seems likely that pain arising in the sinus tarsi has several potential causes: interosseous ligament damage, capsule injury in the mid and hind foot and loss of stabilisation by the tibialis posterior tendon being several of the precipitating factors. Oedema in the sinus tarsi and subchondral bone changes are features but are probably nonspecific findings. This is best seen using MRI (Klein and Spreitzer 1993; Beltran 1994) (Fig 35.12). Injection of local anaesthetic under ultrasound guidance, anterior inferior to the lateral malleolus, may assist in diagnosis of identifying the origin of pain. If this is considered, then low volumes of anaesthetic are advised; otherwise spread may block pain from many sites.

35.5.6 Impingement

Both posterior and anterior ankle joint impingements are common in fast-moving field sports like soccer and hockey. Repetitive actions lead to foci of soft tissue oedema, bone oedema, reactive bone formation and fragmentation of the margins of the joints. The coincidence of a precipitating activity, focal pain and MRI signs of soft tissue and bone oedema make a clear diagnosis (Robinson et al. 2001; Robinson and White 2002; Robinson 2007; Pesquer et al. 2014) (Fig 35.13). Anaesthetic blockade may be a useful diagnostic test in doubtful cases. Management will include activity modification and arthroscopic debridement (cheilectomy).

Fig. 35.13 MRI sagittal T1SE showing anterior impingement with osteophyte formation around the joint

35.6 Imaging

35.6.1 Radiographs

Readily available in trauma units, radiographs remain the mainstay of trauma imaging. Anterior and lateral views will demonstrate fractures, malalignment and degenerative disease. However, there are considerable limitations. Soft tissue can only be indirectly imaged by the observations of swelling and, when studied carefully, the detection of joint effusion. Therefore, some joint effusions will be overlooked, and tendon and ligament injuries without displacement of the joints will not be detected. Most fractures are readily apparent, but commonly missed fractures are those of the articular surfaces, the anterior, lateral and medial processes of the calcaneus and the talar neck when there is minimal displacement. If we exclude small avulsion fragments at ligament insertions, then studies have shown that between 10 and 20 % of significant fractures are occult to analysis by conventional radiographs. Therefore, a normal radiograph does not exclude a fracture, but it will detect most significantly displaced injuries. A normal radiograph does not exclude serious articular surface damage or ligament tears. In practice, this means that the patient with atypical or unexpectedly persistent symptoms or disability warrants review and further investigation.

35.6.2 CT

The radiation dose associated with conventional CT is considerably more than a radiograph (10–50 times greater). Dedicated cone-beam extremity CT allows CT

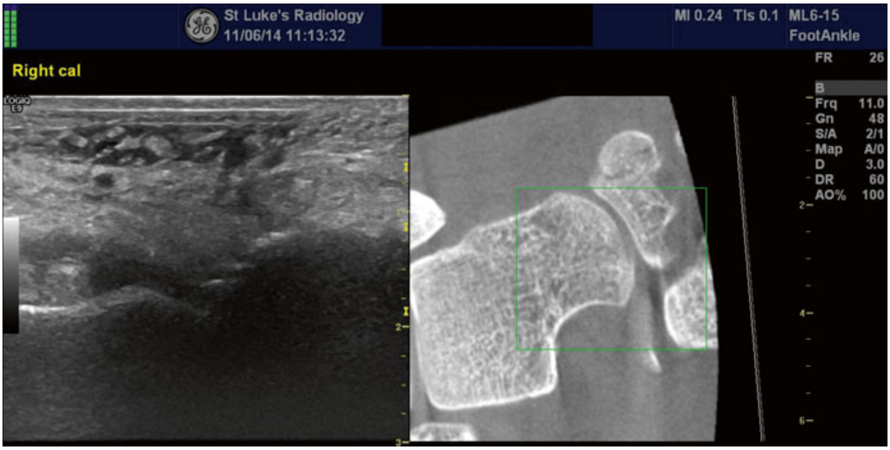

Fig. 35.14 Cone-beam CT with ultrasound fusion imaging shows a navicular fracture. The fracture is seen as a cortical breach on the ultrasound image and a dark line on the CT. The ultrasound shows oedema and haematoma in the soft tissues

examination with thin sections (2 mm) and isotropic data sets at radiation doses of one to two times conventional CT. There is one cone-beam system which allows examination in the standing position. This improved resolution and massive reduction in radiation dose may alter the way in which CT is employed, but as this is new technology, the management pathways are not yet developed.

CT provides cross sections with coronal and sagittal reconstructions. It is very sensitive to displacements of bone or joint and to fractures (Fig. 35.14). It is rare for CT to overlook a fracture although there are occasions where bone contusion with minimal fracture may be overlooked.

CT does not give good soft tissue images, and only substantial change will be readily observed. It is not a good method for detecting ligament, tendon or muscle disease.

35.6.3 Ultrasound

Ultrasound using high-frequency linear probes is an excellent method of examination for the soft tissues, tendons and ligaments. It has higher resolutions than CT and MRI and is especially effective near to the surface. Dynamic stress may be applied during examination adding an additional factor to the diagnostic process. Some minimally displaced lesions will only be detected with this method. Colour (and power) Doppler shows the extent of vascularisation of the soft tissues without the need for intravenous injection. Joint effusions are easily detected. Bone surface defects including cortical fractures, periosteal haematoma and periosteal reaction are seen. This means that it is the preferred technique for examination of ligaments, tendons and muscles. It is also an excellent means of detecting joint effusions. Limitations are that internal changes in bone and lesions affecting the centre of joints are, in certain areas, masked to examination. The techniques take considerable experience to master and examination depends on the operator. It is difficult to review the images remotely as the acquisition of the appropriate data depends on the operator. However, standardisation of technique, video capture and training programmes are beginning to overcome this problem.

Ultrasound fusion imaging, where probe-position sensors allow CT or MR volume data sets to be fused with the ultrasound image, shows particular promise.

35.6.4 MRI

MRI is sensitive to bone, joint, tendon, muscle and ligament disease. It may be reviewed remotely and provides an excellent anatomic analysis. It is the primary method of examining the ankle as it is the most comprehensive, and it does not require injections or ionising radiation.

The principle limitations are the difficulty in detecting bone fragments and the lack of dynamic stress. Fractures will be detected with the highest sensitivity if a water-sensitive and fat-suppressed image is employed. The imaging detects the bone oedema, haemorrhage and soft tissue oedema and is, therefore, the most accurate means of excluding fractures. However, as bone has little intrinsic signal, it is seen as a gap or void in the images and as a result depends on the surrounding structures for delineation. This means that slivers of bone may be overlooked. For the same reason, it is a poor means of assessing the complexity of a fracture for surgical planning. Many will use CT as an adjunct in these circumstances. A normal MR with water-sensitive and fat-suppressed images excludes a fracture, but there may be difficulty in properly classifying those fractures detected.

Injury to tendons and ligaments will also show oedema in the early period. However, when oedema resolves, the integrity of the ligament and tendon may be hard to judge using MRI alone. Here, ultrasound is much more effective; dynamic loading is particularly helpful during the ultrasound examination. As a result, ultrasound examination is the preferred technique for tendon injury.

More advanced methods of MR imaging detect water diffusion and can be used to track fibres in tendons or nerves at high resolution (DTI). However, the clinical value of this method has not been established. Similarly, articular cartilage may be mapped (GAG mapping) to assess early or subtle cartilage damage. Again, as a practical technique, this complex imaging has not gained widespread use.

Some patients are not suitable for MR examination. Implanted electronic devices and intracranial clips may preclude examination for safety reasons. Around 20 % of patients will be claustrophobic and require either examination by open or extremity MR. Sedation or even anaesthesia may be necessary in those severely affected. Alternative strategies for imaging will include a combination of ultrasound and CT for such patients.

35.7 A Practical Approach

Faced with an acute ankle injury, the clinician has a plethora of possible investigations that may be applied. Most will use the Ottawa rules to establish which cases to subject to conventional radiography. However, in the group not examined radiologically, there will be occasions when atypical symptoms and especially persisting pain or disability will precipitate a request for imaging. At this stage, a conventional radiograph will exclude a percentage of fractures, but as there is a significant miss rate and the patient is now a problem case, it would be reasonable to use more complex imaging. CT alone will not cover ligament or tendon injuries. Either ultrasound examination or MR may be used in these cases. A normal examination from either technique should be reassuring. For patients who have normal initial radiographs, a similar management pathway should ensue when clinical progress is less than satisfactory. In those cases where the initial radiograph shows an ankle joint effusion despite no obvious fracture, then there is a substantial risk of occult articular surface injury, and extremity CT or MRI are indicated.

For athletes, there may be advantage in a combination of CT and ultrasound or MRI in the early stages to better determine the optimum rehabilitation, but this approach does not as yet have much evidence to support its widespread use.

35.8 Future Research

It is the authors' view that the principle area for research in the imaging of ankle injury should be in developing pathways that use complex imaging techniques to predict outcome and to judge when early intervention is appropriate.

In this endeavour, newer forms of imaging will be applied, but an emphasis should be placed on using more comprehensive and available techniques with an assessment of the impact on outcome.

Conclusion

Whilst conventional radiographs will exclude or assess the majority of patients for fractures of the ankle, the role of more sensitive imaging methods has not been completely resolved. Ultrasound is the technique of choice in tendon injuries and will provide additional information in some ligament disorders. CT is particularly useful in detecting important but subtle fractures and is of value in surgical planning for fracture fixation. MR is the most comprehensive examination method and should be used in cases of clinical doubt when radiographs are normal.

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Nuclear Medicine Imaging of Ankle Injuries

36

Monika Horisberger, André Leumann, Helmut Rasch, and Michael T. Hirschmann

Contents

Abstract

Given the complex anatomy and function of the ankle, the management of chronic pathologies remains a challenge particularly in high-demand groups of patients such as athletes. Besides conventional X-rays for standard radiologic examination and MRI, nuclear imaging, mostly SPECT/CT, is becoming more and more important. In the last years, SPECT/CT has almost extruded simple

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scintigraphic bone scans in evaluation of complex bony hindfoot disorders and has renewed the interest in nuclear imaging for ankle pathologies. This is mainly due to its unique combination of detailed morphologic information from the CT and the clearly localised metabolic information of each specific bone or even each specific region of particular bones from the SPECT. This ability makes SPECT/CT a new important tool which adds substantial information to the data achievable from MRI examination. However, there is currently only scarce evidence about SPECT/CT around the ankle. This chapter summarises the current scientific knowledge, adds clinical examples and shows future directions to be elucidated to enhance the use of SPECT/CT around the ankle.

Abbreviations

CT	Computed tomography
SPECT	Single-photon emission computed tomography
MRI	Magnetic resonance imaging
PET	Positron emission tomography

36.1 Type and Value of Nuclear Medicine Imaging Techniques in Ankle Injuries

Disorders of the ankle and hindfoot in sports medicine are common and pose a significant clinical challenge given the complex anatomy and function. Therefore, sometimes, it makes it difficult to accurately localise patient's symptoms to a morphologic structure or a specific lesion by routine clinical examination. Imaging plays a crucial role in the management of these patients. In recent years, there has been a significant development of imaging techniques to support the clinician in the management of such situations. Anatomical imaging (X-ray, MRI, ultrasound and CT) and functional imaging (scintigraphic bone scan and SPECT or SPECT/CT, PET/CT, functional MRI and ultrasound) techniques have been used in the management of patients with acute ankle injuries as well as chronic overload lesions or chronic ligamentous instability. Nuclear medicine imaging techniques play an important role in elucidating the cause of prolonged or chronic pain. While bone scintigraphy has been already used for decades, its use in foot and ankle pathologies was only sufficient to indicate focal abnormality but not to show the exact localisation. Furthermore, while the sensitivity of the bone scan in the diagnosis of bony pathology in the foot and ankle is high, specificity remains suboptimal. Nowadays, more precise information about perfusion, blood pool and specific location of a lesion can be obtained by high-resolution and tomographic images (Groshar et al. 1998). Recently, SPECT/CT has been introduced into orthopaedics and recognised as a highly sensitive and specific diagnostic tool around the ankle (Mohan et al. 2010). This is especially true for sports medicine, where often subtle alterations cause major sports impairment in these high-demanding athletes. SPECT/CT as a new image fusion technique overlies single-photon emission computed tomography data and computed tomography images, which were obtained in one imaging procedure. Therefore, SPECT/CT combines detailed functional and anatomical information. CT images provide excellent details of the bony anatomy and pathological processes, which is particularly important in the foot and ankle where a multitude of small bones are overlying each other forming a complex 3D construct. The tracer substance marks osteoblasts, and therefore, the bone scan provides the functional information about local bone metabolism activity. The combination of these two imaging modalities into one imaging procedure allows information about bone metabolism with a resolution of the CT and has demonstrated improved sensitivity and specificity (Mohan et al. 2010).

In our experience, SPECT/CT has almost extruded planar bone scintigraphy as well as SPECT alone in the diagnostic process of osseous lesions around the ankle. However, one has to keep in mind that nuclear medicine imaging and SPECT/CT in particular have little to offer for diagnosis of soft tissue lesions. The strength lies in identifying osseous metabolic activity and correlating this with detailed morphologic information from the CT. Soft tissue lesions are rather the domain of MRI and ultrasound, which are mostly discussed elsewhere. Therefore, the following pages will focus on SPECT/CT in osseous and chondral lesions around the ankle.

Although there is a paucity of high-level studies on SPECT/CT as a diagnostic tool for foot and ankle pathologies yet, there is growing evidence that SPECT/CT improves exact localisation of osseous pathologies due to optimal matching of morphologic abnormalities and increased bone metabolism. This is particularly important when judging small bones and articulations of the foot and ankle. Pagenstert et al. showed that inter- and intraobserver reliability for identifying degenerative changes and nonunions in the foot and ankle was significantly higher for SPECT/CT compared to planar bone scans, CT and simultaneous use of separated bone scan and CT data without image fusion, respectively (Pagenstert et al. 2009). Interobserver reliability increased from bone scan to SPECT/CT for radiologists from 0.71 to 0.88 and for orthopaedic surgeons from 0.66 to 0.88 (Pagenstert et al. 2009).

There seems to be a correlation between localisation of pain and of SPECT activity. Kretzschmar et al. showed that in patients with unclear foot and ankle pain, SPECT/CT-guided infiltration of the metabolic active region with local anaesthetics had a higher predictive value for pain relief than infiltration according to clinical examination. In 33 % of cases in the hindfoot, there was a disagreement between clinical judgement and present metabolically active lesion in SPECT/CT (Kretzschmar et al. 2011).

Knupp et al. used SPECT/CT for the assessment of coronal plane hindfoot deformities. They found that the stage of osteoarthritis seen on plain radiographs correlated significantly with the level of activation detected on bone scans. Moreover, they showed that region-wise radioisotope uptake correlated with the type of malalignment (Knupp et al. 2009). This finding could be used to improve analysis of asymmetric ankle degeneration and help with surgical decision-making in joint-preserving surgery of the ankle.

SPECT/CT encountered particularly high interest in osteochondral lesions of the ankle. Leumann et al. showed that orthopaedic surgeons did change their treatment strategy in 52 % of patients by having the additional information of SPECT/CT added to the information of MRI. These changes are mainly based on different information on the subchondral bone plate and the subchondral bone and not the cartilage layer.

SPECT/CT has also successfully been used to further explore long-standing heel pain in a patient with retrocalcaneal bursitis and plantar fasciitis (Breunung et al. 2012). It has also been suggested to be helpful for the postoperative assessment of hindfoot arthrodesis due to the fact that exact localisation of the site of origin of pain in such patients remains suboptimal on X-ray and CT, while MRI is often unsuitable because of artefacts due to in situ metal hardware (Mohan et al. 2010). An improvement in accuracy of identifying nonunion/malunion, subjacent arthritis or infection as the cause for continuing pain could be expected but has not been scientifically shown yet. Here, there is a lack of knowledge on how long chronic disorders may show additional uptake although they heal uneventfully. For example, in osteochondral lesions, Valderrabano et al. found persisting focal uptake in ten out of ten patients 72 months after surgical treatment with mosaicplasty (OATS), although 92 % of patients reached a good or excellent clinical result.

A combination of SPECT/CT and anti-leucocyte scan could be useful in confirming bone and soft tissue infection (Mohan et al. 2010). However, literature does not yet provide any data about such an application.

36.2 Clinical Examples

36.2.1 Osteochondral Lesions of the Ankle

Osteochondral lesions (OCL) of the talus result from various presumed aetiologies including acute and subacute injuries of the articular cartilage and underlying subchondral bone. Most often, young, sports-active males are affected. In OCL of the talus, radiologic treatment criteria are based on three factors: size, stability and viability of the OCL (Choi et al. 2009; Giannini et al. 2008; Giannini and Vannini 2004). For a long time, MRI was the gold standard for evaluation of osteochondral lesions of the talus (Dipaola et al. 1991; Taranow et al. 1999). The advantage of MRI is that cartilage, bone and surrounding soft tissues can be imaged without radiation exposure. As a disadvantage, many researchers consider the fact that the associated bone marrow oedema is often overestimated and thus might mislead therapeutic decision-making (Leumann and Valderrabano 2010; Schimmer et al. 2001). Verhagen et al. reported that CT was not inferior to MRI in judging OCL of the talus (Verhagen et al. 2005). It provided high quality anatomical images for accurate assessment of the location and size of the OCL lesions. Especially, arthro-CT gives valuable information about cartilage as well as subchondral bone plate and loose bodies. However, it lacks data about the lesions biology, hence metabolic activity. SPECT/CT fills this gap by combining detailed morphologic information and metabolic data. A study has shown that this additional information led to a change in therapeutic decision in 52 % of cases compared to use of MRI alone (Leumann and Valderrabano 2010). While cartilage showed good correlation for interpretation between MRI and SPECT/CT, the subchondral bone plate and subchondral bone showed substantial differences. Poor intraobserver correlation highlighted the different information provided by the two imaging techniques (Leumann et al. 2011). Therefore, the authors of the study recommended the use of both MRI and SPECT/CT for thorough evaluation of OCLs of the talus. For the knee joint, it has already been shown that scintigraphic activity correlated better with pain than bone marrow oedema of MRI (Buck et al. 2009). Osteoblastic activity, which is depicted by scintigraphy, is accompanied by a release of different cytokines; among them, substance P and bradykinin, play an important role in pain perception (Kondo and Togari 2004; Liu et al. 2007).

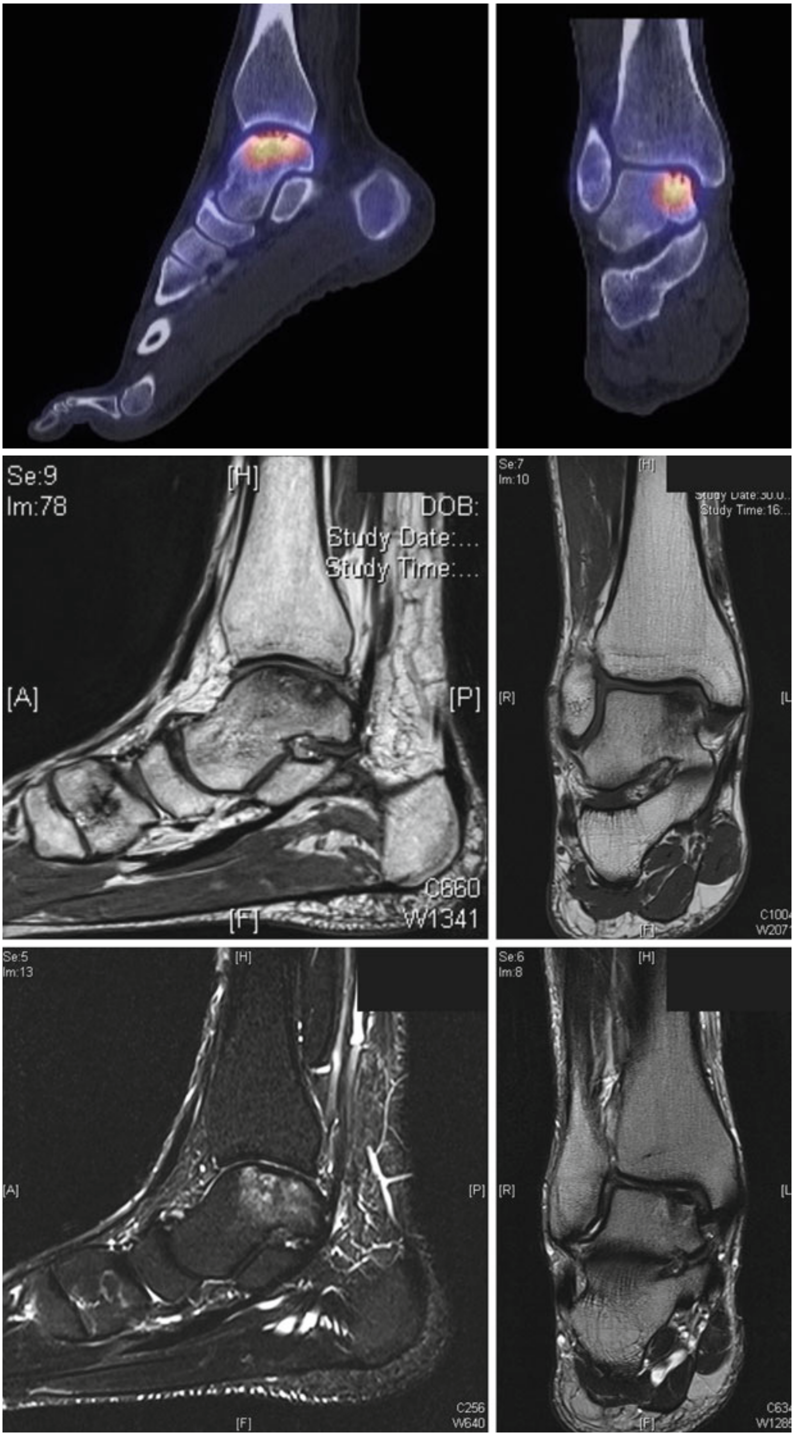
SPECT/CT has also proven its value for follow-up examinations in patients who underwent surgical therapy for OCL (Valderrabano et al. 2009). Under these circumstances, it might even be superior to MRI because of inlaying metal hardware (Figs. 36.1 and 36.2).

36.2.2 Stress Fractures

Stress reactions and fractures around the ankle, especially in the distal tibia and fibula, are important overuse injuries in endurance athletes. While bone scan (Spyridonidis et al. 2014; Krestan et al. 2011) and MRI are established diagnostic tools (Sijbrandij et al. 2002), the sensitivity and specificity for SPECT/CT will have to be determined first. However, a more prominent role of SPECT/CT in the future is likely, since this modality combines the advantages of bone scintigraphy which shows metabolic activity, and CT may show osteopenia, the earliest finding in early stress fracture (Gaeta et al. 2005; Mohan et al. 2010) (Fig. 36.3).

36.2.3 Ankle Impingement

Ankle impingement can be due to abnormal configuration of articulating bones; extreme movements of normally shaped joint partners, e.g. in ballet dancers; accessory bones interfering with otherwise normal joint partners, e.g. os trigonum or as a result of osteophyte formation around the ankle due to degenerative processes, e.g. in soccer's ankle. It can be located anteriorly (e.g. soccer's ankle) or posteriorly (e.g. dancer's ankle). Only in true osseous impingement, bone scan and SPECT/CT play a role, since soft tissue impingement cannot be depicted with current nuclear imaging methods. However, most cases of bony impingement (in particularly anterior impingement) can sufficiently be diagnosed using conventional X-rays or MRI. SPECT/CT might help in unclear cases of persistent ankle pain and then identifies, e.g. an impinging os trigonum with increased metabolic uptake as a reason for deep or posterior ankle pain. In these patients, SPECT/CT is a richer source of information (Fig. 36.4).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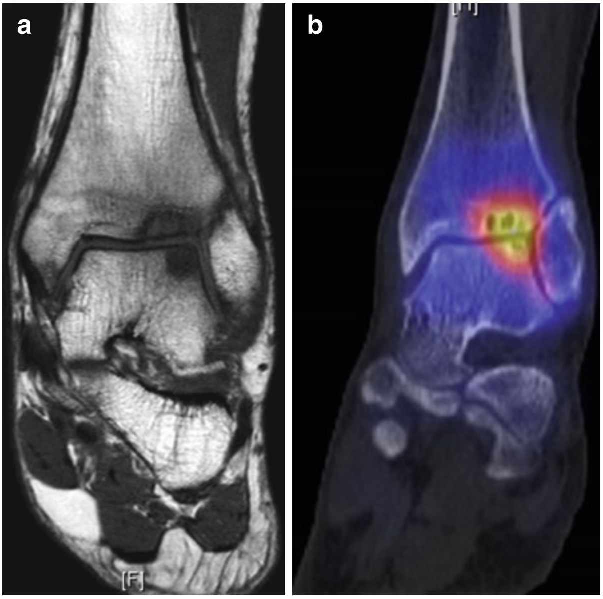


Fig. 36.2 This 40-year-old active snowboarder sustained a fall and ankle sprain in his snowboarding boots one year ago. Because of persistent pain, MRI and SPECT/CT were performed. Both revealed an osteochondral lesion in the centrolateral joint compartment. This example illustrates how much more precise bony structure can be analysed on SPECT/CT images when compared to MRI. Moreover, in SPECT/CT, there is increased tracer uptake at the talar and the tibial side. This information guides further treatment as both lesions have to be addressed

36.2.4 Fractures and Nonunions

Nuclear medicine techniques have no role in diagnosing acute traumatic fractures. However, SPECT/CT might help finding a) stress fractures (see above) or b) persistent pain in the context of an already detected and treated fracture. It is able to precisely show osseous nonunion as well as associated metabolic uptake representing symptomatic pseudoarthrosis (Figs. 36.5 and 36.6).

36.2.5 Bone Bruises and Osteonecrosis

It is very interesting to see the differences of the size of the bone bruise/bone oedema in the MRI and the focal activity in the SPECT/CT. This is not only true for

Fig. 36.1 This patient complained of rotational instability of his ankle joint after recurrent ankle sprains in sports. SPECT/CT and MRI both showed a large OCL of the medial talar shoulder. However, SPECT/CT depicted the extent of subchondral cyst formation more clearly and localised the metabolic active region to a much smaller area compared to the area of oedema in the MRI. SPECT/CT is used to decide to what extent the subchondral bone needs to be reconstructed

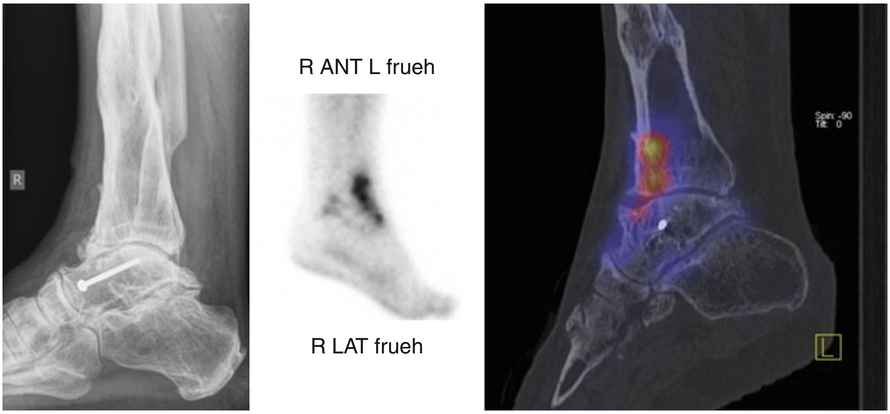


Fig. 36.3 This 62-year-old patient with known posttraumatic upper and lower ankle osteoarthritis presented with right-sided ankle pain. SPECT/CT indicated a stress fracture of the anterior tibia due to the deformity caused by the previous trauma

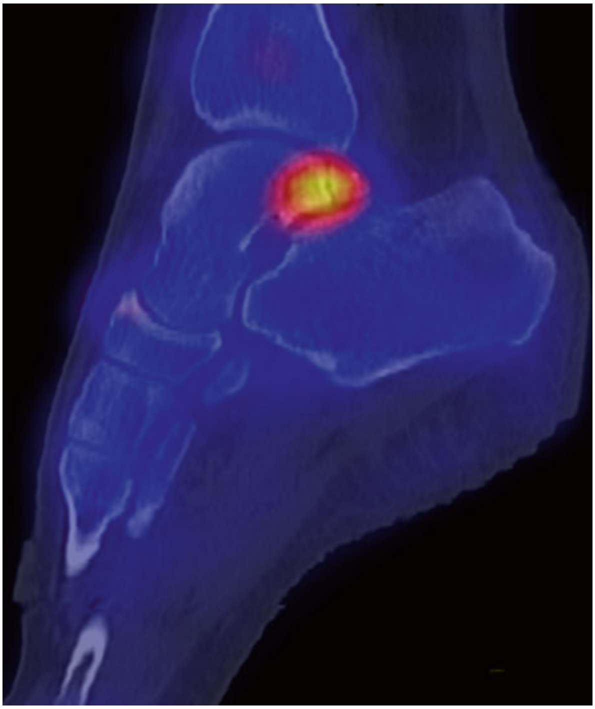


Fig. 36.4 This 27-year-old female patient presented with diffuse ankle pain while running and signs of posterior impingement in maximal plantar flexion. Conventional X-rays showed a mostly normal ankle except for an os trigonum (DD chronic fracture of the posterior talar process). SPECT/CT shows the metabolic activity of the os trigonum which correlated with pain origin. The patient was pain-free after excision of this accessory bone

osteochondral lesions like discussed above but also for perfusion-based disorders such as avascular talar necrosis or chronic regional pain syndrome. While SPECT/CT specifically highlights metabolic activity of osteoblasts, for oedema pattern in

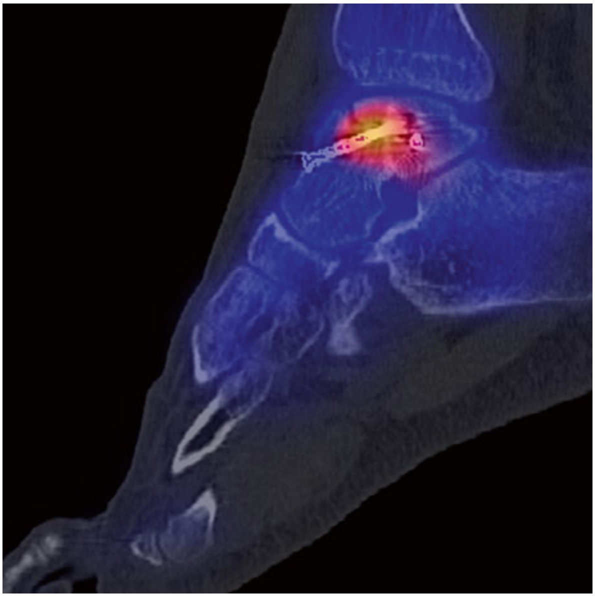


Fig. 36.5 This patient suffered a multifragmentary talar body fracture. Persistent pain nine months post-surgery led to further imaging studies. SPECT/CT clearly showed a nonunion of the anterior fracture region and increased metabolic uptake at that same region which make it likely the origin of the pain in this patient

MRI, it has been shown that this histologically equals a number of noncharacteristic histological abnormalities which make interpretation difficult (Zanetti et al. 2000). For atraumatic medial knee pain, it has even been shown that scintigraphy is more sensitive than MRI (Buck et al. 2009) (Fig. 36.7).

36.2.6 (Posttraumatic) Overload and Malalignment

Posttraumatic or idiopathic ankle malalignment – either varus or valgus – is a reason for early ankle joint degeneration. Knupp et al. showed that SPECT/CT provides the surgeon with an enhanced diagnostic capability to detect early degenerative changes when compared with conventional bone scintigraphy and CT scans (Knupp et al. 2009). SPECT/CT may also prove useful in determining the efficacy of treatment in converting pathologic bone and joint morphology to a more physiologic state. Furthermore, SPECT/CT analysis may support current recommendations for joint-preserving osteotomies designed to realign the ankle and hindfoot, redistribute tibiotalar loads and reestablish more physiologic bone and joint morphology and metabolism (Knupp et al. 2009) (Fig. 36.8).

36.2.7 Soft Tissue Injuries

Current nuclear medicine studies do not play an important role in the diagnostic of soft tissue injuries relevant to the sports physician, such as ligament injuries or

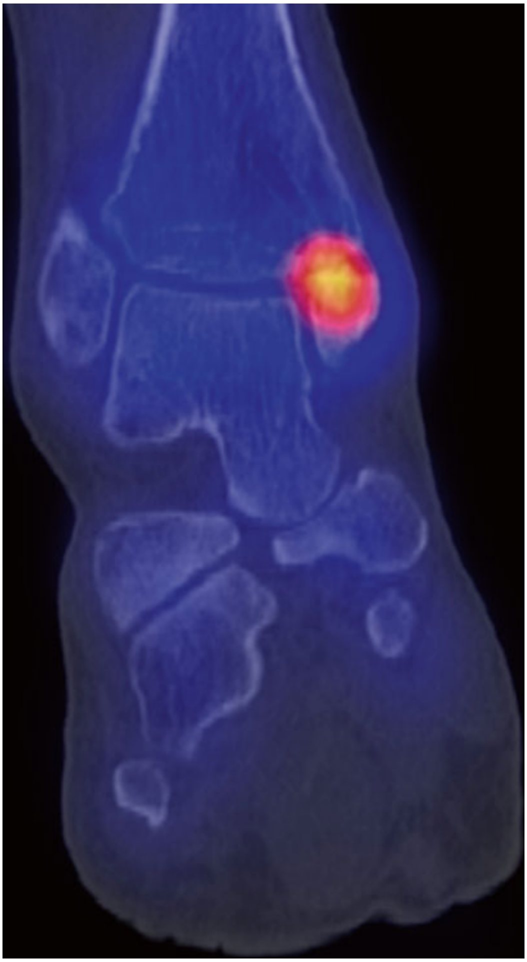


Fig. 36.6 This 30-year-old patient sustained a Maisonneuve-type fracture including a proximal fibular fracture and a displaced medial malleolar fracture. Nine months after open reduction and internal fixation at the medial malleolus, an atrophic nonunion was identified showing absent bridging callus and increased tracer uptake as signs of nonunion

tendon pathologies. Standard radiopharmaceutical tracers used for SPECT bone imaging are directed against hydroxyapatite in active osteoblasts and thus do not visualise metabolic activities in soft tissues. MRI remains the imaging of choice in these conditions as it can demonstrate more anatomical details including disruption of soft tissue structures, associated soft tissue and reactive bone oedema (Joong and El-Khoury 2007; Premkumar et al. 2002). However, in some rare occasions when, e.g. a soft tissue problem such as distal Achilles tendon lesion leads to an associated bony reaction, SPECT/CT nicely depicts the extent of this bony reaction. Other fields of interest for nuclear imaging are infections where radiolabelled autologous leucocytes or tracers directed against granulocytes mark the infected lesion independent of bone or soft tissue (Fig. 36.9).

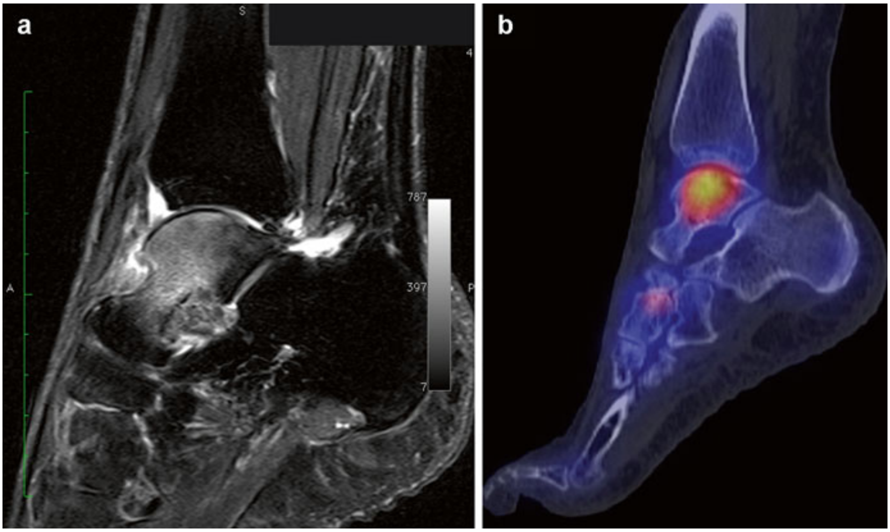


Fig. 36.7 Unexplained ankle pain in a 70-year-old lady, who used to hike several hours a day. MRI (**a**) showed signs of a – idiopathic – talar necrosis. This was confirmed in SPECT/CT. However, this example shows very well, that the lesion size on MRI (representing bone oedema, **a**) is much larger, than on SPECT/CT (representing tracer uptake and remodelling of the bone, **b**). It can also be located to a particular part of the talar body rather than the whole talus. Thus, SPECT/CT helped to determine the region of bone to be treated and to exclude early ankle osteoarthritis. Therefore, a well-directed, arthroscopically guided retrograde drilling through the sinus tarsi could be chosen as minimal invasive therapy

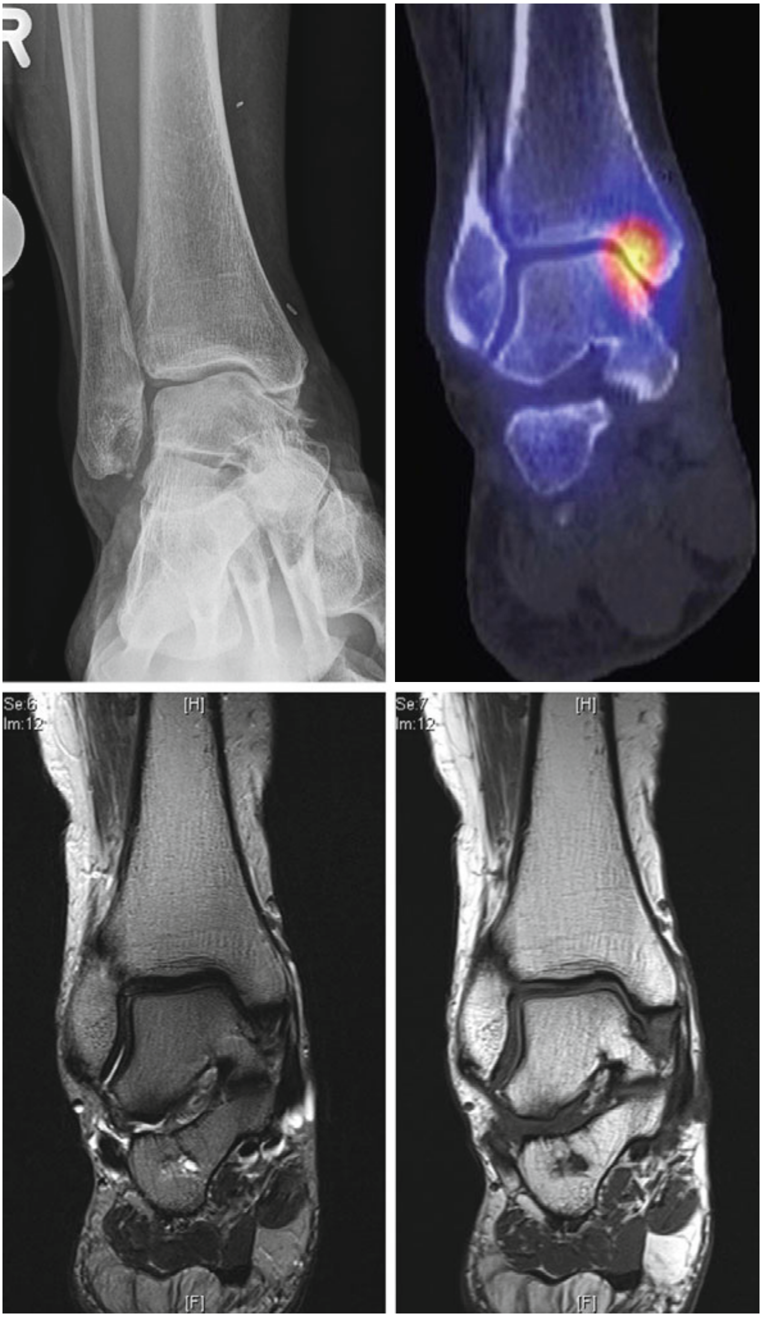
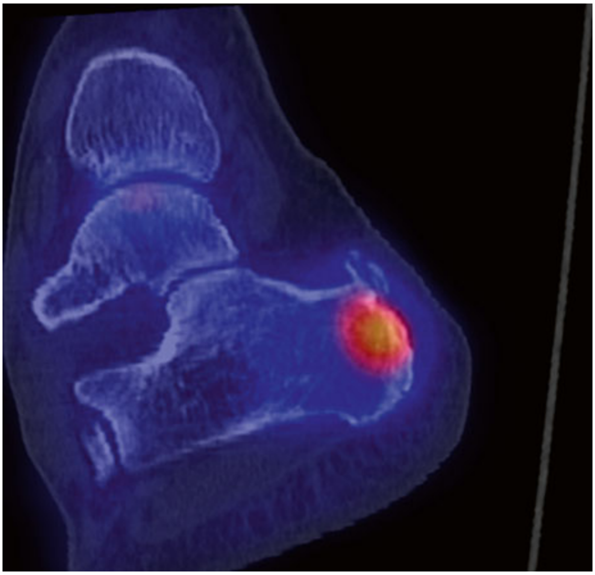


Fig 36.8 This 40-year-old, active sports woman sustained recurrent lateral ankle sprains in a varus situation of her hindfoot. While MRI showed medial cartilage damage, SPECT/CT enhanced diagnostic information showing increased radioisotope uptake in the medial gutter of the ankle joint. This was a decision relevant criterion for justifying supramalleolar osteotomy in this patient

Fig 36.9 This patient suffered of long-standing pain at the Achilles tendon insertion. SPECT/CT not only showed intratendinous ossifications but also metabolic activity of the underlying bone at the tuber calcanei



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Part XII

The Musculoskeletal System Topographically: The Foot

Sports Injuries of the Foot

37

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Abstract

About 40–50 % of the general population will develop a foot disorder at some stage in their lives. Of these injuries, 90 % will concern the forefoot. This comprehensive chapter on injuries of the foot aims to discuss the most common foot injuries in either recreational or elite athletes. Although technological advances in nuclear medicine and radiology enable physicians to obtain a precise diagnosis and monitor the rehabilitation process, a sound understanding of the pathophysiology of these common foot injuries remains the basis for a successful diagnosis and treatment.

This chapter summarizes the most common foot problems that an athlete can encounter. In describing these foot pathologies, the foot is divided into six different zones. For each zone, a description of possible foot injuries is provided in a concise manner. After reading this chapter, the reader will have a better understanding of normal and abnormal foot anatomy in relation to the biomechanical etiology of common overuse injuries of the foot. Although this review is not intended to provide the reader with a complete overview of sports-related foot problems, it will assist clinicians in their differential diagnosis when requesting, e.g., a radiological examination.

37.1 Introduction

The prevalence and incidence of certain sports-related foot disorders varies tremendously with the type of sport. About 40–50 % of the general population will develop a foot disorder at some stage in their lives. Of these injuries, 90 % will concern the forefoot (Mann 1978). In order to understand the etiology of this wide range of sports-related foot pathology, technical and biomechanical knowledge of each sport is often a prerequisite. However, it also requires a firm knowledge of the anatomy of the foot.

In accordance, the objective of the present chapter is to provide the reader with a concise description of most common sports-related foot pathology and increase the reader's understanding of normal and abnormal foot anatomy in relation to the biomechanical etiology of common overuse injuries of the foot.

37.1.1 Disorders at Digit Level

37.1.1.1 Turf Toe

Turf toe is an injury to the connective tissue of the metatarsophalangeal joint (MTP) of the great toe. According to epidemiology, there are no differentiating ethnocultural, sex-related, or age-related determinants connected to turf toe.

Turf toe can occur to any athlete if predisposing factors and the mechanism of injury are present at the time of injury. About 40–50 % of the general population will develop a foot disorder sometime in their lives. Of these injuries, 90 % will concern the forefoot (Mann 1978). The most common activities associated with turf toe are soccer, dance, or following a trauma to the great toe. The pathomechanics of this injury is typically a hyperextension of the MTP joint. It is rarely the result of hyperflexion. The abnormal forces applied to the first MTP joint at the time of injury result in varying degrees of sprain or disruption of supporting soft tissue structures, leading to the injury commonly referred to as turf toe. The extent of tissue disruption influences the treatment planning but can also be used to prognosticate recovery (Childs 2006). High-risk sports include judo, soccer, wrestling, rugby, cycling, gymnastics, and dancing (Allen et al. 2004; Demaj 2009).

37.1.1.2 Hallux Rigidus

This degenerative osteoarthritis of the first MTP joint occurs predominantly in men. The patient's symptoms are often pain and stiffness in the first MTP joint while walking barefoot and in shoes. It is not uncommon that skin irritation and activity-related swelling over a dorsal osteophyte can be present on the first metatarsal head. To minimize discomfort, athletes often have to restrict their activities and modify their shoe wear selection (low heel, stiff sole, and larger toe box). Physical findings suggestive of hallux rigidus include (Alexander 1997; Root et al. 1977):

- Enlargement of the first MTP joint due to a combination of osteophytes and soft tissue swelling.
- Tenderness along the MTP joint line and palpable joint line osteophytes, particularly dorsally.
- First MTP range of motion limitation with/without crepitus.
- Initially, the pain can be provoked with stressed plantar flexion of the MTP. In a later stage, pain will occur with stressed dorsiflexion of the joint. In advanced cases, pain and crepitus are present when the first MTP joint is rotated in the frontal plane (positive grind test).
- High-risk sports: soccer, gymnastics, and dancing.

37.1.1.3 Hallux Abducto Valgus

Pain associated with prominence of the medial eminence of the first metatarsal head (called a bunion) is often a problem in females with a wide forefoot who wear dress shoes with a narrow, constrictive toe box. Hallux valgus or the lateral deviation of the great toe is usually present and may result in additional discomfort due to impingement of the great and second toes. Although a hereditary cause is unknown, metatarsus primus varus may play an etiological role (Kilmartin and Wallace 1991), and patients often report a positive family history for hallux valgus problems. Despite the discomfort, athletes with hallux abducto valgus will often continue to wear aggravating shoes, either because their sport demands it or because they find shoes that will accommodate their deformity socially unacceptable. Individuals with severe deformities will experience pain in even the most forgiving shoes, and alleviation of the discomfort that these athletes experience over the bunion will often necessitate surgical intervention if corrective orthotics supporting the first ray and/or straight-lasted shoes do not alleviate the pain. Although radiographic findings are most important in deciding the appropriate surgical procedure, patient's history and specific findings during a physical examination should be considered as well. One of the most common causes of failed bunion surgery is hallux rigidus, not being recognized prior to surgery (Alexander 1997; Root et al. 1977).

Coexisting hallux rigidus should be suspected if physical findings as previously described are present. Athletes with pure hallux valgus will localize their discomfort directly to the prominent medial eminence and usually have no discomfort walking barefoot due to lack of shoe irritation.

Bunion correction will do nothing to alleviate any component of the athletes pain related to inflammatory arthritis. The type of corrective procedure chosen depends on specific findings related to the deformity: Athletes with passively correctable lateral deviation of the hallux will, in most cases, be adequately treated with a less invasive distal metatarsal osteotomy and medial capsular reefing. Individuals with hallux valgus greater than 30°, pronation of the great toe, and fixed deformity usually require extensive soft tissue releases in addition to proximal osteotomy of the first metatarsal. Rigid lateral deviation and pronation of the hallux suggest fixed lateral positioning of the sesamoids with a lateral capsular contracture (Mertens 2012; Perera et al. 2011).

37.1.1.4 Tailor's Bunion

Tailor's bunion is a deformity of the 5th metatarsal position which produces an abnormally prominent 5th metatarsal head. Shearing between the unstable metatarsal head and overlying soft tissues fixed by shoe pressure results in an inflamed adventitious bursa called a tailor's bunion. Besides an idiopathic condition, its etiology finds its basis in the following (Root et al. 1977):

- *1st factor:* abnormal subtalar joint pronation during the midstance and early propulsive periods result in hypermobility of the 5th metatarsal. This hypermobility produces internal shearing between the 5th metatarsal head and the overlying soft tissue. This soft tissue is fixed by shoe pressure and cannot move with the hypermobile metatarsal. The latter may occur in sports activities that require stiff footwear such as, soccer, basketball, rugby, and volleyball. Properly fitting shoe (especially an appropriate width) is an absolute requirement for treating this condition.
- *2nd factor:* any uncompensated varus position of the forefoot or rearfoot in a fully pronated foot, for example, no forefoot varus compensation for a rearfoot valgus.
- *3rd factor:* a congenital plantar-flexed or dorsi-flexed fifth ray deformity.

37.2 Disorders of Midfoot and Forefoot Level

37.2.1 Osseous Disorders

37.2.1.1 March Fracture

The march fracture usually occurs at second ray level of the foot and is the result of a brutal overload such as a long march with an unprepared athlete. Initially, there is often a tolerable pain, which occurs during landing and loading of the second ray.

Intolerable pain characteristically occurs at a progressively earlier stage of exercise as the condition develops. The pain worsens with athletes who keep training and pain occurs also during walking or even at rest. Sometimes, a clear swelling can be seen at the site of the pain (Verdonk 2006). Various bones may be affected including metatarsals and calcaneum. Stress fractures of the metatarsals may occur secondary to hallux valgus. In the early stages, these fractures may not be visible in plain radiographic views. In these cases, technetium bone scans or MRI scans are useful (Greida 1988; Bjerregaard and Siggaard 1981).

37.2.1.2 Morbus Köhler I

The Köhler 1 disease is an avascular necrosis of the navicular bone with collapse seen in the growing child usually between 4 and 9 years old. Its etiology is similar to Perthes' disease at hip level and Kienböck's disease at the level of lunate bone of the wrist. The symptoms are sudden occurrence of pain, joint movement sensitivity or restriction, and swelling. In a more advanced stage, muscle atrophy of the leg will be present. A plain radiographic view confirms the diagnosis. The disease evolves without sequelae (Alexander 1997; Root et al. 1977; Verdonk 2006).

37.2.1.3 Morbus Köhler II

As seen with Morbus Köhler I, an avascular necrosis can be reticent but now at the level of the second metatarsal head of the growing child. In most cases, the disease is asymptomatic and evolves with minor sequelae in the young adult (Verdonk 2006; Chi et al. 2009).

37.2.1.4 Accessory Navicular Syndrome

The accessory navicular bone is an extra bone or piece of cartilage that is incorporated within the posterior tibial tendon located on the inner side of the foot just above the arch. The condition presents at birth (congenital) and is not part of normal bone structure and therefore not present in most athletes. However, athletes who have an accessory navicular bone often are unaware. Some people with this extra bone develop a painful condition known as accessory navicular bone syndrome when the bone and/or posterior tibial tendon is overloaded. On radiographs, this accessory navicular bone is categorized in three different types; only type II (with syndesmosis of synchondrosis of the accessory bone with the navicular bone) and type III (synostosis of the accessory bone with the navicular bone to form an elongated navicular bone also called os cornutum) are related to symptoms, and overuse of the posterior tibial tendon and spring ligament may have constitutional flatfeet or develop flatfeet. Type I accessory navicular bone constitutes of a small rounded bone fragment in the distal posterior tibial tendon without relationship to the navicular bone. Symptomatic type II and III accessory navicular bone can result from any of the following (Chi et al. 2009; Lobo and Geisenberg 2007):

- Traumatic cause: as in a foot or ankle sprain
- Chronic irritation: from shoes or other footwear rubbing against the accessory bone
- Overuse: excessive rise in activity, constitutional flatfeet, and obesity

Many athletes with accessory navicular syndrome also have acquired or constitutional pes planovalgus feet. Type II and III accessory navicular bone results in an abbreviation of the inframalleolar part of the tibialis posterior tendon putting more strain the tendon, and also having a constitutional flat foot puts more strain on the posterior tibial tendon, which can produce inflammation or irritation of the accessory navicular bone (Lobo and Geisenberg 2007).

Acquired flatfeet is a result of spring ligament insufficiency accompanied by tibialis posterior tendinopathy and/or tenovaginitis. Adolescence is a common time for the symptoms first to appear. This is a time when bones are maturing and cartilage is developing into bone. Sometimes, however, the symptoms do not occur until adulthood.

Symptoms of accessory navicular bone syndrome include:

- A visible bony prominence on the midfoot more specifically on the inner side of the foot, just above the medial arch
- Redness and swelling of the bony prominence
- Vague pain or throbbing in the midfoot and medial arch, usually occurring during or after periods of physical activity
- Acquired flatfoot

37.2.1.5 First Ray Disorder

Dudley J. Morton (1884–1960) was a physician, anatomist, and anthropologist. His work focused on the shortened first metatarsal, hypermobility of the first metatarsal segment, and correlation of first ray mechanics to excessive foot pronation. In his book, "The Human Foot, Its Evolution, Physiology, and Functional Disorders," he describes first the load deformation of the first ray (Morton 1964).

He states that if the plantar ligaments of any segment are slack when the head of its metatarsal bones lies on the same plane as the others whose ligaments are taut, that segment will fail to share in the carriage of body weight. Morton believed that hypermobility of the first metatarsal affects the foot in several ways (Kirby 2012):

- The second metatarsal has an increased burden since the first metatarsal fails to assume its normal share of weight.
- The foot hyperpronates because the medial buttress is ineffective until slack in its ligaments is taken up as pronation increases.
- As pronation advances, functional stresses are put increasingly on muscles on the inner side of the ankle, imposing them undue strain.

37.2.2 Soft Tissue Disorders

37.2.2.1 Morton's Neuralgia

This condition was first described by Thomas George Morton (1835–1903). The medial and lateral plantar nerve joins in the foot between the head of metatarsals III and IV (third web space). There is elevated pressure at this location which could lead to interneuronal fibrosis in the course of the nerve also called Morton's neuroma and/or intermetatarsal bursitis. Clinically, the patient complains of pain, especially in the morning and during activity in the foot flat – heel-off sequence of gait (Zollinger and Jacobs 1989). Symptoms are reproduced by the lateral squeeze test at the level of the metatarsal heads. Radiological differential diagnosis is made by dynamic ultrasound or MRI. Infiltration, minimally invasive US-guided techniques, and surgical neuroma removal are established therapies.

37.2.2.2 Metatarsalgia

Pain in the forefoot region is referred to as metatarsalgia, a nonspecific term. It refers to forefoot pain caused by a number of underlying pathologies. Common etiologies of pain originating in the joint (*intra-articular*) include capsulitis, capsular tear, synovitis, osteoarthritis, arthritis, and avascular necrosis of the metatarsal head or Freiberg's disease. Frequent *extra-articular* causes include flexor tenosynovitis, interdigital neuroma (Morton's neuroma), and metatarsal stress fracture. Effective treatment of metatarsalgia depends on making an accurate diagnosis of the underlying condition and establishing diagnosis-specific therapy. Radiographs are not particularly helpful in making an accurate diagnosis since many of the causes of forefoot pain originate in the soft tissues. A thorough physical examination is therefore warranted. Important features in the history of the patient are to be included to specify the diagnosis, and these include the character, location, and radiation of pain as well as specific aggravating factors. Likewise notable in the history taking are the location and degree of any swelling, as well as factors affecting its variability. A stepwise examination of the involved ray should include (Alexander 1997):

- Inspection of the toe and forefoot for misalignment and swelling
- Palpation of the dorsal and plantar aspect of the MTP joint, the long flexor tendon proximal and distal to the joint, the dorsal metatarsal neck and shaft, and the web and distal intermetatarsal space for tenderness and bone or soft tissue deformity

37.2.2.3 Splayfoot

An abnormal transverse plane spreading of the metatarsus that results in a pathologically increased width of the forefoot is commonly called *splayfoot*. In most cases, abnormally large intermetatarsal angulations develop. However, the primary spreading occurs between the first and second and between the fourth and fifth metatarsals. The splayfoot involves the three cuneiforms in conjunction with the five metatarsals. The pathomechanics can be described as the result of the following factors (Root et al. 1977):

- *1st factor*: function loss of the transverse pedis muscle.
- *2nd factor*: abnormal subtalar joint pronation that causes eversion of the foot during propulsion.
- *3rd factor*: metatarsus primus adductus deformity is an acquired condition that is weakly associated with caused by hallux abductovalgus deformity. It results in a very large abnormal angulation between the first and second metatarsals.

37.3 Disorders at the Level of the Plantar Side of the Foot

37.3.1 Musculotendinous Disorders at the Level of the Plantar Foot

37.3.1.1 Plantar Fasciopathy

More recently, the term plantar fasciosis has been advocated to de-emphasize the presumed inflammatory component and reiterate the degenerative nature of histological observations at the calcaneal enthesis. The plantar fascia, or aponeurosis, spans the arch of the foot. It consists of three components: medial, central, and lateral. They originate from the medial tubercle of the calcaneus and blend distally with the plantar soft tissues of the MTP joint complex and anchor into the phalangeal bases. Several biomechanical functions are attributed of the plantar fascia (Kirby 2012):

- Serves to stiffen medial and lateral longitudinal arches and reduce longitudinal arch flattening
- Assists in resupination of the subtalar joint during the propulsive phase of walking or running
- Assists the deep posterior compartment muscles by increasing subtalar joint supination moment
- Assists the plantar intrinsic muscles in reducing longitudinal arch flattening
- Reduces tensile forces in the plantar ligaments
- Prevents excessive interosseous compression forces on the dorsal aspects of midfoot joints
- Prevents excessive dorsiflexion bending moments on the metatarsals
- Passively maintains digital purchase and stabilizes proximal phalanx against the ground in the sagittal plane
- Reduces ground reaction force on the metatarsal heads during late midstance and propulsion
- Helps to absorb and release elastic strain energy during running and jumping activities

With the calcaneus acting as the patellar bone of the ankle joint, it is not surprising that there is a direct relationship between the tension in Achilles tendon and plantar fascia. Erdemir et al. found that plantar fascia tension was directly proportional to Achilles tendon tension in cadavers in dynamic gait simulator (Erdemir et al. 2004). Also Carlson et al. found that increasing tension within Achilles tendon caused increase in plantar fascia tension at four different angles of MTP joint dorsiflexion (Thomas et al. 2010).

A plantar fascia overload condition is estimated to affect 10 % of runners (Sherman 1999). Athletes with a tendinosis of the plantar fascia experience pain along the arch and almost invariably heel pain, which is in most cases their primary complaint. Start-up pain with first weight-bearing in the morning or after prolonged sitting is severe but usually relents after 15–20 steps. Generally, late in the day, persistent aching pain becomes progressively worse. Tenderness along the fascia, made taut by passive toe extension, is usually maximal in the midfoot region.

Marked tenderness at the calcaneal attachment of the fascia is a frequent finding (Thomas et al. 2010).

37.3.1.2 Plantar Fibromatosis

Plantar fibromatosis, first described by Ledderhose in 1897, is a rare, benign proliferative process of the plantar aponeurosis. Local proliferation of abnormal fibrous tissue in the plantar fascia is typical for this condition. The plantar aponeurosis is then gradually replaced by the locally invasive tissue and progresses to form thickened fascia and nodules that range in size from 0.5 to 3 cm. Subsequently, invasion of the skin and flexor tendon sheath may occur. Eventually, the cords thicken, the toes stiffen and bend, and walking becomes painful. A similar disease is Dupuytren's disease, which affects the hand and causes bent hand or fingers (English et al. 2012).

37.3.2 Soft Tissue Disorders at the Level of the Plantar Foot

37.3.2.1 Fat Pad Syndrome

Heel fat pad syndrome is often caused by a decreased elasticity of the fat pad. Usually, this condition is seen with athletes due to extrinsic factors: a fall onto the heel from a height or chronically excessive heel strike with poor footwear. Contributing intrinsic factors like increased age and weight decrease the elasticity of the fat pad. Clinical signs and symptoms include heel pain felt more laterally of the heel especially when the heel gets loaded (heel strike). Magnetic resonance imaging investigations will reveal changes in the fat pad showing signs of swelling (Thomas et al. 2010; Jahss et al. 1992; Sherman 1999).

37.3.2.2 Medial Plantar Nerve Entrapment

The medial plantar nerve can become entrapped by the fascia beneath the navicular bone and talus as it passes through dorsomedially along with the flexor hallucis longus tendon or by the abductor hallucis muscle. Burning or shooting pain will be felt that radiates toward the plantar aspect of the medial two toes. The pain may be accompanied by tingling numbness. High arch supports can exacerbate the symptoms. Tenderness may occur along the medial arch. The condition may be confused with flexor tenosynovitis, but unlike in the latter condition, the tenderness is not made worse by resisted flexion of the toes or by passive dorsiflexion in the toes. In making a diagnosis, a positive Tinel's sign[1] can be helpful (Murphy and Baxter 1985; Sherman 1999).

37.3.2.3 Lateral Plantar Nerve Entrapment

Behind the medial malleolus, this nerve usually separates from the tibial nerve into the lateral plantar nerve. The entrapment of this nerve is possible where it passes between the abductor hallucis muscle and quadratus plantae muscle. This condition

[1] From the French neurologist Jules Tinel (1879–1952): to elicit a sensation of tingling one taps lightly over the nerve

often presents with medial plantar heel pain, which in some cases radiates into the lateral foot or proximally, and in 10–15 % of cases is associated with plantar fasciopathy. On clinical examination, maximum tenderness is found along the abductor muscle on the medial aspect of the heel. Paresthesia may occasionally be produced by palpation. There is no consensus on the usefulness of neurophysiological investigations in this condition. Often heel pads, a heel lift, and stretching exercises for the Achilles tendon and plantar fascia relieve the pain (Murphy and Baxter 1985; Sherman 1999).

37.4 Disorders at the Level of the Posterior Side of the Foot

37.4.1 Osseous Disorders at the Level of the Posterior Side of the Foot

37.4.1.1 Haglund's "Exostosis"

Also known as "pump bump" and often used interchangeably with the term "retrocalcaneal bursitis," the two are distinct entities. A pump bump is characterized by a bony prominence that usually is located just lateral to the Achilles tendon proximal to its insertion. The term "exostosis" suggests an osteochondroma, i.e., a bone and cartilage forming tumor at the surface of bones. However, in Haglund's "exostosis," the bony overgrowth is not covered with a cartilaginous cap and is merely an anatomical variant. The orientation of this bony overgrowth is longitudinally parallel to the Achilles tendon. The overlying skin often appears erythematous, and tenderness is localized to the prominence, in addition to the presence of the unilateral bony bump. The athlete complains primarily of local irritation from the shoe's heel counter. Adjusting a (thermoplastic) heel counter of the shoe to the shape of the bony prominence can be a simple but effective solution. The absence of diffuse swelling helps to distinguish this condition from retrocalcaneal bursitis (Alexander 1997; Koulouris and Morrison 2005; Verdonk 2006). Lateral calcaneal radiographs are used to document the "exostosis," while bursitis and Achilles tendon disorders are demonstrated and staged on US or MRI.

37.4.1.2 Os Trigonum and Posterior Impingement Syndrome

Posterior ankle pain can be the end result of several pathologies. The posterior ankle impingement syndrome, also known as os trigonum syndrome and posterior tibiotalar compression syndrome, is a clinical disorder characterized by acute or chronic posterior ankle pain triggered by forced plantar flexion, which causes chronic repetitive microtrauma (Chiereghin et al. 2011). The os trigonum can become pinched between the posterior tibia and the calcaneus if large enough, which subsequently can result in a pseudoarthrosis, arthritis at the articulation, as well as posterior recess effusion and synovitis (Sherman 1999).

In accordance, football players, ballet dancers, and fast bowlers in cricket may be at risk for this condition. The triangular bone at the posterior margin of the talus onto which the posterior talofibular ligaments insert can be seen on a lateral radiographic view. Generally, this condition is straightforward differentiated from a Shepherd fracture (a fracture of the posterior talus).

37.4.1.3 Anterior Tibiotalar Compression/Impingement Syndrome

The condition is also known as anterior impingement. This is a common problem seen primarily in dancers, secondary to the repetitive forced ankle dorsiflexion inherent in ballet (Caino et al. 2012). Impingement syndrome was also reported in kicking sports (Sherman 1999). Symptoms generally occur progressively and may respond to conservative treatment including addressing biomechanical faults that contribute to the problem. As impingement progresses, osteophytes and enthesophytes anterior to the talus may develop, and the athlete's essential movements, i.e., ankle dorsiflexion, may become impaired. If conservative measures fail, arthroscopic ankle surgery may be required for both diagnosis and treatment, allowing athletes to return to their sport (O'Kane and Kadel 2008).

37.4.1.4 Calcaneal Stress Fracture

Generally stress fractures can be divided into fatigue fractures (normal bone vs. abnormal stress) and insufficiency fractures (abnormal bone vs. normal stress). Both can be related to repetitive injury that is too low to cause an acute fracture but that exceeds the elastic limit of load-bearing trabeculae (Sherman 1999).

The etiology of calcaneal stress fractures is similar to metatarsal stress fractures and usually caused by a sudden increase in walking or running distance without appropriate footwear (Fredericson et al. 2006; Salzler et al. 2012). Calcaneal stress fractures can be divided into intra-articular and extra-articular types. Extra-articular fractures are distraction-type stress fractures and consist mainly of avulsions and anterior process fractures. Achilles avulsions are most commonly seen in diabetic athletes. The intra-articular fractures are typically compression-type stress fractures caused by axial load resulting in a vertical fracture. About 5–10 % of intra-articular calcaneal fractures are bilateral, and there is also a 10 % association with fractures of the thoracolumbar spine (Sherman 1999).

37.4.1.5 Tarsal Coalition

Tarsal coalition is a congenital bridging between the tarsal bones of the foot caused by a failure of differentiation and segmentation of the primitive mesenchyme (Caino et al. 2012). The coalition may be osseous, fibrous, or cartilaginous. The actual incidence is difficult to determine since many coalitions are asymptomatic (Lysack and Fenton 2004).

A history of multiple ankle sprains and subtalar joint stiffness on physical examination is suspicious for a tarsal coalition (Caino et al. 2012). Coalitions most commonly occur in the talocalcaneal (subtalar) or calcaneonavicular joints, and they account for 90 % of ankle coalitions (Koulouris and Morrison 2005). The loss of hindfoot mobility leads to abnormally high stresses on other structures in the foot. Subtalar/hindfoot mobility should always be examined when investigating foot problems. Bony coalitions may be seen on plain radiographs but are often more easily demonstrated with computed tomography. Magnetic resonance imaging will show both bony and fibrous coalitions and is able to demonstrate bone marrow edema in case of stress reactions at the site of the coalition (Koulouris and Morrison 2005; Sherman 1999).

37.4.1.6 Subtalar Joint Arthritis

Classical signs of subtalar joint osteoarthritis include joint space narrowing, marginal osteophytes, intra-articular loose body formation, subchondral cysts, and subchondral sclerosis. Trauma is the most common predisposing factor, including injuries such as lateral ligament tear with resultant instability and/or osteochondral injury, as well as intra-articular fracture (Koulouris and Morrison 2005). Other findings include swelling below and behind the malleoli and also tenderness along the posterior facet and in the sinus tarsi.

37.4.2 Musculotendinous Disorders at the Level of the Posterior Side of the Foot

37.4.2.1 Midportion Achilles Tendinopathy and Enthesopathy

The Achilles tendon, with a length of ~15 cm, is subject to extreme loads during running and jumping. Despite the fact that this tendon is built to repeatedly produce these forces without injuries, lesions can occur in four different locations. Tendinopathy of the Achilles tendon is nowadays regarded as a three-stage continuum consisting of reactive tendinopathy, tendon disrepair, and degenerative tendinopathy (Cook and Purdam 2009). Pain and tenderness are most often located at the level of the middle third of the tendon (about 2–6 cm proximal to the insertion site). The Achilles tendon is a type one tendon without synovial tendon sheath and may be affected at the height of its epitenon which is called paratenonitis. The tissue surrounding the tendon is thereby generally inflamed. Also the Achilles tendon is accompanied by a retrocalcaneal bursa, which is kept between the tendon and calcaneum and an adventitious retroachilles bursa located between the enthesis and the subcutaneous tissue. An inflamed retrocalcaneal bursa is called a retrocalcaneal bursitis that sometimes may be associated with a Haglund's "exostosis." There may also be an injury at the insertion level of the Achilles tendon (insertion tendinopathy actually described as enthesopathy). The patient may separately present with these various conditions or in a combined form.

In chronic tendinopathy patients, there is a continuous interaction between the intrinsic (alignment, suboptimal biomechanics, etc.) and the extrinsic (training load, training type, surface, etc.) factors. Many authors believe that both intrinsic and extrinsic factors lie at the basis of Achilles tendon problems. Kvist 1994 even considers that two thirds of the Achilles tendon problems seen with athletes are due to the intrinsic factors. When analyzing suboptimal biomechanics, we concise that the Achilles tendon is heavy loaded during walking, running, and jumping. Abnormal pronation or supination can lead to focal biomechanical overload (Kvist 1994).

If extreme pronation of the calcaneus is present during heel landing and/or midstance phase, the medial fibers undergo more tension (frontal overload). Also seen with late pronation (during the second half of the midstance phase and during the propulsion phase), the foot will drive the lower leg into further internal rotation (from an ascending kinetic chain). The forward swing of the swing leg forces the standing leg to perform an external rotation. Thus, the knee and Achilles tendon can be affected if the movements that are driven from the top are not synchronized with the movements that are driven from the bottom (Schepsis et al. 2002). A proximal external rotational force combined with a distal internal force leads to a forceful twist that is called the "wringing-out phenomenon" (horizontal overload). When stepping or running forward, the body will be slowed by the posterior muscle chain in an eccentric manner. This eccentric muscle work goes into concentric work during the propulsion phase. This three-dimensional overload will cause to load collagen fibers outside their safety zone and microtraumata will occur. In a pes cavus, a similar but opposite mechanism may be seen (Roosen and Van de Steene 2007).

37.4.2.2 Achilles Tendon Rupture

A traumatic Achilles tendon rupture generally occurs in the adult male between the age of 30 and 35 years. In tennis and squash, the athlete mentions a sudden stab in the lower calf without any sudden overload. Physical examination shows loss of single-leg heel raise with preservation of normal walking (Alexander 1997). The Thompson squeeze test is described as squeezing the patient's calf of the leg with the patient lying prone, feet dangling over the end of the table, this squeezing should produce plantar flexion of the foot if the achilles tendon is intact. The absence of passive plantar flexion is consistent with complete disruption of the Achilles tendon (Alexander 1997).

37.4.2.3 Heel Spur

This is the most prevalent complaint presenting to a foot and ankle specialist in 11–15 % of adults. The term heel spur lends some importance to the presence of a calcaneal spur (as seen on radiographic imaging) to clinical symptoms. Literature describes the main cause to be of biomechanical origin, stating that heel pain is established by mechanical overload, whether the result of biomechanical foot abnormalities, obesity, or work habits putting the plantar fascia and its enthesis is under too much stress (Kosmahl and Kosmahl 1987). Although spur formation at the inferior calcaneus is often implicated in this process, it actually has little association with pain, and in most cases, removal of the plantar heel spur does not seem to add to the success in treatment of plantar heel pain. The spur is merely an enthesophyte, and like enthesophytes elsewhere in the body, they are seen incidentally and are consequence of normal aging (English et al. 2012; Thomas 2001).

37.4.2.4 Retrocalcaneal Bursitis

In retrocalcaneal bursitis, proximal to the Achilles tendon insertion, the thin-walled bursa becomes inflamed accompanied by thickening of this bursal synovial wall and fluid accumulation. It is often seen in association with insertional tendinopathy and may also be associated with a Haglund's "exostosis" as stated above. Edema follows the path of least resistance, namely, medially, laterally, and superiorly. The swelling causes loss of Achilles tendon margins. In the acute phase, tenderness is reported medial and lateral to the Achilles tendon. The condition can occur both in males and females at any age. Although three studies (Aronow 2005; Reinherz et al. 1990; Ruch 1974) have shown that females aged 20–30 years are most commonly affected (Alexander 1997; Root et al. 1977).

37.4.2.5 Calcaneal Apophysitis

This is a condition that is also known by the name of Sever's disease. It is seen with skeletally immature adolescent (usually) male athletes (8–12 years). The condition presents with pain over the posterior aspect of the heel, apical heel tenderness, and discomfort on passive stretching of the Achilles tendon. A reduction in activities is required for symptomatic relief. The precipitating sport involves running on hard surfaces that provide no impact absorption (Chu et al. 2012; Wiegerinck et al. 2012). Load reduction and calf muscle strengthening may help somewhat to reduce pain. A recent systematic review, however, indicates there is currently limited evidence to support the use of heel raises and orthoses for children who have heel pain related to calcaneal apophysitis (James et al. 2013).

37.5 Disorders at the Level of the Lateral Side of the Foot

37.5.1 Musculotendinous Disorders at the Level of the Lateral Side of the Foot

37.5.1.1 Subluxation or Tendinopathy of the Peroneal Tendons

Lateral foot pain without a definite cause is often related to the inflammation of one or both peroneal tendons. Swelling is unusual, and simultaneously both tendons may be involved. Tenderness is localized to the involved tendon. The tendons under tension will be more tender than lax tendons, and this is a typical sign of tendinosis (Alexander 1997; Sherman 1999).

Pain may occur also due to anterior luxation of the tendons related to loosening or rupture of the fibular attachment of the superior peroneal retinaculum. Lesions of the retinaculum peroneorum superius are related to ankle distortion and overuse. The discomfort is localized approximately 2 cm proximal to the tip of the distal fibula. Some athletes know the cause of their pain and can sublux or dislocate the long peroneal tendon by everting and abducting the foot. The physician can also provoke a subluxation by asking the athlete to forcefully evert and abduct the foot against resistance (Alexander 1997; Sherman 1999). Subluxation of the posterior tibial tendon may occur but is much less common and related to loosening or rupture of the tibial attachment of the flexor retinaculum.

37.5.2 Soft Tissue Disorders at the Level of the Lateral Side of the Foot

37.5.2.1 Inversion Trauma

An inversion injury is defined as an overstretching or partial tear of the fibers of the lateral ligaments. The lateral ligamentous complex, which consists of the lig. talofibulare anterior, the lig. calcaneofibulare, and lig. talofibulare posterior, is frequently affected in inversion-type ankle sprains. The provocative mechanism is a plantar flexion, adduction, and supination accompanied by an external rotation of the tibia on the fixed foot. An inversion trauma will occur more frequently than an eversion trauma. On the one hand, the lateral malleolus is positioned more distally than the medial malleolus, and secondly, the medial deltoid ligament is recognized as a much more solid complex (Roosen and Van De Steene 2007).

37.6 Disorders at the Level of the Medial Side of the Foot

37.6.1 Musculotendinous Disorders at the Level of the Medial Side of the Foot

37.6.1.1 Posterior Tibial Tendon Tendinopathy

The description of this disorder has a long history: First reports were found by Kulowski in the year 1936. Posterior tibial tendon dysfunction is generally accepted to contribute to the pes planovalgus. This condition is in contemporary literature described as "the adult-acquired flatfoot." The question still remains whether this muscle is the primary etiology of the progressive pes planus.

Jennings and colleagues published a study that shows the importance of the so-called spring ligament complex. This complex contains four essential ligaments: the lig. calcaneonavicularis inferior, the superomedial calcaneonavicular ligament, the anterior portion of the superficial deltoideum ligament, and the tendon of the posterior tibial tendon. These ligaments form a sling around the articular surface of the caput tali of which the primary function is to maintain control of the three-dimensional movement of the talo-calcaneonavicular joint.

The dynamic support given by the tibialis posterior muscle and tendon is supplementary to the static, passive support of the spring ligament complex, in order to maintain control of the medial movement of the caput tali.

A loss of the dynamic inter-supportive mechanism of the posterior tibial tendon will result in rupture of the complex due to repetitive stress (Demaj 2009).

A study by Holmes and Mann shows that the condition is three times more common in women than in men. Athletes with pes planus are also predisposed to the problem and localize their pain to the course of the tibialis posterior tendon along the border of the medial malleolus and distally into the longitudinal arch. The symptoms are pain around the medial ankle, medial midfoot, and proximal arch (Demaj 2009).

A literature review shows that the adult-acquired flatfoot appears to be caused by loss of static and dynamic loss arch supporting structures. It is important that the condition is recognized in the early stages I and II. In stages III and IV, the ligamentous integrity of the foot is lost and progressive foot deformation can occur (Demaj 2009).

37.6.1.2 Anterior Tibial Tendinopathy

Anterior tibial tendon injury typically occurs as a chronic overuse injury in patients older than 45 years. The anterior tibial tendon can also be injured in distance runners and soccer or football players who forcefully dorsiflex a plantar-flexed foot against resistance, placing an eccentric stress on the tibialis anterior muscle (Howard 2009).

In most cases, dorsiflexion of the foot against resistance is painful. Tendinitis of the anterior tibial tendon is uncommon, and usually anteromedial pain is attributed to intra-articular pathology. In case of intra-articular pathology, dorsiflexion relieves the pain. Examination may also reveal absence of the tendon in case of a rupture. Sporting shoes having a posterior heel flare above 12° have been reported to cause anterior tibial tendinitis, increasing the deceleration force of the foot at initial heel strike (Alexander 1997; Verdonk 2006).

37.6.1.3 Flexor Hallucis Longus Tendinopathy

The flexor hallucis longus muscle is a stance-phase muscle. It begins to contract at the end of the contact period and continues to contract until late in the propulsive period. Its main function is to maintain stability of the entire hallux against the ground during propulsion. This function is dependent upon prior conversion of the hallux into a rigid beam by the extensor mechanism. High forces going through the tendon can be the cause of the tendinopathy as well as overuse due to suboptimal biomechanics. Symptoms are pain and swelling over the posteromedial aspect of the ankle and seen in dancers or athletes who use repetitive push-off maneuvers. The great toe flexor passes in a groove between the medial and lateral tubercles of the posterior process of the talus. Passive extension as well as resisted flexion of the hallux also provokes pain. In advanced cases, a swelling can be found just proximal to the talar tubercles. If left untreated, this can further result in a functional hallux rigidus (Alexander 1997; Root et al. 1977).

37.6.2 Soft Tissue Disorders at the Level of the Medial Side of the Foot

37.6.2.1 Tarsal Tunnel Syndrome

Tarsal tunnel syndrome is a term used to indicate an entrapment neuropathy of the tibial nerve within the tarsal tunnel (Sherman 1999). In the retromalleolar region, the tibial nerve divides into the medial plantar nerve, the lateral plantar nerve, the first branch of the lateral plantar nerve, and the calcaneal nerve; in the distal part of the tarsal tunnel, these nerves run in separate tunnels (Heimkes et al. 1987).

Tarsal tunnel syndrome may occur spontaneously or secondary to swelling of other structures within, or adjacent to, the tarsal tunnel (such as ganglia or flexor tendon tenosynovitis). Spontaneous cases are often associated with a foot that is repeatedly pronated such as the inside foot in a track runner (Sherman 1999). One study (Kinoshita et al. 2006) showed that activities resulting in pain were sprinting, jumping, and performing ashibarai, a training method for judo involving sweeping one's opponent's legs with one's foot. Most of the symptoms were shooting pain, tingling, burning, and electric shock sensation extending from the medial ankle into the foot, often with paresthesia continued all day, even after stopping the sporting activity. Some predisposing underlying physical factors were found such as existence of talocalcaneal coalition, accessory muscles, and bony fragments around the tarsal tunnel. During physical examination, Tinel's sign is often positive. Electrophysiological studies may help to confirm in diagnosis.

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Radiological Imaging of Foot Injuries

38

David J. Wilson and Gina M. Allen

Contents

Abstract

Injuries of the foot are less common than those to the ankle. Stress or insufficiency fractures are a particular feature and are best excluded using MR with water-sensitive fat-suppressed sequences. Foot deformity may lead to metatarsalgia and Morton's neuroma. These lesions will be detected and can be partially treated using ultrasound. Both ultrasound examination and MR have a role in detecting ligament, tendon, plantar fascia and plantar plate injuries.

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Abbreviations

CT Computed tomography
MRI Magnetic resonance imaging
US Ultrasound examination

38.1 Introduction

Injuries of the foot are much less common than those of the ankle in sports people. However, those involved in field sports, particularly hockey, soccer and rugby disciplines, are more likely to be injured. The advent of soft flexible footwear has increased the risk, whilst the agility of the athlete has also worsened the problem. Whilst in the ankle the majority of injuries are acute sprains, this is less in the case of the foot. Here, repetitive strain injuries, stress fractures, enthesopathy, ligament injuries and joint capsule problems are more frequent.

As in all other areas of the body, a clinical history with review of risk factors and a clinical examination often lead to a diagnosis or to at least a short differential. However, imaging is fundamental in detecting the location and severity of injuries, offering a reasonably accurate prognosis and excluding those patients in whom no intervention is required.

38.1.1 Predisposing Lesions

Deformity of the foot extending from the hindfoot to the forefoot is likely to alter the biomechanics and therefore predispose an individual sports person to injury. Common abnormalities include the high arch or a dropped arch. Less common are coalitions and hindfoot and midfoot such as tarsal coalition (Di Caprio et al. 2010) (Fig. 38.1). Very common in the older age group is hallux valgus. Hallux valgus is usually precipitated by a fall in the medial arch of the foot leading to rotation of the first metatarsal, which in turn leads to a varus deformity of the first ray. As a secondary effect, the great toe now flexes on its rotated metatarsal, which has the appearance of hallux valgus (Fig. 38.2). This in turn crowds the second metatarsal into the third and sometimes the fourth metatarsal, which can cause a friction effect between the metatarsal heads leading to the condition, termed Morton's neuroma. More properly, this condition should be described as a fibroma or colloquially as an internal callus, which can impinge on the digital nerves. Therefore, patients in the older age group may present with a foot deformity that predisposes to athletic injury (Hockenbury 1999). Fatigue fractures are described in detail below. The mechanisms are usually that of an excessive load placed on a limb that is not used to the type of activity. It is therefore typical in new army recruits who are not used to heavy weight bearing and long distance marching. Athletes who have eating disorders will be at greater risk of insufficiency fractures due to the poor mineralization of the bone. This is particularly important in the

Fig. 38.1 MRI sagittal STIR of a hindfoot coalition of the calcaneus and navicular with a stress response

Fig. 38.2 X-ray showing a hallux valgus

syndrome of the female athlete who undertakes endurance running as a means to lose weight but is also intrinsically anorexic. In such individuals, their bone mineral density may be considerably lower than the norm for their age. Other precipitating factors include recent changes in training workload, smoking and the use of performance-enhancing drugs including anabolic steroids (Lappe et al. 2001).

38.2 Mechanisms of Injury

38.2.1 Acute Injuries

38.2.1.1 Fractures

Common fractures in the athlete include avulsion of the proximal end of the fifth metatarsal, which is secondary to a traction injury caused by the peroneus brevis. This lesion must be distinguished from a normal apophysis, which occurs in this location in adolescence (Fig. 38.3a, b). The apophysis has its alignment parallel to the shaft of the metatarsal, whilst the fractures are closer to 90° to the axis of the metatarsal. Considerable confusion may occur when there is an avulsion of the apophysis in a young athlete or if there is a fracture through the apophysis. In these

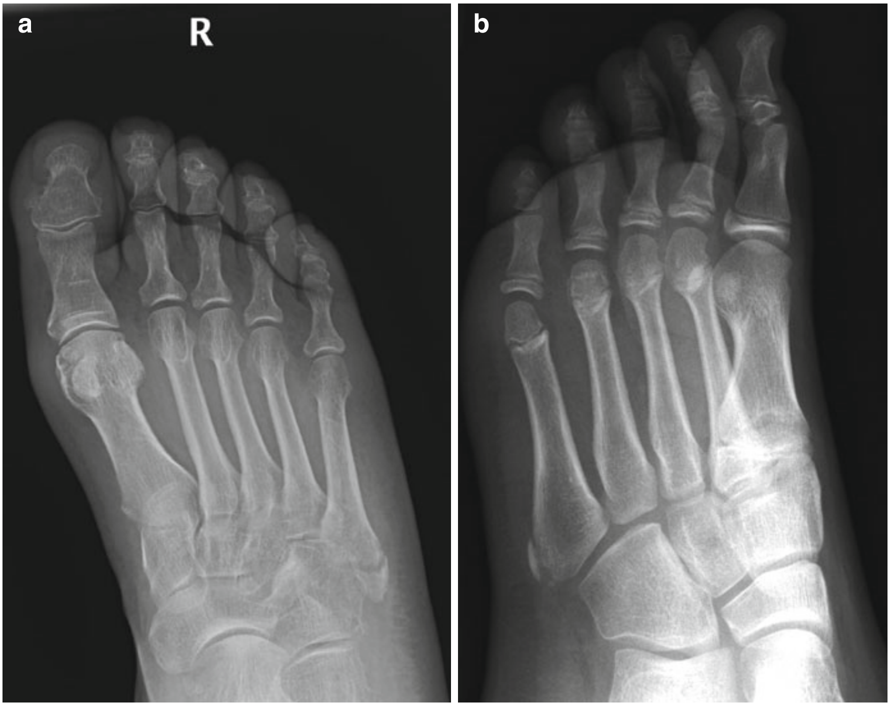

Fig. 38.3 (**a**) X-ray showing a fracture of the base of the fifth metatarsal. (**b**) X-ray showing a fifth toe apophysis

circumstances, imaging is of considerable importance, as it will detect the bone oedema and also the fracture margins.

An avulsion fracture of the base of the fifth metatarsal has to be distinguished from Jones' fracture (also called dancer's fracture) that is located more distally with transverse course at the proximal diaphyseal or metaphyseal area. This fracture may be related to acute ankle inversion trauma but also to stress from running (fatigue fracture) or osteopenia (insufficiency fracture). Jones fractures unlike avulsion fractures are prone to delayed and even non-union and often need operative intervention (Jones 1902).

Fractures of all the tarsal bones and metatarsals may occur as an acute event. Midfoot injuries are often the result of stamping by another athlete. The fractures seen are identical to those that occur in nonathletes. Avulsion of the medial border of the os naviculare by the tibial posterior insertion is a potential adolescent or children's injury. This must be distinguished from a secondary ossification centre occurring at this site. Some would argue that the so-called os naviculare is an old avulsion injury. Those with a secondary ossification centre or a normal variant at this location tend to be at greater risk of avulsion displacement, and, therefore, pain in the region of an apparently normal variation should be considered seriously and investigated further when the clinical symptoms suggest that this is the location of the pain (Mellado et al. 2003; Tuthill et al. 2014) (Fig. 38.4).

38.2.1.2 Ligament Tears

Specific ligamentous or capsular injury is the condition termed "turf toe" (Clanton and Ford 1994). This is an avulsion or traction injury of the plantar plate most typically of the great toe but also rarely seen in other toes. This is associated with the use of soft and flexible footwear whilst competing on artificial turf. The sudden deceleration of the foot with hyperextension can lead to an avulsion injury where the plantar plate is detached from its normal insertion (Fig. 38.5). This condition can range from an enthesopathy with flexor tendon thickening to tears of the plantar plate, metatarsal-sesamoid ligament and/or inter-sesamoid ligament and, in the worst case, to complete avulsion of the insertions with or without associated osseous or cartilage injury. There will be localised pain, tenderness, dysfunction and oedema. This injury may lead to chronic problems if not properly treated in the

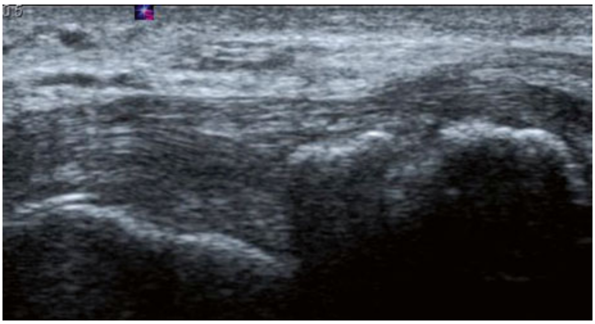

Fig. 38.4 Ultrasound showing the distal insertion of the tibialis posterior tendon and an os naviculare

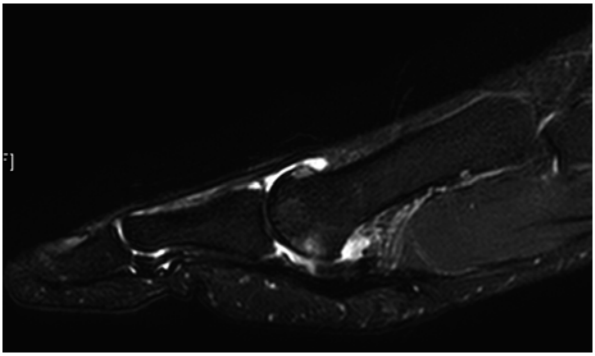

Fig. 38.5 MRI sagittal PDFS showing a plantar plate injury

early stages (Allen et al. 2004). Other ligament injuries may occur in the midfoot particularly in the intertarsal and tarsometatarsal ligaments (Lisfranc and Chopart). The spring ligament has been dealt with in the ankle chapter.

38.2.1.3 Tendon Injuries

The distal portions of the tendon of tibialis posterior, tibialis anterior, flexor digitorum longus and the peroneal tendons are subject to chronic tendinopathy. The nature of which will depend upon the precipitating mechanism. Thickening of the tendon, tendon sheath fluid and paratenon oedema are all features. Delamination may occur in the tendon itself and enthesopathy at its insertion. These may be relatively acute injuries with avulsion and rupture. Chronic tendinopathy is dealt with later in this section. Avulsion injuries of the tendons in the feet may lead to considerable retraction at the tendon ends. Extensor tendon injuries are less common although the tibialis anterior may be affected by impaction against the anterior part of the footwear.

38.2.1.4 Muscle Injury

Although these are rare in the athlete, unusual injuries can occur due to a direct blow or a sudden change of direction of the foot (Fig. 38.6) (MRI of foot muscle injury).

38.2.2 Chronic Injuries

38.2.2.1 Stress Injuries

Stress (fatigue and insufficiency) injuries occur in the foot due to repetitive activity. There are precipitating factors: particularly congenital, deformity and previous fracture.

The stress response in bone will start as bone oedema. Next, periosteal oedema and then periosteal new bone formation may occur. Eventually, thickening of the cortex and the type of the stress injury with separation and full fracture may also occur. If patients rest and remove the load to the bone, then the fractures will heal spontaneously with initial resorption and then sclerosis as part of the bone repair process. There will be localised cortical thickening which in time will remodel. As athletes often return to physical activity too early in the stage of healing,

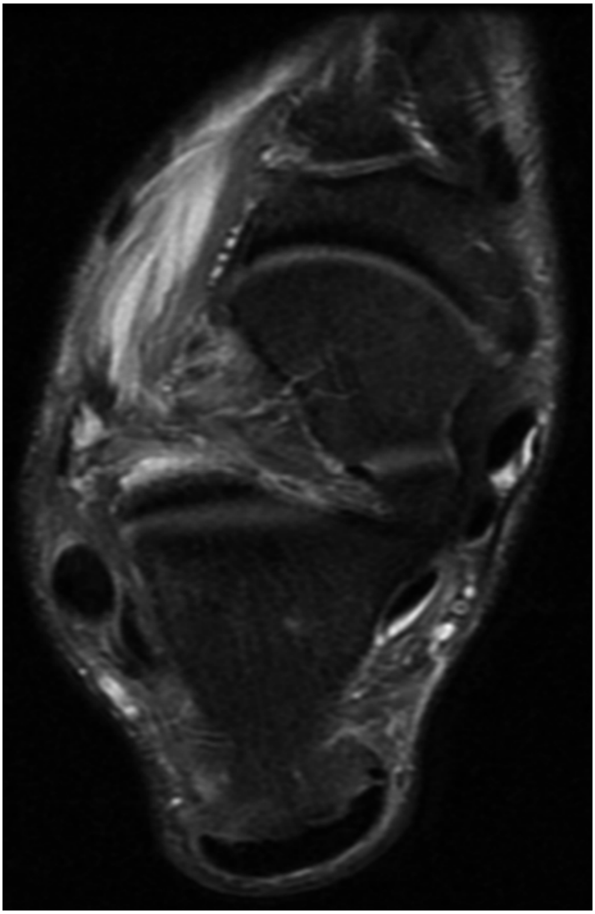

Fig. 38.6 MRI of a foot muscle injury – extensor hallucis brevis

secondary new bone formation periosteal response is sometimes seen in healed or partly healed fractures. Therefore, any stage of the oedema, periosteal response and bone defects may be seen in combination. Stress injuries may occur in the midfoot, particularly in people with hindfoot or midfoot deformity which may also occur in any of the bones (Dixon et al. 2011) (Figs. 38.7, 38.8, and 38.9).

38.2.2.2 Tendinopathy

In chronic tendinosis, delamination is more common, with swelling of the tendon, which leads to thickening and increased water content on imaging and neovascularisation of the tendon. The most common tendons in the feet are the tibialis posterior, peroneus tendons and tibialis anterior tendons (Fig. 38.10).

38.2.2.3 Enthesopathy

A traction injury at the tendon insertion, or enthesis, will lead to oedema, swelling and thickening of the enthesis and distal tendon, small collections of adjacent fluid and neovascularity both within the tendon and the adjacent tissues. Enthesitis or

Fig. 38.7 MRI STIR sequence sagittal of a second metatarsal stress fracture

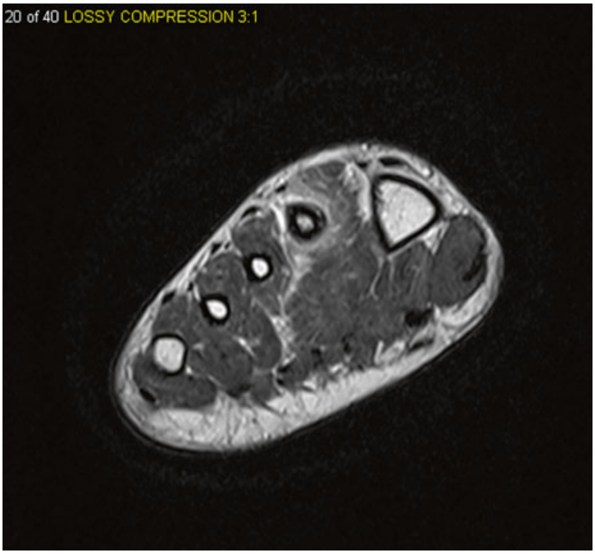

Fig. 38.8 MRI STIR sequence axial of a second metatarsal stress fracture

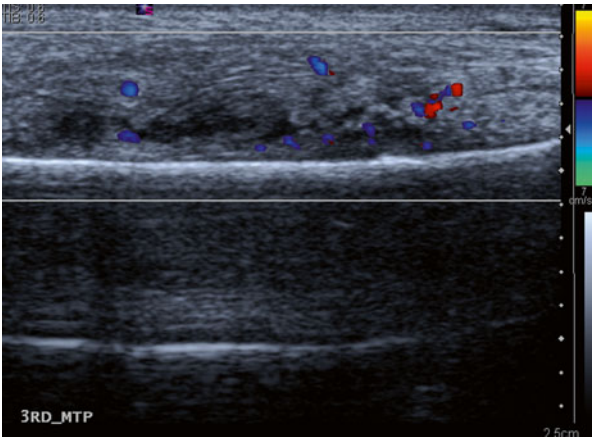

Fig. 38.9 US with colour Doppler of a third metatarsal stress fracture

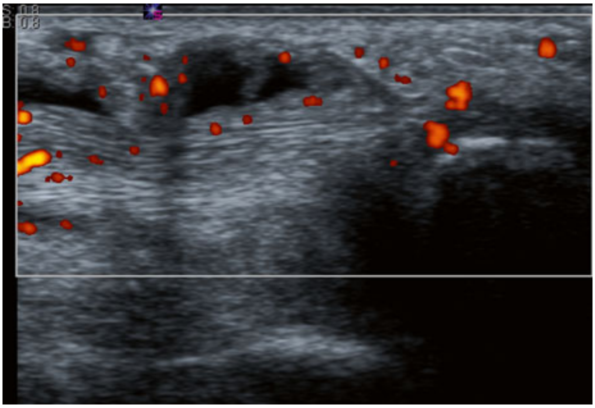

Fig. 38.10 Ultrasound showing the distal insertion of the tibialis posterior tendon with tenosynovitis and neovascularisation

traction bony spurs may occur with associated underlying bone oedema. Common sites for enthesopathy are at the insertion of the Achilles, tibialis posterior on the navicular bone and at the insertion of the peroneus brevis on the fifth metatarsal bone.

38.3 Plantar Fascia

Plantar fascia is a fan or tree-like structure which extends from its root in the calcaneus to the insertion of the fascia on the anterior part of the foot where it is spread out in a lateral and medial direction. Conditions which affect the plantar fascia in athletes include rupture of the fascia, chronic traumatic or overuse fasciitis and traction enthesopathy at the plantar fascia insertion in the calcaneus. Patients with plantar fibromas or contractures (Lederhosen disease) may present in an athletic environment although this is an intrinsic genetic disorder.

Plantar fasciopathy typically occurs at the medial aspect of the insertion of the plantar fascia on the calcaneus. It is seen as thickening of the plantar fascia insertion. This is one of the locations in which a measurement is particularly useful. The normal plantar fascia should measure less than 4 mm adjacent to the insertion on the calcaneus. Any thickening to or above 4 mm is regarded as abnormal, and it is a specific sign of plantar fasciopathy (Cheng et al. 2012) (Fig. 38.11). Oedema both in the fascia insertion and in the adjacent soft tissues is common. Neovascularity will occur in the chronic lesion. Using MR examination, bone oedema will be seen deep into the plantar fascia insertion when the disease is active (Hoffman and Bianchi 2013; Hoffman et al. 2014) (Fig. 38.12).

Ultrasound-guided injection of this region is an effective treatment and commonly prescribed. If performing the procedure from a medial approach, the operator should be careful to avoid damage to the lateral plantar nerve which runs across the midfoot to hindfoot in this region.

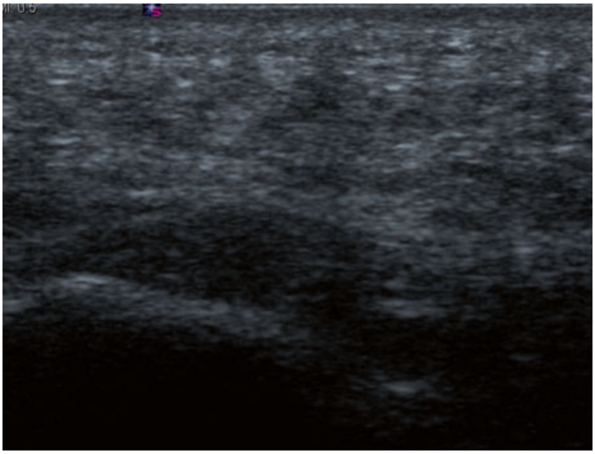

Fig. 38.11 Ultrasound of an insertional plantar fasciitis

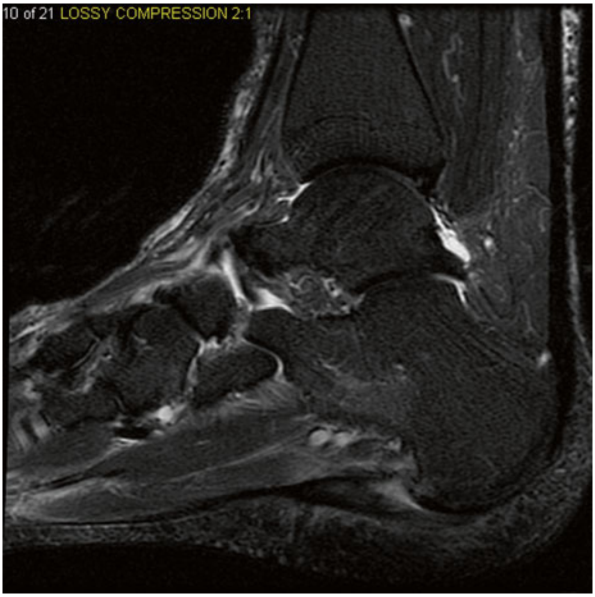

Fig. 38.12 MRI sagittal STIR showing an insertional plantar fasciitis and enthesopathy

38.4 Instability

Forefoot instability is relatively uncommon. Previous injuries in the midfoot can rarely cause instability around the Chopart and Lisfranc ligaments. A particular group are diabetic patients in whom a neuropathic joint may lead to an aggressive neuroarthropathy (Charcot) and gross instability with rocker bottom deformity. If diabetic patients are involved in athletic activity, it may be difficult to distinguish the nature of the injury. The observer should always be aware that diabetic patients

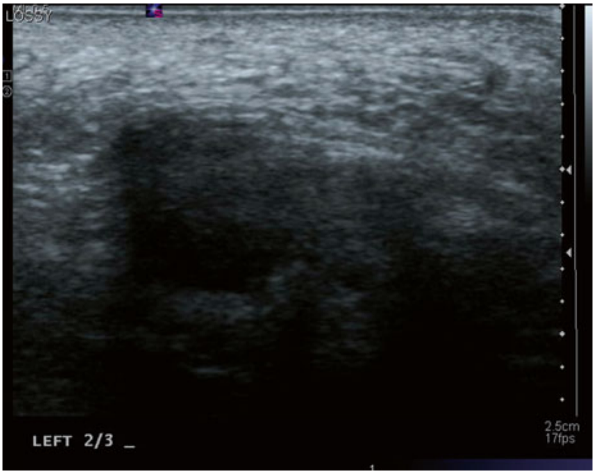

Fig. 38.13 Ultrasound of the sagittal view of a Morton's neuroma

are prone to infection. In general, infections tend to occur in the forefoot with neuropathic joints in the midfoot although the differentiation may be very difficult. Occasionally, there may be a need to resort to serial examination and even biopsy. It is important to distinguish diabetic neuroarthropathy from infection as the treatment in the early stages is entirely different.

38.5 Nerve Injuries

Direct trauma to the deep peroneal nerve on the dorsum of the foot has been observed in footballers. This is due to the repetitive kicking of the ball on the medial aspect of the dorsum of the foot (Tagliafico et al. 2010).

Morton's neuroma is a thickening of tissues around the interdigital nerve. It occurs in athletes often secondary to a biomechanical imbalance that leads to irritation of the nerve in the interspace. It is easily identified using ultrasound (Beggs 1999) (Fig. 38.13) but can be detected using MRI especially if contrast agent is administered.

38.6 Imaging

38.6.1 Conventional Radiographs

Conventional radiographs of the foot are normally performed in AP and dorsal oblique directions. In athletes, it is often useful to include a lateral view, particularly in the standing position, as this assesses the arch of the foot and the alignment of the midfoot and forefoot in the weight-bearing position. Additional views that may be required include a skyline with tangential views of the sesamoids when looking for sesamoiditis, osteoarthritis and fractures. Conventional radiographs are relatively insensitive to tendon disease, enthesopathy and ligamentous injuries. In turf toe, lateral views or fluoroscopic examination during extension of the first toe may demonstrate a widening of the distance between the sesamoids and the base of the first phalanx. Stress injuries of bone will lead to areas of sclerosis, cortical thickening and eventually fracture lines. However, the oedematous phase and early periosteal phase will not be visible on conventional radiographs, and therefore, a normal conventional radiograph does not exclude an early stress fracture. As it is important to treat the patients at this stage, this is a significant deficiency of an examination by conventional radiographs.

In assessing hindfoot and midfoot alignment, weight-bearing views are required. This is easily performed when the patient is standing on a block of wood to a degree of elevation to allow a horizontal beam view.

Whilst hallux valgus can be relatively diagnosed using conventional radiographs, the severity of symptoms associated is unrelated to the deformity. Many patients with hallux valgus have no symptoms, whilst some with relatively minor changes develop metatarsalgia and intermetatarsal disorders including Morton's neuroma and bursitis.

38.6.2 CT

Computed tomography is particularly useful in assessing midfoot injuries where the anatomy is complex. The examination is normally performed in the supine position with extended legs in axial (long axis of the foot) imaging plane. Multiplanar reconstructions in sagittal and coronal planes are useful. Cortical defects, new bone formation and malalignment are important features to assess. In patients with potential midfoot fracture dislocations (Lisfranc injury), careful examination of the midfoot using standing lateral radiographs and CT are important as these fractures may be relatively subtle and difficult to detect whilst potentially being catastrophically unstable. Early surgical management is indicated in midfoot fracture dislocations, and therefore, a careful intricate analysis is vital. Whilst CT is more sensitive to stress response in the bone as it will show areas of sclerosis and periosteal new bone, it remains less sensitive than MRI in the assessment of stress injuries.

CT is of relatively little value in the assessment of ligaments, tendons and the soft tissues although oedema, swelling and calcification may be observed.

38.6.3 Ultrasound

Ultrasound examination is particularly suited for assessing tendons, ligaments, joints for effusion, joint capsules and the intermetatarsal soft tissues. Ultrasound examination is sensitive to early periosteal reaction and stress fracture and may often be positive when conventional radiographs are normal. Having said this, MRI is more sensitive to bone oedema and therefore overall the most sensitive examination for bone stress injuries.

Ultrasound is especially useful in making a diagnosis of tendinopathy and tendon rupture. Dynamic examination will allow the identification of retracted tendon ends with paradoxical movements on both passive and dynamic movements of the affected part (Molini and Bianchi 2014).

Neovascularity is readily identified using Doppler ultrasound, and the lack of it is a useful negative sign. Chronic enthesopathy may persist in its morphological changes (thickening, enthesitis and echo pattern change within the tendon). These signs may be present long after the symptoms have settled. However, neovascularity is a sign of a relatively subacute to chronic active lesion and related to pain symptoms.

Ultrasound examination is a very useful test in the assessment of the intermetatarsal space. Careful examination looking for mass lesions in this location will detect readily small and of course large Morton's neuroma (fibroma). The significance of these lesions is often clinically debatable as some, usually smaller ones, are asymptomatic. Therefore, palpation and assessment of symptoms by performing the Mulder's test, a plantar-sided ultrasound examination during lateral squeeze test at the level of metatarsal heads, are useful. A bursal fluid collection in the intermetatarsal space is often associated with neuroma and may occur in isolation. During Mulder's test, a neuroma appears at the plantar side, whilst in bursitis, the fluid is displaced to the dorsal side of the foot. These features are part of the complexity of intermetatarsal pain, but they may be amenable to injection therapy. Ultrasound is particularly useful in guiding injection therapy with Morton's neuroma and intermetatarsal bursitis.

Integrity of the plantar plate may be assessed using dynamic ultrasound. The morphological changes are readily identified, especially using comparison with the opposite normal side. Thickening of ligaments may occur before rupture and can be identified by comparative measurements. In turf toe with volar plate or ligament rupture or elongation, widening of the distance between the base of the first toe and the sesamoid bones during extension is obvious. Ultrasound is particularly useful for assessing joint effusions.

The intertarsal ligaments are Chopart and Lisfranc, and the plantar fascia are readily identified using ultrasound; their integrity and stability are well assessed using this imaging technique.

38.6.4 MRI

MRI is the most generally useful examination in injuries of the foot including acute and chronic injuries. A specific weakness is that it is difficult to identify fracture complexes although the bone oedema will be readily apparent. Therefore, the location of the bone injury is easily identified on MRI, and a normal examination excludes significant bone injury. However, to assess the nature of the fracture and often the need for surgical intervention, conventional radiographs and especially CT are important additional examinations. Fracture fragments may be missed using MRI, and avulsed segments of bone may also be overlooked.

Bone marrow oedema is very easily detected using water-sensitive techniques with fat suppression and in particular the STIR sequence. Bone stress lesions may be apparent in many locations other than the primary site of pain as biomechanical abnormality producing a single stress fracture often affects other parts of the foot. Therefore, in patients with a recognised stress response on conventional radiographs, MRI has an adjunct use in assessing the extent and severity of the biomechanical problems. Bone marrow oedema will persist a long time after symptomatic recovery, and therefore, MRI is less useful in assessing the follow-up of stress injuries. Here, CT is relatively useful as bone infilling of stress fracture defects is an important sign of recovery.

MRI is useful in the assessment of tendons and soft tissues looking for oedema and tendon thickening; however, its resolution is not as high as ultrasound, and therefore, early changes may not be detected. In addition, tendon avulsions or ruptures with retraction may be surprisingly difficult to identify with MRI, particularly as the soft tissue oedema is often very extensive and masks the retracted tendon part. In these circumstances, a combination of MRI and (dynamic) ultrasound is useful. MRI is an effective method of diagnosing Morton's neuroma and intermetatarsal bursitis, however, as ultrasound is equally if not more sensitive and as it is much faster to perform, ultrasound remains the preferred technique.

38.6.5 Nuclear Medicine

Bone scintigraphy is useful in assessing bone response. In patients where MRI shows oedema and there are questions as to whether this is a chronic lesion, which is recovering, or one that is still showing bone activity, bone scintigraphy can be important. Three-phase images, showing increased blood flow and blood pool and increased tracer uptake, are useful in assessing the severity of the neovascularity in an area of bone. As ultrasound cannot assess a neovascularity inside the bone, nuclear medicine remains the only physiological technique for judging bony response. In patients who are recovering from stress injuries of bone, nuclear medicine may be a useful adjunct in the occasional case. However, MRI remains the mainstay of diagnosis in this condition.

In patients with suspected infection and where there is a question mark as to whether they may have a neuropathic joint, bone scintigraphy will be positive in both cases. Bone repair in neuropathic joints and infection will give similar appearances. However, labelled white cell studies are much more specific for infection and may be useful in discriminating conditions where biopsy is inappropriate.

38.7 Future Research

The association between foot deformity and Morton's neuroma intermetatarsal impingement is one that is potentially important in the ageing athletic population. It is unclear at present whether footwear may affect the outcome and morbidity of patients with various foot deformities. Therefore, there is potential for investigation in this area.

Conclusion

Whilst clinical assessment often reaches a fairly short differential diagnosis and may be sufficient in the relatively asymptomatic patient to assess adequately, imaging is often required to provide a definitive diagnosis and predict the necessary measures for early recovery. Imaging is especially useful in the detection of fractures and tendon injuries. In patients with a suspected acute fracture, a conventional radiograph should be the first examination, and if there is any doubt, one can proceed to CT. In patients with chronic injuries, MRI is more likely to be a more encompassing examination showing abnormalities in both bone and soft tissues. However, the fractures may be difficult to detect particularly small avulsion injuries. In patients with tendon injury or rupture, ultrasound is the preferred primary technique, as it will more readily diagnose retraction of tendons using dynamic assessment. Ultrasound is also particularly useful in guiding injection therapy.

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Nuclear Medicine Imaging of Foot Injuries

39

Lenka M. Pereira Arias-Bouda and Frits Smit

Contents

Abstract

In sports medicine, foot disorders present a significant clinical challenge due to the complex anatomy and function of the foot. Injuries are complex involving soft tissue as well as bony structures. Bone scintigraphy is a sensitive technique, which provides essential functional information which correlates better with clinical symptoms and treatment response than anatomical abnormalities. It is a useful tool to detect conditions affecting the bony structures of the foot in an early phase, but can also be helpful in the initial evaluation of soft tissue injuries. MRI though remains better in delineating most soft tissue injuries. The emergence of SPECT-CT has increased the accuracy of bone scintigraphy. This is particularly true for the recently developed hybrid systems, which are capable of

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acquiring high-resolution multislice CT images. Bone SPECT-CT has shown to have incremental value in orthopedic conditions and sports injuries. However, one should be aware of the fact that available evidence concerning the clinical value of bone SPECT-CT in sports injuries in the foot is scarce; especially the specificity of the technique needs to be further elucidated.

Abbreviations

CT	Computed tomography
MRI	Magnetic resonance imaging
MTP	Metatarsophalangeal joint
SPECT	Single-photon emission tomography
SPECT-CT	Single-photon emission tomography-computed tomography

39.1 Introduction

Foot disorders present a significant clinical challenge due to the complex anatomy and function of the foot. In many sports activities, all the forces of the body come together in the foot, often being the only contact point with the ground surface. This is also the reason why in contact sports direct injuries are often more severe. Conditions of the foot are complex including soft tissue problems like sprains, tendinopathies, and plantar plate pathology, as well as bone pathologies like (occult) fractures, osteochondroses, accessory bone syndromes, arthropathy, and bony or fibrous coalition. Besides that, patients with sports injuries often have had previous injuries with or without anatomical abnormalities, making it difficult to distinguish fresh from old injuries.

Since several decades, bone scintigraphy has been used to characterize various types of bone pathology. Bone scintigraphy is a highly sensitive technique, demonstrating radiotracer uptake in an early phase of the pathologic process before the occurrence of anatomical abnormalities. It provides essential functional information, which correlates better with clinical symptoms than anatomical abnormalities (Pagenstert et al. 2009). Three-phase bone scintigraphy also provides information about hyperemia and capillary leakage.

For a long period of time, the use of bone scintigraphy in sports medicine and orthopedics was limited. This was due to several factors such as the evolvement of radiologic techniques over the past three decades especially of magnetic resonance imaging (MRI), lack of guidelines concerning imaging in musculoskeletal diseases, varying experience of sport physicians and orthopedic surgeons with nuclear medicine techniques, and the dependence on local availability of modern hybrid devices as single-photon emission computed tomography-CT (SPECT-CT). With SPECT-CT, we are able to interpret subtle, vague abnormalities on bone scans as specific focal areas of pathology. SPECT-CT has provided new indications for bone

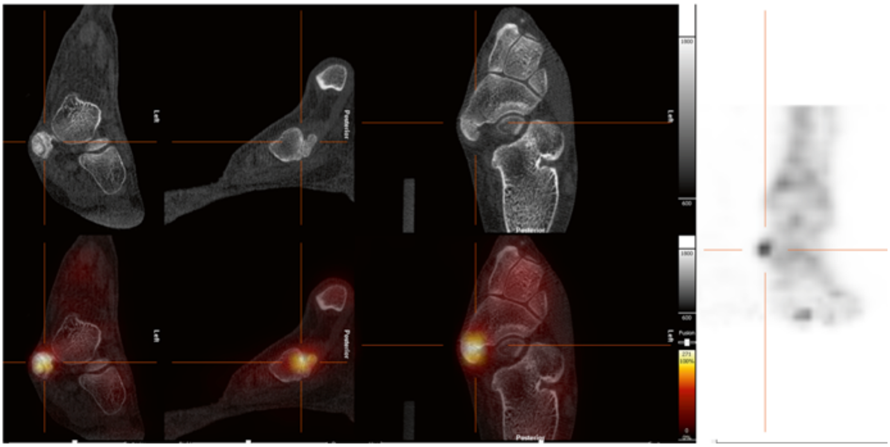

Fig. 39.1 SPECT – (high resolution) CT images (*left* to *right*: transverse, sagittal, and coronal) of the left foot of a 21-year-old female with an os tibiale externum in both feet and a history of fixation of the os tibiale externum at the left side, with persistent pain. SPECT-CT shows high focal activity in the os tibiale externum at the left side, indicative of nonunion. No increased activity is found at the side of the right os tibiale externum (not shown) (Images provided by J. Lavalaye, St. Antonius Hospital Nieuwegein, The Netherlands)

scintigraphy and is increasingly recognized as a promising diagnostic tool in orthopedic conditions (Scharf 2009) and sports injuries (Hirschmann et al. 2011), especially in complex bony structures as the foot and ankle. Recently, hybrid systems capable of acquiring high-resolution multislice CT images have been developed, which will further increase the diagnostic accuracy (Fig. 39.1). With this combined technique, the intrinsic low resolution of the SPECT can be overcome. Available evidence concerning the clinical value of bone SPECT-CT in sports injuries is scarce though and needs to be further investigated.

39.2 Tendinopathies

All tendons in the foot are at risk for tendinopathy due to overuse. Most common tendinopathies in the foot are related to muscles of the lower leg. For instance, overuse of the peroneal and tibial muscle groups can result in tendinopathy in the foot near the insertion (enthesopathy) but also near the ankle because of friction in its fibro-osseous groove between the retinaculum and the bones of the ankle. Examples of frequently involved tendons are the posterior tibial tendon, the peroneal tendon (Fig. 39.2), the flexor hallucis longus tendon, and the anterior tibial tendon. The most common soft tissue injuries of the foot in athletes are Achilles paratendinopathy and insertional Achilles tendinopathy.

The cause of tendinopathy is still not clear. Multiple risk factors, including genetic factors, are implicated in the etiology of soft tissue injuries including Achilles tendon injury (Collins and Raleigh 2009). These injuries are related to

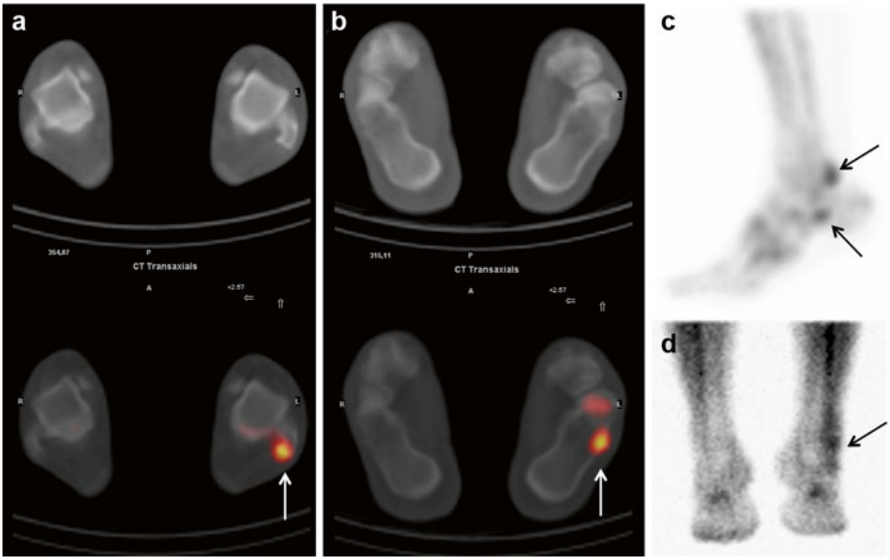

Fig. 39.2 Transverse SPECT-CT images (**a**, **b**), maximum intensity projection (**c**), and planar soft tissue phase images from the anterior (**d**) of a 26-year-old male with pain and swelling at the lateral side of the left ankle. The early images show hypervascularity and increased soft tissue uptake at the lateral side of the left ankle along the anatomical course of the peroneal tendon; SPECT-CT shows focal increased tracer uptake at the posterocaudal side of the lateral malleolus and in the area of the trochlea peronealis calcanei (*arrows*) due to friction between the retinaculum and the calcaneus, suggestive of peroneal tendinitis

relative overuse (Tan and Chan 2008), secondary to an imbalance between intensive training leading to repetitive mechanical and chemical microtrauma and (inadequate) recovery leading to a breakdown in tissue reparative mechanisms (Cosca and Navazio 2007). Eventually, this may result in the formation of ectopic bone deposits in tendon tissue. Although acute injury may lead to true tendinitis, histopathologic studies have shown that overuse tendinopathies are degenerative rather than inflammatory (Cosca and Navazio 2007). The histopathological findings in athletes with overuse tendinopathies are consistent with those in tendinosis, which is a degenerative condition of unknown etiology (Khan et al. 1999). Tendinopathy is a clinical diagnosis. Additional imaging may be conducted to validate the diagnosis. In heel pain, lateral X-rays of the foot may show a Haglund's deformity, which is an enlargement of the posterosuperior prominence of the calcaneus, frequently associated with insertional Achilles tendinopathy. However, Kang and coworkers showed in a retrospective radiographic review of 44 patients with insertional Achilles tendinopathy that a Haglund's deformity was not indicative of insertional Achilles tendinopathy and was also present in asymptomatic patients (Kang et al. 2012). Three-phase bone scintigraphy may be helpful in confirming the diagnosis. In tendinopathy, increased activity in the early phase is seen because of hyperemia, related to angiogenesis at the tendon and/or to a secondary inflammatory reaction during active resorption of the calcific deposit. In the delayed phase, bone scintigraphy shows increased uptake at the insertion of the tendon (Fig. 39.3).

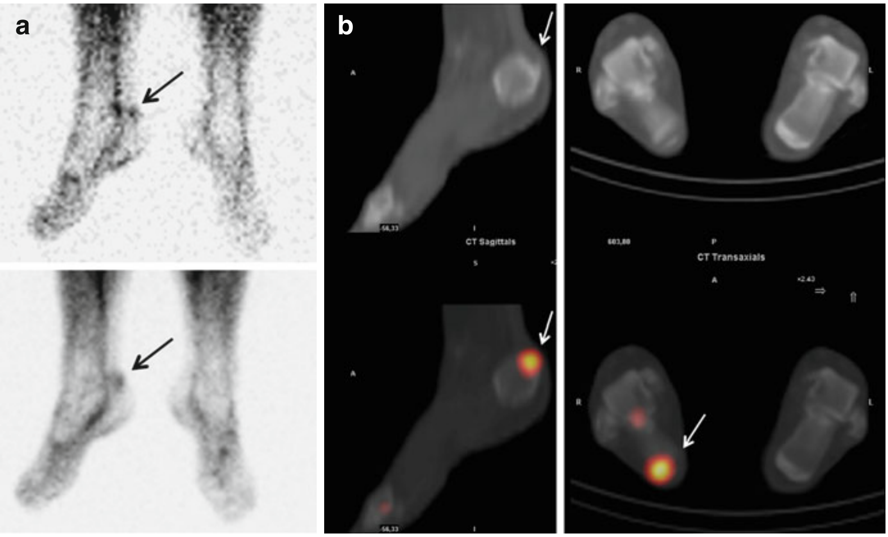

Fig. 39.3 Early images (**a**, vascular phase (*upper*) and soft tissue phase (*lower*)) and SPECT-CT (**b**) with a sagittal image of the right foot (*left*) and a transverse image of both feet (*right*) of a 70-year-old female with pain at the dorsal side of the right heel. The early images show focal hypervascularity and increased soft tissue uptake at the dorsal side of the right calcaneus (*arrow*); SPECT-CT shows a Haglund's deformity at the right side and focally increased bone activity at the insertion of the tendon (*arrow*)

39.3 Plantar Fasciitis

Plantar fasciitis is thought to result from microtrauma of the plantar fascia related to overuse. As in tendinopathy, histological studies show no evidence of inflammation but the characteristics of a fasciosis (Lemont et al. 2003; Cutts et al. 2012). A better definition for this condition is plantar enthesophytosis or inferior calcaneal enthesophytosis. However, the fact that many patients react to local corticosteroid injections or oral anti-inflammatory drugs suggests that inflammation may play a role in a subgroup of patients, possibly triggered by the microscopic tears in the plantar fascia (Woolnough 1954; Cutts et al. 2012).

As is the case with tendinopathy, plantar fasciitis is a clinical diagnosis, which can be supported by additional imaging. Plain lateral radiographs may show a calcaneal spur. Studies have demonstrated a significant association between plantar fasciitis and calcaneal spur formation: a calcaneal spur is present in 85–89 % and 32–46 % of patients with plantar fasciitis and controls, respectively (Osborne et al. 2006; Johal and Milner 2012). But it is not clear whether this association is causal; the spur is not related to the plantar fascia and is the attachment of the quadratus plantae muscle. So, the heel spur could represent an unrelated incidental finding. Osborne and coworkers demonstrated that the key radiological features that differentiate patients with plantar fasciitis from controls were not spurs but rather changes in the soft tissues like plantar fascia thickness and fat pad abnormalities (Osborne et al. 2006), which can be measured by ultrasonography (Kane et al. 2001).

Three-phase bone scintigraphy shows (focal) hyperemia and a focal accumulation anteromedially in the calcaneus in patients with plantar fasciitis. Ultrasonography and bone scintigraphy have shown to be equally effective in the diagnosis of plantar fasciitis (Kane et al. 2001). Frater and colleagues demonstrated that especially focal hyperemia in the early phase of bone scintigraphy seems to correlate well with response to treatment (Frater et al. 2006).

39.4 Sprains

In sports activities, direct or indirect trauma can result in all kinds of sprains. Most sprains involve the ligaments of the ankle and not the foot. Sprains involving ligaments of the foot are, for example, located in the midfoot and in the first metatarsophalangeal joint (see Sect. 39.5). In the situation that these sprains are the only trauma, three-phase bone scintigraphy will show hyperemia in the early phases and almost no activity in the third phase, except discrete diffuse uptake due to the hyperemia. In more severe sprains, the bone in the adjacent joints is often also traumatized resulting in bone bruising or even small fractures. This will give rise to focal uptake in the third phase of a bone scan. Examples are the Lisfranc and Chopart injuries (see Sect. 39.7.1).

39.5 Injuries Involving the First Metatarsophalangeal Joint and Hallucal Sesamoids

The sesamoid complex is located centrally and plantar to the first metatarsal head, where the sesamoids are imbedded within the tendon of the flexor halluces brevis. Several injuries and pathologic conditions can involve the hallucal sesamoidal complex and plantar capsular structures of the first metatarsophalangeal joint. The hallucal sesamoids are crucial to normal weight bearing and foot mechanics; during push-off, the complex can transmit loads of more than 300 % of body weight (Dedmond et al. 2006). These high stresses may lead to both acute and chronic pathologies of the hallucal sesamoids, including, stress fracture, avascular necrosis, osteochondral fractures, and chondromalacia. In addition, the abnormal motion range of the metatarsophalangeal joint during sports activities (Riley et al. 2012) can lead to the so-called turf toe injury, a plantar capsuloligamentous sprain of the first MTP joint (McCormick and Anderson 2010).

As the clinical presentation and physical findings of the different pathologic entities may be identical, imaging plays an important role in the diagnostic process and in directing appropriate therapy. Radiographs are often normal in the first six months following onset of symptoms. In contrast, bone scintigraphy is a highly sensitive technique demonstrating radiotracer uptake in an early phase of the pathologic process. The combination with SPECT-CT makes it possible to locate the pathology with high accuracy. The simultaneously acquired functional and anatomical data can clarify the nature of the pathology and distinguish, for example, fractured

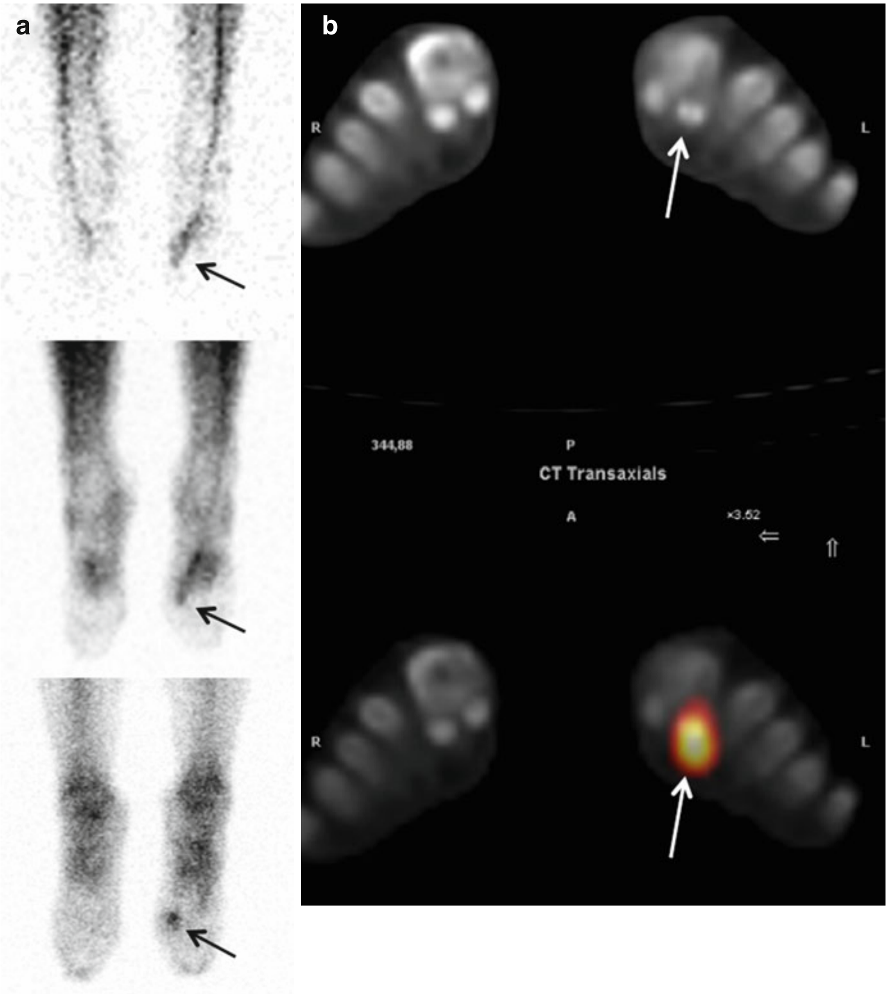

Fig. 39.4 Planar images of the feet from anterior (**a**, vascular phase (*upper*), soft tissue phase (*middle*) and delayed phase (*lower*)) and transverse SPECT-CT image (**b**) of both feet of a 23-year-old female with pain and swelling at the left forefoot. The early images show focal hypervascularity and increased soft tissue uptake in the region of the first metatarsophalangeal joint of the left foot and increased tracer uptake at this site in the delayed phase (*arrows*). SPECT-CT images locate the increased uptake at the lateral sesamoid ossicle (*arrow*); the concomitantly acquired CT shows a fractured lateral sesamoid

sesamoids from other causes of sesamoid pathology or even an anatomical variant (Fig. 39.4). One should be aware of the fact that tracer uptake in the first metatarsophalangeal joint is frequently observed in asymptomatic patients with beginning, age-related arthrosis (O'Duffy et al. 1998). Although the intensity of uptake in such cases is usually mild, the specificity of the bone SPECT abnormalities in this area needs to be further elucidated.

MRI offers little in the direct evaluation of sesamoid pathology, but may be helpful in differentiating sesamoid pathology from other conditions affecting the hallucal sesamoid complex such as plantar plate injury, since it can better delineate soft tissue injuries in this complex region of the foot (Sanders and Rathur 2008; Mohan et al. 2010). Bone SPECT-CT may be helpful in the initial evaluation of turf toe injuries, but MRI is the method of choice in grading the extent of plantar plate injury (Sanders and Rathur 2008).

39.6 Tarsal Coalition

Tarsal coalition is a condition in which there is an abnormal bony or fibrous bridging across two or more tarsal bones, most frequently concerning calcaneonavicular and talocalcaneal fusions. These abnormal connections cause abnormal stress on the hindfoot, resulting in painful deformity of the hindfoot with restricted motion. Due to varying projection angles, plain radiographs may not be sufficient for thorough evaluation of a complex subtarsal coalition, and false-negative and false-positive findings with radiographs can occur (Scharf 2009). MRI and CT are considered to be the gold standard techniques (Newman and Newberg 2000), but are not able to differentiate between asymptomatic and symptomatic joints (De Lima and Mishkin 1996; Scharf 2009). Bone scintigraphy with SPECT-CT is superior to CT alone because of the addition of supplementary functional information, demonstrating the location of the stress forces on this abnormal connection between the bones (Fig. 39.5). This information may be helpful in further decision-making as in guiding intra-articular injections (Mohan et al. 2010).

39.7 Stress Fractures

Stress fractures in athletes concern fatigue fractures caused by unusual, repeated physical activity, which initiates focal bone remodeling and results in failure of the bone. Stress fractures can be classified as at-risk or less critical fractures according to their location and relative importance in clinical treatment (McBryde 1995). Most stress fractures in the foot are found in the metatarsal bones. Less common are the tarsal navicular bone, talar body (Rossi and Dragoni 2005), calcaneus, and sesamoids. Especially fractures of the navicular bone and second and fifth metatarsals require additional treatment because of tendency to develop delayed union or non-union. In the majority of stress fractures, there is no obvious abnormality on plain radiographs because of the lack of dislocation. Bone scan and MRI have demonstrated high sensitivity in identifying early stress injury (Rupani et al. 1985; Ammann and Matheson 1991; Sijbrandij et al. 2002). The three-phase bone scan shows focal hyperemia, increased soft tissue uptake, and a sharply delineated focal area of increased uptake in the involved bone in an early stage of accelerated

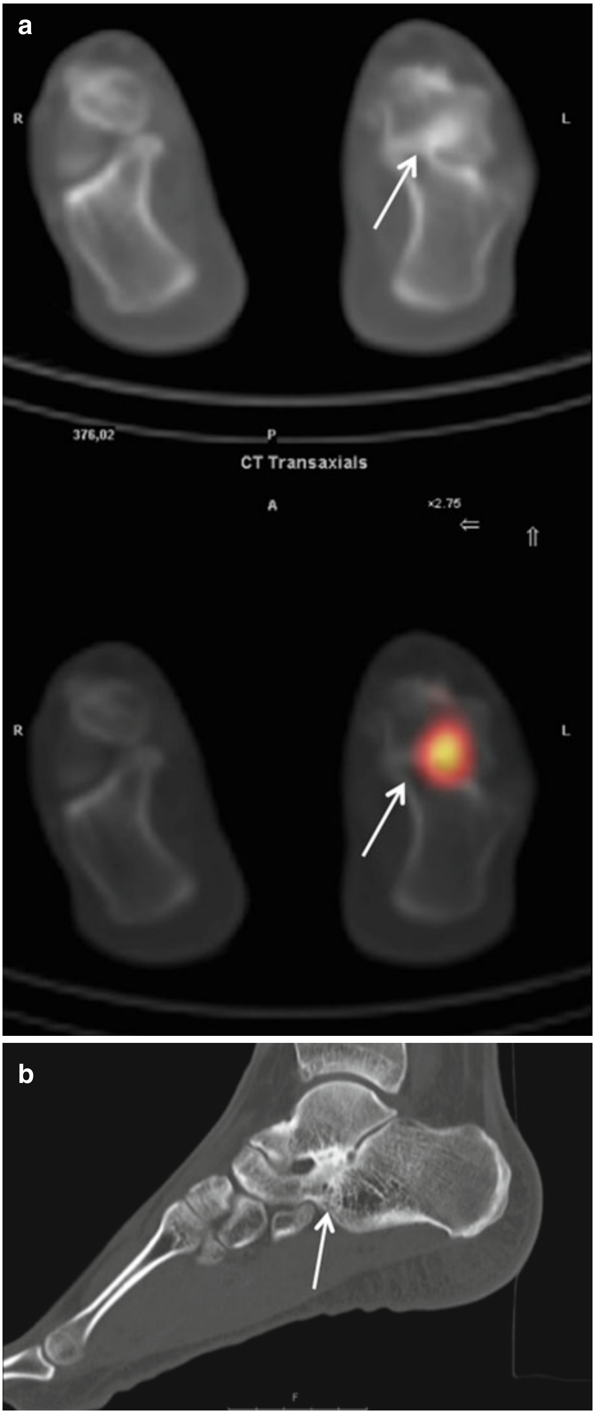

Fig. 39.5 Transverse SPECT-CT images of both feet (**a**) and sagittal high-resolution CT image (**b**) of the left foot of a 31-year-old male who complained of persistent pain in the left foot and heel. Plain radiographs showed mild degenerative abnormalities in the talonavicular joint (not shown). SPECT-CT reveals the presence of a bony coalition between the talar and calcaneal bone and also a bony coalition between the calcaneal and navicular bone, which was confirmed with high-resolution CT. The focally increased tracer uptake on the SPECT-CT images (*arrow*) demonstrates the location of the stress forces on this abnormal connection between these bones

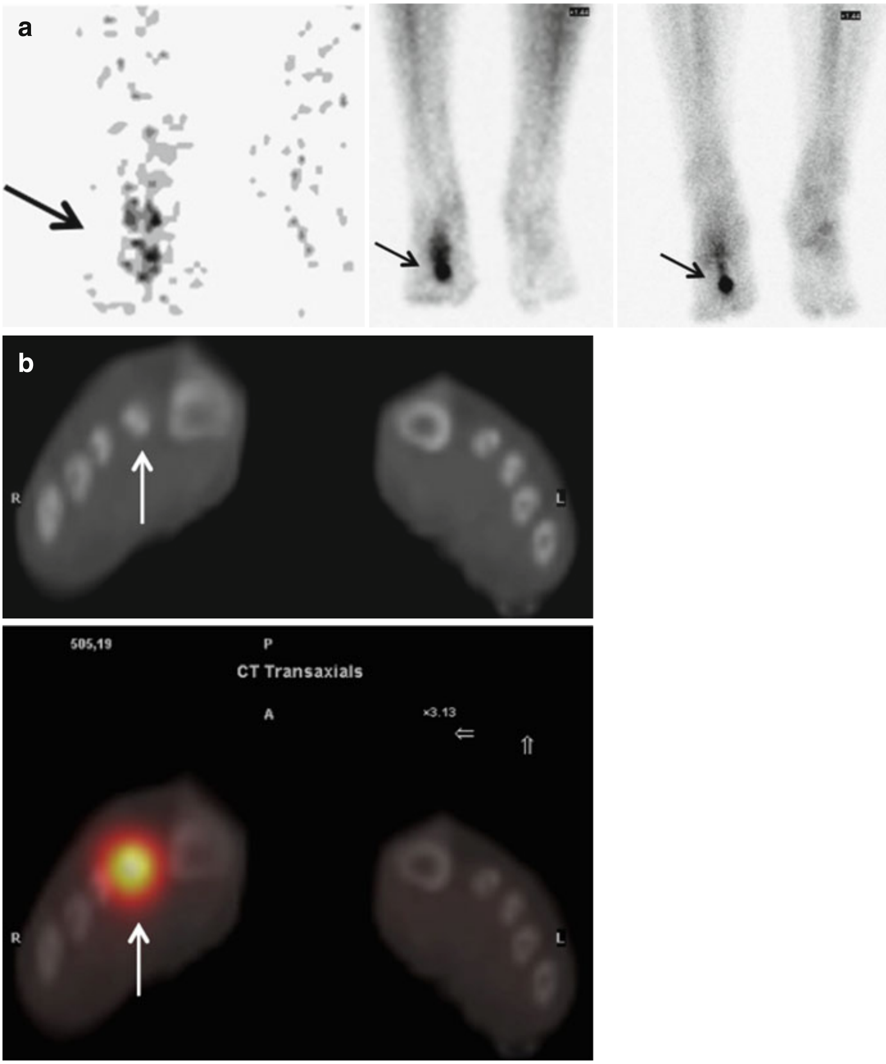

Fig. 39.6 62-year-old female with forefoot pain at the right side. Plain radiographs showed no specific abnormalities (not shown). Three-phase bone scintigraphy (**a**, with vascular phase (*upper*), soft tissue phase (*lower left*), and delayed phase (*lower right*) from anterior) and SPECT-CT (**b**) show focal hypervascularity, focally increased soft tissue uptake and bone uptake in the distal second metatarsal bone at the right side (*arrows*), indicative of a stress fracture

remodeling (Fig. 39.6). SPECT-CT is helpful in locating the injury and to distinguish a stress reaction from a stress fracture (Brukner and Bennell 1997). The role of SPECT-CT could become even more prominent since it has been suggested that the earliest finding of abnormal repetitive stress may be osteopenia, which can only be demonstrated by high-resolution CT imaging (Gaeta et al. 2005).

As mentioned before, one of the difficult challenges in evaluating patients with sports injuries is that many have had previous injuries, the age of which may be difficult to determine. Bone scintigraphy can be used to age fractures or stress injuries. When combined with SPECT-CT, details of complicated combinations of old and new injuries can be sorted out (Scharf 2009). In addition, Dobrindt and coworkers suggested that bone scintigraphy could be a reliable method for predicting healing time of stress injuries: in their study, the healing time of scintigraphic high-grade injuries was significantly longer than of scintigraphic mild stress injuries (Dobrindt et al. 2011).

39.7.1 Lisfranc and Chopart Injuries

Midfoot fractures can easily be missed clinically and radiographically because of their rarity; Chopart joint injuries are extremely rare, and Lisfranc joint injuries are uncommon (Vuori and Aro 1993). Lisfranc injuries include fractures and fracture dislocations of the tarsometatarsal joints. Approximately, one third of these injuries are sports related. Standard imaging includes multi-view radiographs, eventually combined with weight-bearing radiographs. However, investigators showed that the injury was occult on initial radiographic images in a significant number of patients with Lisfranc injury (Vuori and Aro 1993). Because of its high sensitivity, bone scintigraphy with SPECT-CT is helpful in the initial evaluation. It shows hyperemia and increased activity in the delayed images at the Chopart or Lisfranc region, characteristic to diagnose the injury. The concomitantly acquired CT may be used to better visualize fracture patterns (Benirschke et al. 2012). Eventually, MRI can be used to evaluate the midfoot soft tissues and to select patients who need to undergo stress examinations (Raikin et al. 2009).

39.8 Osteochondroses and Apophyseal Injuries

Osteochondroses are caused by single or repetitive trauma and vascular compromise leading to subchondral fracture and osteonecrosis. Osteochondroses and apophyseal injuries like Kohler's disease (osteochondrosis of the tarsal navicular bone), Freiberg's infraction (involving the metatarsal heads), and Sever's disease (calcaneal apophysitis) are the most common skeletal foot injuries in young athletes (Gillespie 2010). Osteochondroses affect children and adolescents, and radiographic images of the foot may be difficult to interpret at these ages. The bone scan appearances following avascular necrosis are initially reduced tracer uptake due to diminished blood supply. Bone scintigraphy shows a photopenic navicular bone in the early phase of Kohler's disease and therefore is useful in the early diagnosis (Groshar et al. 1998). In the revascularization phase of osteochondroses, the three-phase bone scan shows hypervascularity and increased soft tissue uptake together with focal increase in activity in the involved bone (Fig. 39.7). In Sever's disease, radiographs are often normal. The three-phase bone scan shows hyperemia, increased soft tissue uptake, and increased activity at the apophysis in the delayed phase, correlating to bone remodeling.

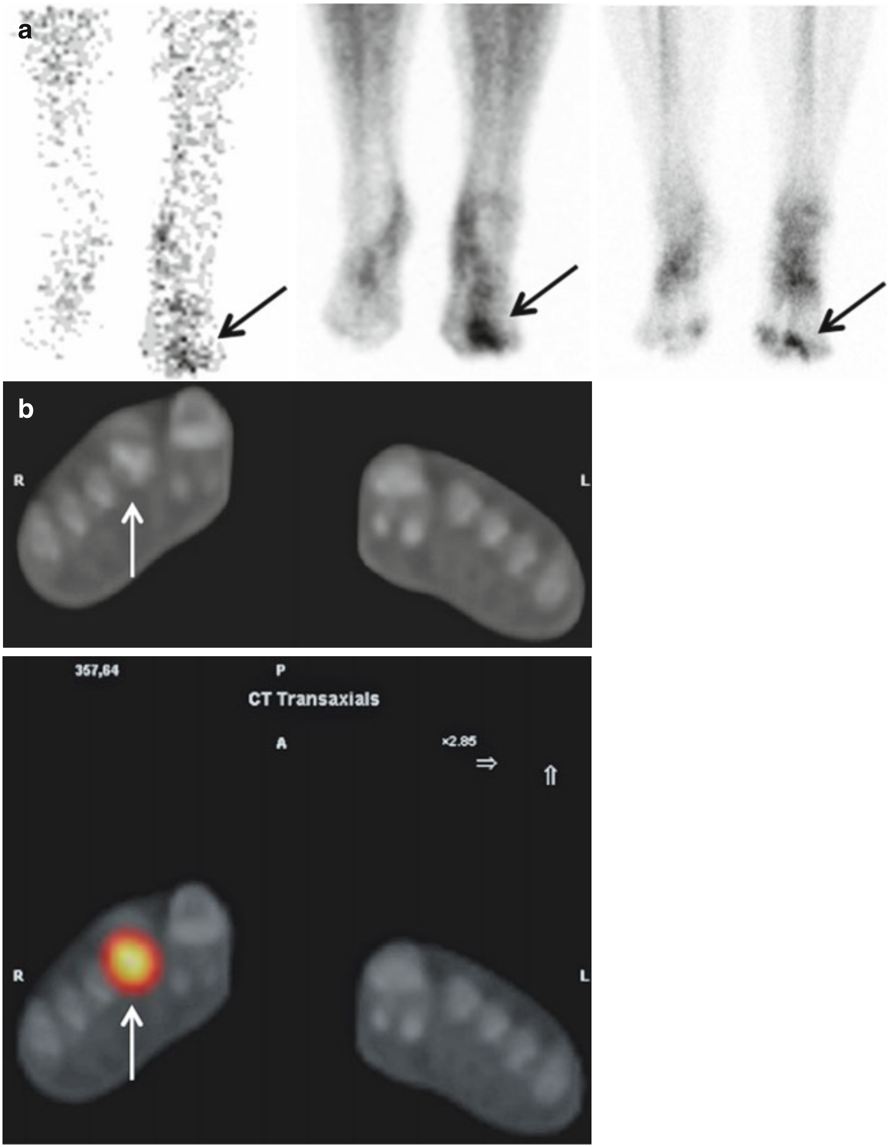

Fig. 39.7 24-year-old female with persistent pain in the right forefoot. Plain radiographs showed no abnormalities (not shown). Three-phase bone scintigraphy (**a**, with vascular phase (*upper*), soft tissue phase (*lower left*), and delayed phase (*lower right*) from anterior) and SPECT-CT (**b**) show hyperemia, increased soft tissue uptake, and focally increased tracer uptake in the head of the second metatarsal bone at the right side with sclerosis on CT (*arrow*), suggestive of Freiberg's infraction

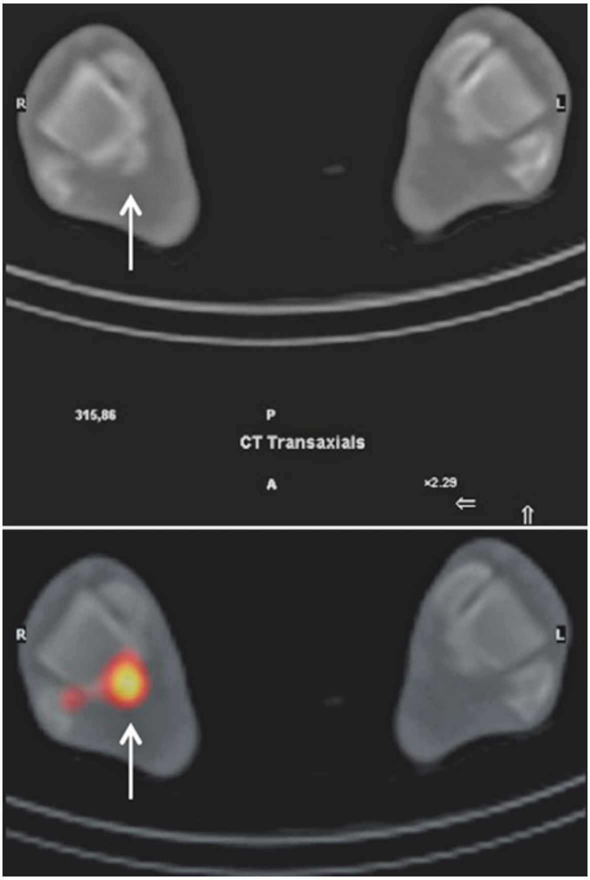

Fig. 39.8 Transverse SPECT-CT image of the ankle area of both feet. This 28-year-old male complained of pain at the dorsal side of both feet. Plain radiographs showed an os trigonum at both sides (not shown). SPECT-CT images show increased tracer uptake in the os trigonum on the *right side* (*arrow*). In contrast, no increased uptake is found in the os trigonum on the *left side*

39.9 Accessory Bone Syndromes

Accessory bones such as os trigonum, os tibiale externum, and os supratalare are common entities in the foot. These normal variants sometimes lead to chronic pain due to trauma, degeneration, or soft tissue inflammation. Bone SPECT-CT is a valuable technique for localization of the pathology and differentiation of the cause of the pain. The os trigonum syndrome is related to an accessory bone at the posterior margin of the talus; Johnson and coworkers postulated that abnormal tracer uptake on the delayed images (Fig. 39.8) may be helpful in the decision regarding removal of the ossicle (Johnson et al. 1984). Accessory tarsal navicular bones (also called os tibiale externum), situated adjacent to the medial and posterior margins of the tarsal navicular, are part of the insertion of the tendon of the posterior tibial muscle and have been studied with bone scanning and MRI (Sella et al. 1986; Romanowski and Barrington 1992; Mosel et al. 2004). Symptomatic ossicles show increased radiotracer uptake or marrow edema across the synchondrosis. Although sensitivity in symptomatic patients is high (Romanowski and Barrington 1992; Chiu et al. 2000), it has been reported that a significant number of asymptomatic accessory navicular bones also show increased uptake (Chiu et al. 2000; Mosel et al. 2004).

39.10 (Secondary) Degenerative Joint Disease

It is well-known that in osteoarthritis of the knee, the pattern and intensity of tracer uptake on bone SPECT correlate well with pain and could be useful for determining the clinical severity of osteoarthritis (Kim et al. 2008). Pagenstert and coworkers evaluated 20 consecutive patients with pain of uncertain origin in the foot and ankle by radiography and SPECT-CT. They found excellent intraobserver reliability and a significantly higher interobserver agreement for SPECT-CT in identifying active osteoarthritis than for any other imaging modality. They concluded that SPECT-CT is useful in localizing active arthritis, especially in complex bony structures (Pagenstert et al. 2009). One should keep in mind though that especially in the midfoot and first metatarsophalangeal joint, functional abnormalities can be found in asymptomatic patients (O'Duffy et al. 1998), and their presence in the setting of the symptomatic patient should be interpreted with caution.

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Part XIII

General Chapters

Specific Issues in Adolescent Athletes Involved in Jumping Sports Including Length Prediction Methods

40

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Abstract

An increasing number of children are becoming involved in competitive sports. More young athletes are becoming exposed to high and/or repetitive load training. As more children participate in sports, there is an increase in overuse injuries. The immature musculoskeletal system is less able to cope with repetitive biomechanical stress; the growing cartilage is more vulnerable to stresses with disorders of the developing growth plate and surrounding ossification centers (apophyses) as a result. We focus on the overuse injuries in jumping sports of the lower extremity (knee and calcaneus). Girls are generally affected with overuse apophysitis at a younger age compared to boys. It is hypothesized that the stage of the apophyseal ossification determines the most vulnerable period. This would suppose that the vulnerable period is best determined by the bone age and not by the calendar age of the youngster. Bone age also defines the residual growth capacity of children; in specific sports, high stature is requested. Prediction of adult height in adolescent basketball and volleyball players may be requested to select talented children that want to enroll to a talent academy to practice basketball or volleyball. The Greulich and Pyle method based on an X-ray of the hand is the system most frequently used and discussed in literature for assessing bone age and calculating adult height. The BoneXpert computerized system automatically determines bone age by the Greulich-Pyle method and automatically predicts adult height of a child. Other techniques are not so often discussed in literature. Two different multi-predictor methods are published for use in adolescent boys and girls providing an accurate estimation of adult height without calculation of bone age and without exposure to radiation.

Abbreviations

s	Second
BA	Bone Age
CA	Calender Age
DXA	Dual-Energy X-Ray Absorptiometry
G and P	Greulich and Pyle
OS	Osgood Schlatter
SLJS	Sinding Larsen Johansson Syndrome
TW	Tanner-Whitehouse

40.1 Introduction

An increasing number of children are becoming involved in competitive sports. More young athletes are becoming exposed to high and/or repetitive load training. As more children participate in sports, there is an increase in overuse injuries. The immature musculoskeletal system is less able to cope with repetitive biomechanical stress; the growing cartilage is more vulnerable to stresses (Dupuis et al. 2009) with osteochondrosis as a result. We use the term osteochondrosis to describe the group of disorders of the developing growth plate and surrounding ossification centers (apophyses). The result of biomechanical stress is a traction apophysitis due to the repetitive strain on the secondary ossification center (Gholve et al. 2007). The most common sites of these injuries at the knee are the tuberositas tibiae and apex patellae (Osgood Schlatter (OS) and Sinding-Larsen-Johansson disease, respectively), at the heel at the tuber calcanei (Sever's disease), and at the elbow at the level of the epicondylus medialis (little league elbow) (Adirim and Cheng 2003). Other areas are the spina iliaca anterior inferior (origin of the straight head of the rectus femoris muscle), pubic bone apophysis at the adductor longus origin, and the tuber ischiadicum at the hamstrings origin. We focus on the overuse injuries in jumping sports of the lower extremity (knee and calcaneus). The population-based prevalence of OS was calculated in Brazilian adolescents by de Lucena et al. at 9.8 % (11.0 % of boys and 8.3 % of girls; boys, 13.5 ± 1.07 years; girls, 13.6 ± 1.01 years) (de Lucena et al. 2011). Prevalence of osteochondroses in childhood and adolescent soccer players calculated at 75.5 % by Suzue et al., Osgood Schlatter being the most frequent (43.5 %), Sever's disease and patella bipartita second most frequent (11.5 %), and Sinding Larsen Johansson third most frequent at 9 %; osteochondritis dissecans of the distal femur and spondylolysis were encountered rarely (Suzue et al. 2014).

40.2 Osgood-Schlatter Disease

Osgood-Schlatter disease is a traction apophysitis of the tibial tuberosity caused by repetitive strain from the quadriceps muscle on the secondary ossification center (Nakase et al. 2014). It involves the tibial tuberosity in growing children and presents with local pain, swelling, and tenderness of the tuberosity. Symptoms can be aggravated by sporting activities that involve jumping (basketball, volleyball, running, soccer) and by direct contact (kneeling). The common age of presentation is between 12 and 15 years in boys and from 8 to 12 years in girls (Gholve et al. 2007), although several articles mention other ages. The disease is more frequent in boys than girls, but girls are more and more involved (Ehrenborg 1962). Osgood-Schlatter frequently presents bilaterally (20–30 %) (Bloom et al. 2004; Wall 1998).

40.2.1 Etiopathogenesis

Repeated tensile extension forces are applied to the weak apophyseal cartilage of the tibial tuberosity resulting in avulsion of the secondary ossification center (Ogden et al. 1976). The repetitive strain is from the strong pull of the quadriceps muscle produced during sporting activities. It is confirmed that quadriceps tightness increases with tibial tuberosity development (Nakase et al. 2014). The increased stress exerted on the tibial tubercle may result in a partial avulsion fracture through the ossification center. Once the avulsed portion is pulled away, the cartilage or bone may continue to grow, ossify, and enlarge; this is called reactive secondary heterotopic bone formation (Dupuis et al. 2009). This results in a visible and painful bump, the main physical finding in Osgood-Schlatter disease. This ethiopathogenetical theory is generally supported today. Formerly, it was thought that the small particles of necrotic bone resulted from mechanical separation or from avascular necrosis.

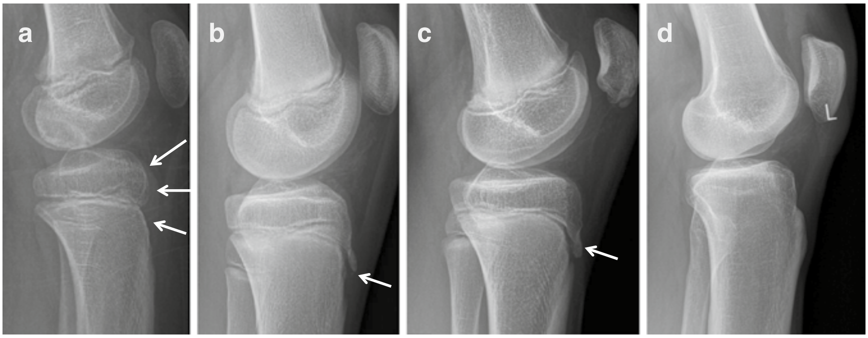

Fig. 40.1 Radiographic ossification and fusion of the tibial tuberosity, lateral radiographs of four different male individuals. (**a**) Eight-year-old boy, no ossification is detected at the tibial tuberosity (*arrows*). (**b**) 14-year-old boy, tongue-like ossification of the tibial tuberosity with small loose-calcified part (*arrow*). (**c**) 15-year-old boy, tongue-like ossification of the tibial tuberosity without loose-calcified parts. (**d**) 23-year-old adult male, ossification of the growth plate with fusion of the tibial tuberosity

40.2.2 Skeletal Maturation of the Tibial Tuberosity

The tibial tuberosity arises from an apophysis which begins to ossify at the ages of 8–10 years. The process starts earlier in girls than in boys. It develops as an anterior extension of the proximal tibial physis (Fig. 40.1a). In the first stage, a small tongue of ossification projects inferiorly from the anteroinferior edge of the proximal tibial epiphysis (Fig. 40.1b). Between the ages of 10–12 years, the tongue of ossification extends distally. One or more separate centers of ossification in the distal portion of the apophysis may arise. Between the ages of 12–14 years, the centers of ossification fuse, and the proximal tibial epiphysis and the tibial apophysis become continuous (Fig. 40.1b, c). Between the ages of 14–16 years, the line of separation between the epiphysis and apophysis is slowly obliterated, and they fuse into a solid whole (Fig. 40.1d). There is no consensus about the age of closing. Another article mentions the age of 13–15 years in girls and 15–19 years in boys of bony fusion of the epiphysis and apophysis (Dupuis et al. 2009). The apophysis of the tibial tuberosity is composed of fibrocartilage with greater tensile strength, this in contrary than the usual columnar cartilage of other physes. As a result, it better tolerates the great stress placed on it by the musculus quadriceps femoris via the patellar tendon. As the tibial tubercle matures, the tibial apophysis ossifies, and the fibrocartilage gradually is replaced by the relatively weaker columnar cartilage. The result is a greater risk of fracture of the tubercle. The skeletal maturation of the tibial tuberosity is examined using ultrasonography (Nakase et al. 2014). This study defined an ultrasonographic classification referred to by the Ehrenborg classification. They classified the skeletal maturation of the tibial tuberosity into three stages. First stage is the *sonolucent* stage, characterized by a large amount of apophyseal cartilage. Next is the *individual* stage, characterized by apophyseal cartilage with an individual ossicle. Last is the *connective* stage, characterized by a connection of the secondary ossification and tibial epiphysis (Nakase et al. 2014). Another classification of the ultrasound appearance of the patellar tendon attachment also defines three stages. Stage one is the *cartilage attachment* (Fig. 40.2a),

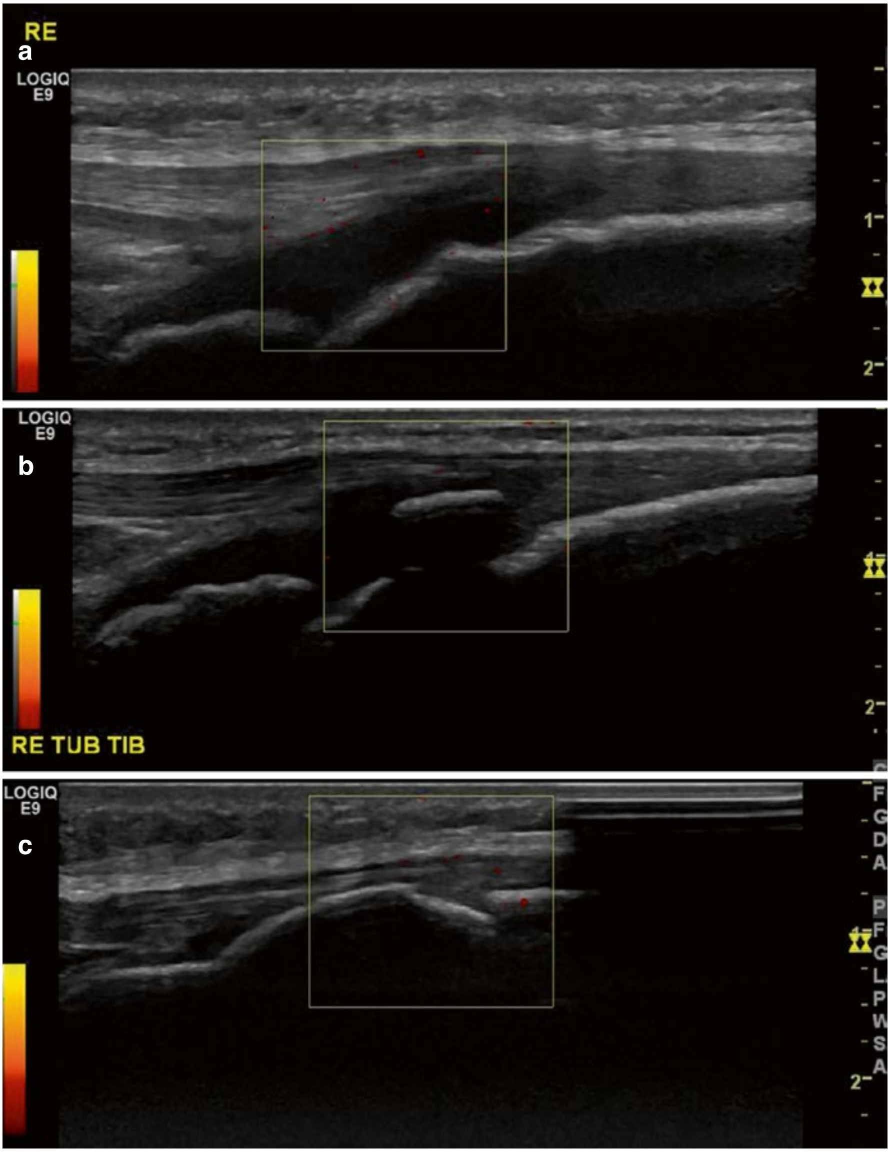

Fig. 40.2 Ducher ultrasound classification of osteochondrosis. (**a**) Cartilage attachment, characterized by a large amount of apophyseal cartilage and anechoic appearance without interspersed ossicles, with ultrasonographic band-like echogenic structures. (**b**) The second stage is the insertional cartilage, characterized by a progressive attachment of the collagen fibers onto the bone surface. A thin layer of cartilage is still visible, and the apophyseal surface appears smoother. (**c**) The third stage is the mature enthesis, characterized by a complete attachment of the collagen fibers onto the bone surface

characterized by a large amount of apophyseal cartilage and anechoic appearance without interspersed ossicles, with ultrasonographic band-like echogenic structures. The second stage is the *insertional cartilage* (Fig. 40.2b), characterized by a progressive attachment of the collagen fibers onto the bone surface. A thin layer of cartilage is still visible, and the apophyseal surface appears smoother. The third stage is the *mature enthesis* (Fig. 40.2c), characterized by a complete attachment of the collagen fibers onto the bone surface. Apophyseal cartilage is barely visible anymore (Ducher et al. 2010a and b). These ultrasonographic features of the patellar tendon insertion to the tibia during growth are consistent with the observations made at the Achilles tendon insertion (Grechenig et al. 2004). Still another classification by Ehrenborg and Engfeldt is radiographic and exists of four stages. First is the cartilaginous stage between 0 and 11 years, second the apophyseal stage between 11 and 14 years, third the epiphyseal stage between 14 and 18 years, and last the bony stage, when the epiphysis is fully fused after 18 years (Ehrenborg 1962). Studies suggest that Osgood-Schlatter disease is caused by overuse in the period from the *individual stage* to the *connective stage* or in the *apophyseal stage* in the Ehrenborg classification (Nakase et al. 2014).

40.2.3 Clinical Features

Pain at the knee is mild and intermittent, although in the acute phase, it can be severe and continuous in nature. Pain exacerbates after sporting activities involving jumping (basketball, volleyball, running) or on direct contact (kneeling) (Flowers and Bhadreshwar 1995). Physical examination usually finds tenderness directly over the area of the tibial tuberosity and local swelling. The pain can be reproduced with extension of the knee against resistance. Once the acute phase heals, the pain and tenderness subside, and the only positive physical finding may be an anterior mass. Most studies claim spontaneous resolution and self-limiting nature of the symptoms with recovery expected in about 90 % of the patients. In approximately 10 % of the patients, the symptoms continue unabated into adulthood, despite conservative treatment (Gholve et al. 2007).

40.2.4 Incidence and Prevalence

Osgood-Schlatter disease affects approximately one in five adolescent athletes (Hogan and Gross 2003). It is more prevalent in males than females. However, more and more girls are affected, because over the years more girls are participating in sports and girls become taller, so they have a growth spurt equally like boys. Osgood-Schlatter is seen in males between 12 and 15 years and in females between 8 and 12 years of age, although other studies mention other ages for girls, between 11 and 13 years of age (Duri et al. 2002). The difference in age is due to the earlier onset of puberty and the associated earlier epiphyseal plate closure (Gholve et al. 2007). The condition is more common in patients that experience a rapid growth during adolescence (Vreju et al. 2010). It frequently presents bilaterally 20–30 % (Bloom et al. 2004; Wall 1998).

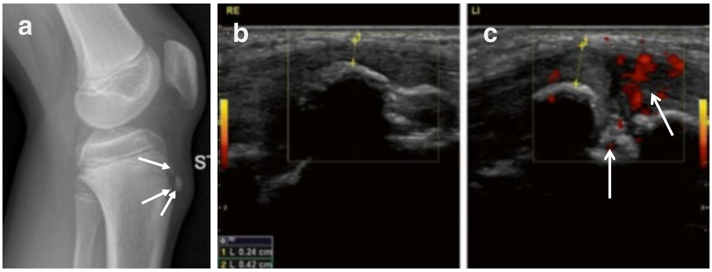

Fig. 40.3 Radiograph and ultrasound of Osgood-Schlatter disease. Thirteen-year-old boy with chronic pain at the left tuberositas tibiae. (**a**) Lateral radiograph of the left knee shows soft tissue swelling at the tuberositas tibiae with fragmentation of the ossifications at the tuberositas tibiae (*arrows*). (**b**) Ultrasound midsagittal imaging plane at the level of the normal right tuberositas tibiae and (**c**) of the left tuberositas tibiae showing soft tissue thickening in front of the tuberositas and angiogenesis at the noncalcified parts (*arrows*)

40.2.5 Diagnosis

The diagnosis is mostly made clinical, but imaging methods are often used to confirm it. Plain radiographs of the knee are recommended in all unilateral cases of Osgood-Schlatter disease to rule out other conditions such as acute tibial apophyseal fracture, infection, or tumor. A lateral view of the knee with the leg internally rotated 10–20° shows irregularity of the apophysis with separation from the tibial tuberosity in early stages and fragmentation in the later stages (Fig. 40.3). A persistent bony ossicle may be visible in a few cases after fusion of the tibial epiphysis (Gholve et al. 2007). The isolated appearance of an irregular ossification center in the absence of surrounding inflammatory changes is a normal development variant and should not be the only criterion used to make the diagnosis (Dupuis et al. 2009).

MRI may assist in the diagnosis of an atypical presentation. The role in the diagnosis is currently limited. On MRI, the normal infrapatellar tendon appears as a homogeneous band of low-signal intensity on all sequences. Hirano et al. studied the MRI appearance of Osgood-Schlatter. They proposed five stages of the disease on MRI: normal, early, progressive, terminal, and healing stage. In the normal stage, the MRI scan is normal although the patient has developed symptoms. The early stage does not reveal any MRI evidence of inflammation or avulsed portion of the secondary ossification center. There may be edema-like changes around the tibial tuberosity, but a normal MRI is not ruling out early Osgood-Schlatter. In the progressive stage, a partial tear in the secondary ossification center is detected. If the tear is extended, the anterior parts that consist of bone and cartilage are avulsed. The terminal stage is characterized by the presence of separated ossicles (Fig. 40.4). The avulsed part is pulled superiorly and separated completely. The ossicle is formed from this avulsed part. The healing stage shows an osseous healing of the tibial tuberosity without separated ossicles. The intervening region may heal subsequently by fibrocartilage. If the gap is small, the bridge of fibrocartilage may ossify. However, larger gaps may remain,

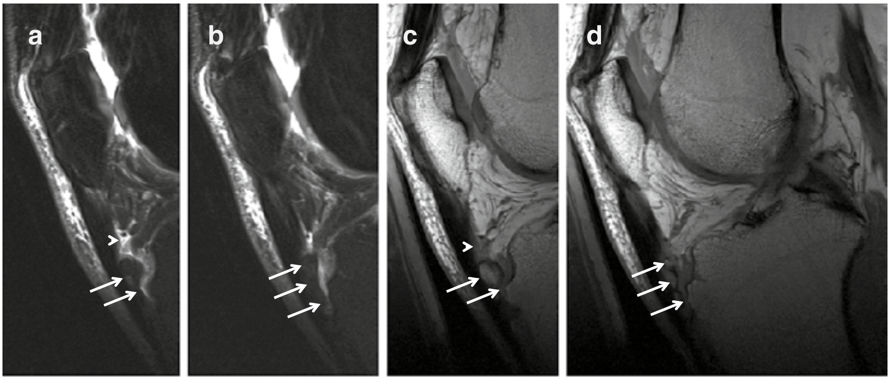

Fig. 40.4 MRI in Osgood-Schlatter disease. Adult, 56 years old, male with long-standing complaints at the right tuberositas tibiae that started during adolescence. Fragmented aspect of the tuberositas tibiae with increased T2 time surrounding the bone fragments (*arrows*), thickening of the distal patellar tendon, and fluid signal at the deep infrapatellar bursa (*arrowheads*). (**a**, **b**) Sagittal intermediate TE with FS and (**c**, **d**) sagittal PD WI. A and C have identical slice position and thickness and (**b**, **d**) have identical slice position and thickness

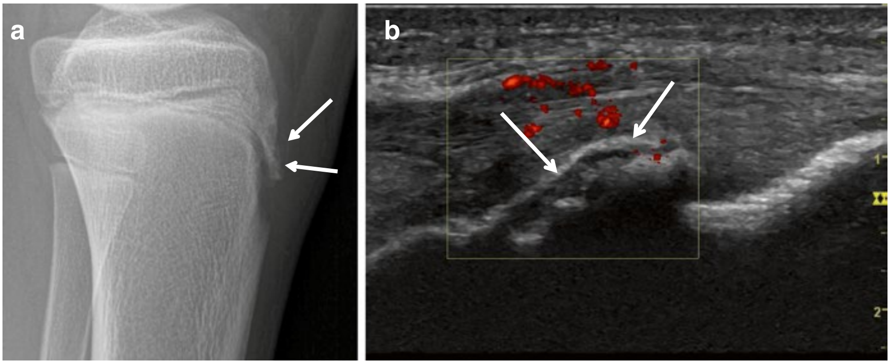

Fig. 40.5 Radiograph and US of Osgood-Schlatter, Igloo aspect. Thirteen-year-old boy soccer player with fracture of the left tuberositas tibiae. Radiographically, (**a**) a shell-like fracture fragment is documented (*arrows*). On ultrasound, (**b**) the shell-like fragment presents like an igloo with shine through of the deeper calcified parts of the tibial tuberosity. The noncalcified parts of the tibial tuberosity are hypervascular on power Doppler ultrasound

with the avulsed fragments maturing to form separated ossicles within the patellar tendon (Hirano et al. 2002; Gholve et al. 2007).

Ultrasonography is more and more used to diagnose Osgood-Schlatter. It has a superior spatial resolution over MRI and provides a rapid, cheap, accessible imaging technique to assess the infrapatellar tendon. On ultrasonography, the parallel tendon fibrils are echogenic. Osgood-Schlatter disease is characterized by pretibial soft tissue swelling, cartilage swelling, fragmentation of the tibial tuberosity's ossification center, thickening at the insertion of the patellar ligament, and inflammation of the deep infrapatellar bursa (Figs. 40.3, 40.5, 40.6 and 40.7). Calcifications are easily detected by ultrasonography compared to MRI. On ultrasonography, Osgood-Schlatter can be divided into three types. Type one is characterized by delamination of the internal ossification center, resulting in an igloo-like deformation of the physeal part of the tibial tuberosity (Fig. 40.5). Other signs are a deep infrapatellar bursitis and/or fibrosis due to a shared arterial supply with the tibial tuberosity, inflammation of the patellar ligament secondary to the main injury and deep infrapatellar bursitis, and a superficial infrapatellar bursitis secondary to deep infrapatellar bursitis or secondary to the main injury. The prognosis of type one is very favorable as it leaves minimal disturbance to the shape of the tuberosity and the state of the patellar ligament. Type two is characterized by a delamination tear or fracture of the epiphyseal part of the tibial tuberosity and a significant anterior displacement of the proximal attachment of the patellar ligament due to the displacement of the fractured cartilage (Figs. 40.6 and 40.7). Other signs are a deep infrapatellar bursitis due to bleeding from the torn cartilage or ossification center, inflammation or fibrosis of the patellar ligament secondary to the main injury and the deep infrapatellar bursitis, and a superficial infrapatellar bursitis secondary to the deep infrapatellar bursitis and the inflammation involving the enthesis zone of

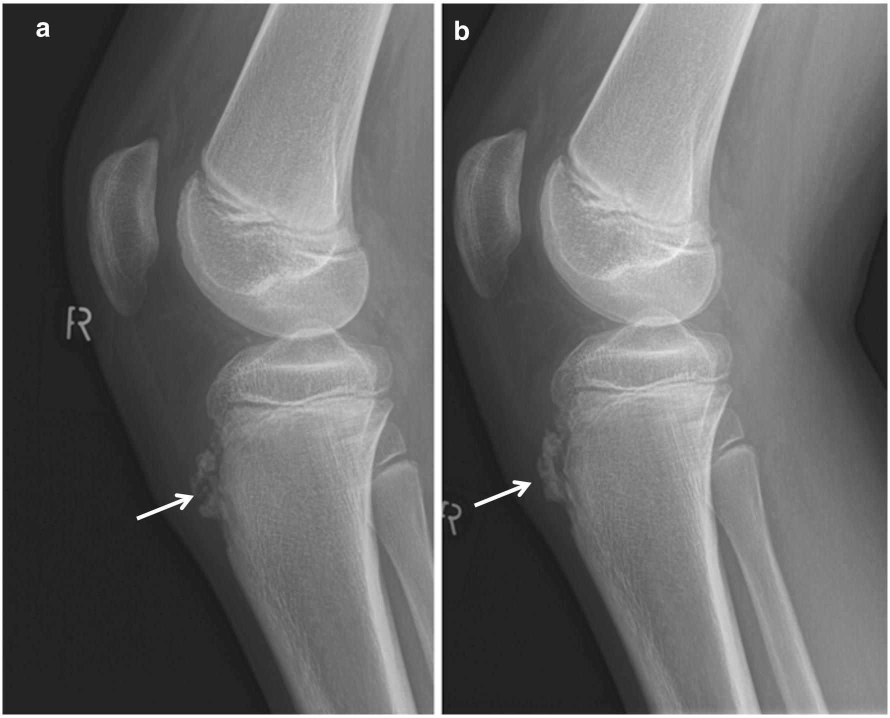

Fig. 40.6 US and radiograph of Osgood-Schlatter disease. Boy, 11 years old, with right-side Osgood-Schlatter disease, lateral radiographs, and ultrasound examinations (**a** and **c**) with follow-up three months later (**b** and **d**. Fractured aspect of the tuberositas tibiae on radiograph (**a**) and ultrasound (**c**) (*arrows*) with thickening of the patellar tendon. Left tibial tuberosity for comparison (**e**). Three months later, ossification at the fracture line (*arrows*) of the tuberositas tibiae on radiograph (**b**) and ultrasound (**d**). Decreased thickness and angiogenesis of the noncalcified parts

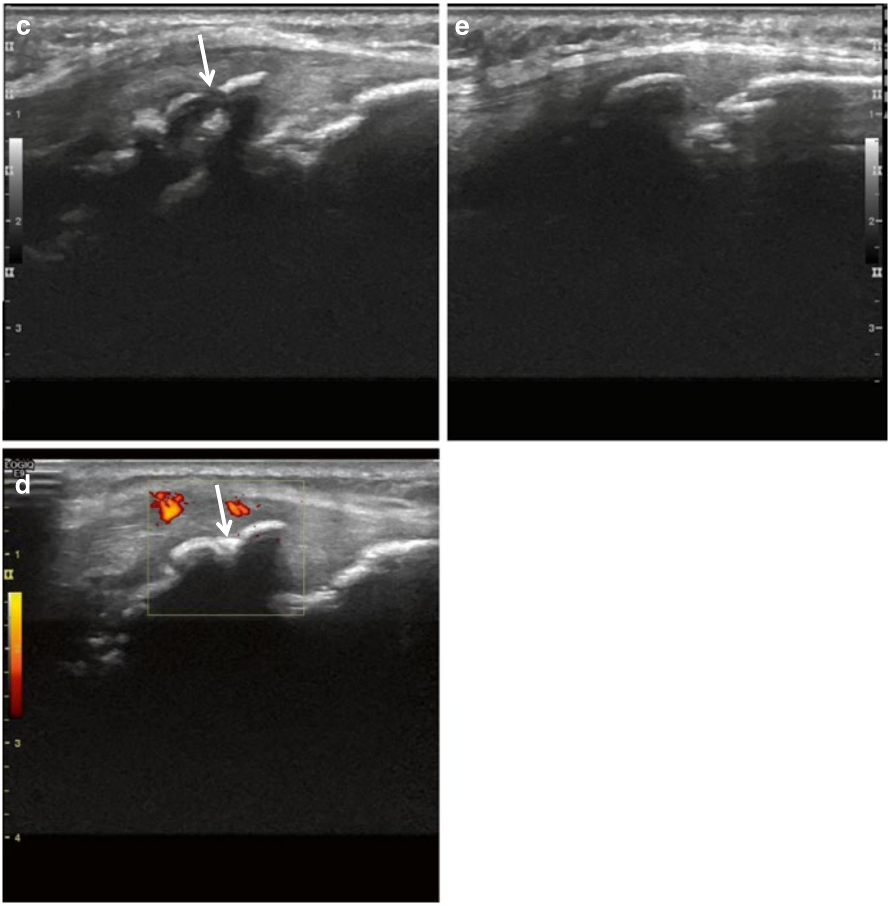

Fig. 40.6 (continued)

the patellar ligament. The prognosis of type two is moderately favorable as it tends to create significant bursal fibrosis including impairment of dynamic behavior of the fatty apron of the deep infrapatellar bursa (Hoffa's fat pad). However, it doesn't leave a significant scarring within the patellar ligament. Type three is characterized by a delamination tear of the ossification center resulting in an irregular deformation of the tuberosity; there is a cartilage fracture with or without significant anterior displacement of the proximal attachment of the patellar ligament. The cartilage fracture has to be located at least partially within the footprint of the patellar ligament insertion. Other signs are, first, a deep infrapatellar bursitis or fibrosis due to an injured arterial supply within the tibial tuberosity, the bleeding from the patellar ligament, and the fractured cartilage; second, an inflammation of the patellar ligament; and last, a superficial infrapatellar bursitis and a focal scarring or possible

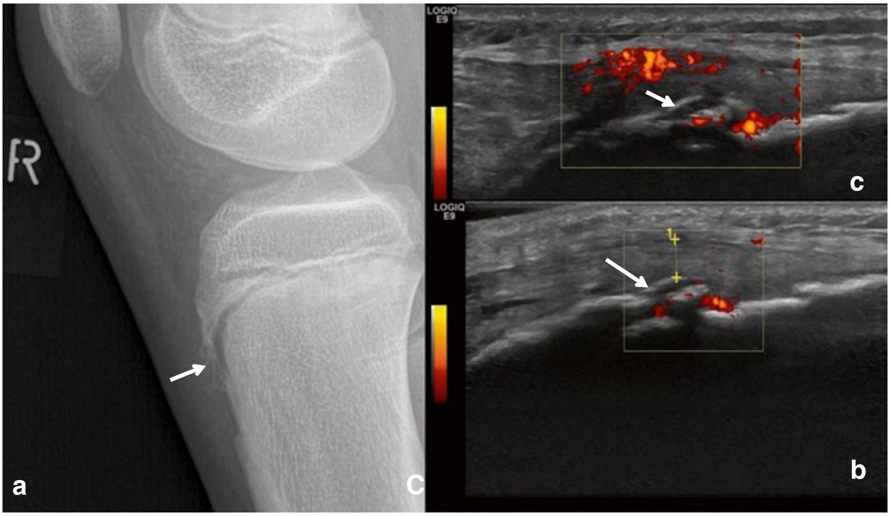

Fig. 40.7 Radiograph and US of Osgood-Schlatter disease; US demonstration of angiogenesis and combined fractured and igloo aspect. Twelve-year-old boy with right-sided Osgood-Schlatter disease. Fragmented tuberositas tibiae (**a**) with igloo aspect on ultrasound (**b** and **c** *arrows*) and angiogenesis at noncalcified parts of tuberositas. Nonfavorable clinical evolution with increased pain and swelling, follow-up ultrasound examination 6 weeks (**c**) later with increased angiogenesis and increased fragmentation

bone formation due to a tear in the patellar ligament arising from its tibial insertion. For this type, the prognosis is unfavorable with a high probability of chronic symptoms due to fibrosis of the deep infrapatellar bursa and ectopic bone formation within the patellar ligament's scar (Czyrny 2010) (Fig. 40.6).

Bone scintigraphy is not generally used in clinical suspicion of osteochondroses. Regarding Osgood-Schlatter, only a case report is available describing a young adult male in which the activity status of the disease correlated better with the scintigraphic activity status; actually, this is better and with less radiation burden achieved with ultrasound with Doppler imaging (Namey and Daniel 1980).

40.3 Sinding-Larsen-Johansson Syndrome

Sinding-Larsen-Johansson Syndrome (SLJS) is affecting the patellar apex at the proximal insertion of the patellar tendon accompanied by radiographic evidence of fragmentation or a calcification at the patellar apex. It has a similar etiology as Osgood-Schlatter disease in that it is the result of repetitive microtrauma and excessive prolonged stress occurring at a well-defined skeletal region which is mechanically and biologically weak when stress exceeds intrinsic resistance (Figs. 40.8,

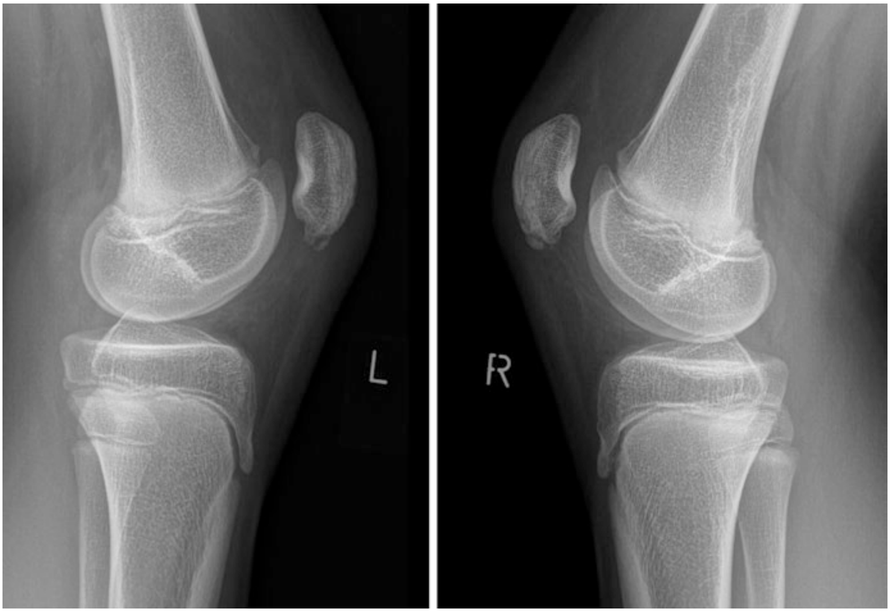

Fig. 40.8 Radiographs of SLJS. Fifteen-year-old boy with chronic complaints at both patella apices. Sinding-Larsen-Johansson disease of both patella, fragmented aspect of the apex of the patella on radiographs in advanced disease

40.9, 40.10 and 40.11). However, in this condition, the stress is directed at the attachment of the patellar tendon on the inferior pole of the patella and not at a cartilaginous growth center. Some authors classify SLJS as jumper's knee in pediatric setting, although jumper's knee is a tendinopathy of the patellar tendon (Dupuis et al. 2009; Hogan and Gross 2003).

40.3.1 Clinical Features

SLJS is clinically characterized by pain localized at the distal pole of the patella, swelling of the infrapatellar soft tissues, and functional limitation. Patients complain of activity-related pain, especially with jumping, running, kneeling, or with climbing stairs.

40.3.2 Incidence and Prevalence

SLJS is seen in adolescents between 10 and 12 years (Gholve et al. 2007). Other studies mention that it typically occurs in adolescent males between 10 and 14 years of age (Draghi et al. 2008).

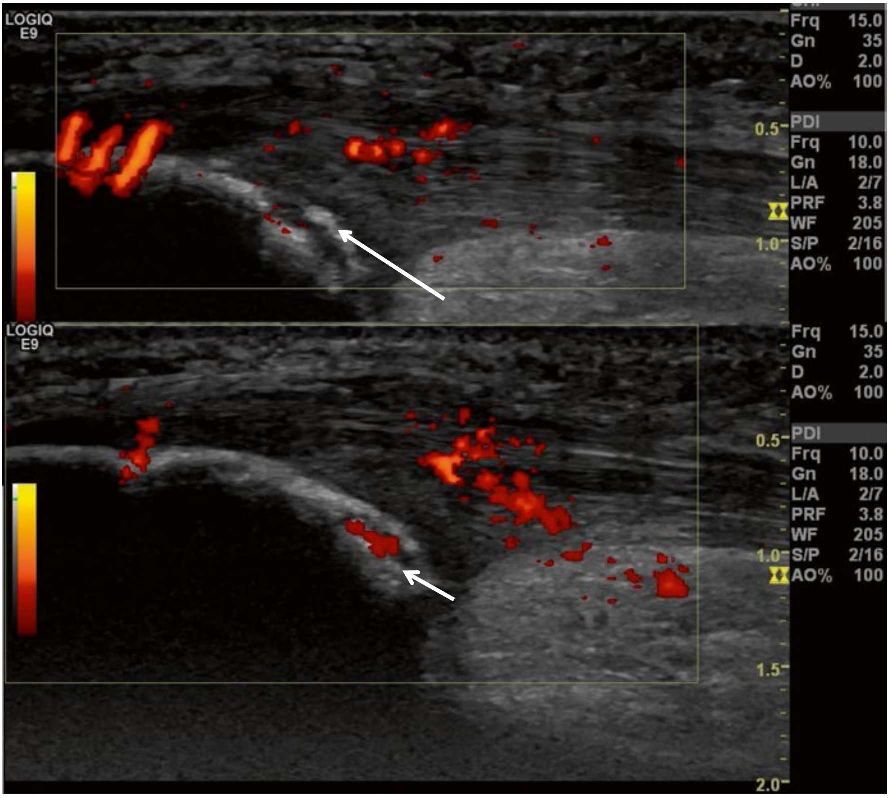

Fig. 40.9 US of SLJS. Eight-year-old girl with chronic pain at the left patella apex. Sagittal ultrasound image at the level of the left patella apex with loose fragment (*arrow*) and angiogenesis (*short arrow*) at the level of the patellar tendon origin and the cartilaginous part (*short arrow*)

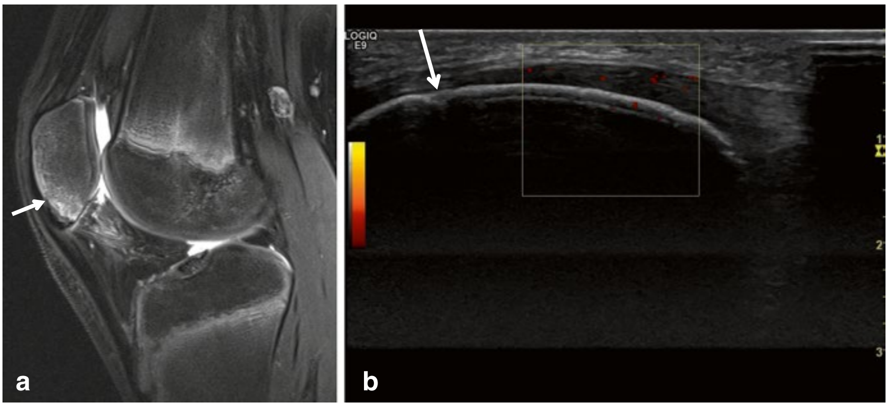

Fig. 40.10 SLJS, MRI, and US. Twelve-year-old boy with Sinding-Larsen-Johansson disease of both patella. MRI and US examinations. Sagittal MRI TSE intermediate TE with FS, increased SI at the patella apex and origin of the patellar tendon. Minor cortical irregularity at the mid-third of the patella (**a**, *arrow*) distending into the patella apex isolating a bone fragment. Only minor abnormalities on US with demonstration of the minor irregularity at the anterior cortical lining of the patella (**b**, *arrow*), minor thickening and angiogenesis at the prepatellar part of the patellar tendon

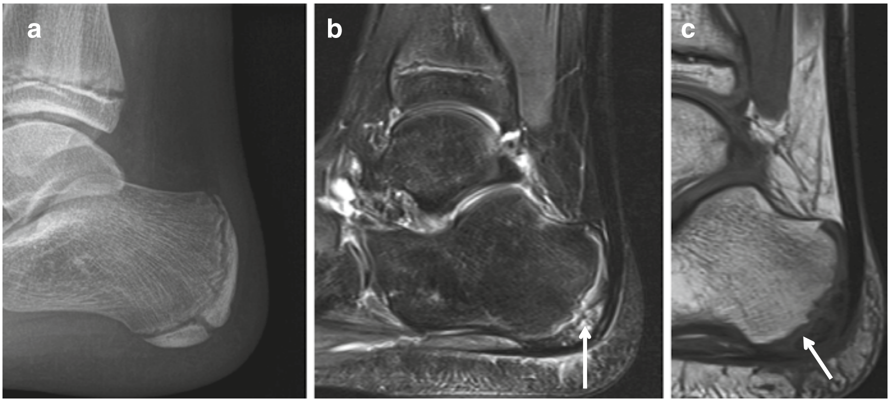

Fig. 40.11 MRI of Sever's disease. Nine-year-old boy with pain at tuber calcanei since a few weeks, ultrasound and radiographs were inconclusive (**a**), MRI, sagittal images, TSE intermediate TE with FS (**b**) and SE T1 WI (**c**) demonstrating bone marrow edema at the apophysis with increased T2 time and reduced SI on T1 (*arrows*)

40.3.3 Diagnosis

Like Osgood-Schlatter disease, the diagnosis of SLJS is mostly based on clinical findings. SLJS results in calcification or ossification of the patellar tendon in the late stages of the disease, which can be often demonstrated on plain radiography. MRI (Fig. 40.10) demonstrates edema at the inferior pole of the patella and in the proximal portion of the patellar tendon and adjacent soft tissues (Dupuis et al. 2009). Ultrasonic findings are the same as those in Osgood-Schlatter disease: cartilage swelling, patellar tendon swelling at its proximal insertion, and patellar fragmentation at its distal pole (Figs. 40.9 and 40.10) (De Flaviis et al. 1989).

40.4 Sever's Disease

Sever's disease or apophysitis of the calcaneus is a common cause of heel pain in children and adolescents. The condition is overuse related in children between the age of 8 and 10 years in girls and 10 and 12 years in boys (Madden and Mellion 1996).

40.4.1 Etiopathogenesis

Sever's disease is an osteochondrosis. The apophysis of the os calcis is an epiphyseal plate that develops along the posterior border of the bone. The Achilles tendon inserts on this calcaneus apophysis. The growth plate is weak and subject to injury.

The most significant etiologic factor is overuse and microtrauma in sports (Michelli et al. 1987). Additionally, Sever's disease can be caused by bursitis or necrosis of the apophysis (Mathieson et al. 1988). Sever's disease occurs in children aged from 8 to 12 years although Heneghan and Wallace recorded cases from 10 to 13 years (Heneghan et al. 1985).

40.4.2 Clinical Features

The athlete complains of heel pain, which is aggravated by activity and frequently occurs bilateral. Physical exam reveals well-localized tenderness of the posterior heel at the site of insertion of the Achilles tendon (Hogan and Gross 2003).

40.4.3 Normal Development of the Achilles Tendon Insertion

Until the age of 3 years, no ossification of the secondary ossification center of the calcaneus is visible. From 4 to 6 years old, early signs of ossification of the secondary ossification center are present. In children from 7 to 11 years, a hypoechoic gap representing the growth plate cartilage can be seen between the posterior bony outline of the calcaneus and the ossified secondary ossification center at the calcaneal tuberosity. Among adolescents from 12 to 18 years of age, the apophyseal cartilage between the posterior bony contour of the calcaneus and the secondary ossification center of the calcaneal apophysis can appear as a hypoechoic gap (Fig. 40.8). The apophyseal growth plate fuses toward the end of skeletal growth (Grechenig et al. 2004).

40.4.4 Diagnosis

Today, ultrasonography plays an important role in the diagnosis and evaluation of pathologies of the Achilles tendon (Kainberger et al. 1990). Particularly in children, it is used frequently because it is noninvasive, rapid, dynamic, inexpensive, painless, and uses no radiation. Plain radiographs can visualize only sclerosis and fragmentation of the tuberositas tibiae; the Achilles tendon itself is not evaluated. However, there is still controversy about the radiographic aspect of calcaneal apophysitis. Some authors showed that sclerotic changes can be observed in normal children (Griffin 1994). MRI can visualize more than only the ossified components of the immature skeleton, but disadvantages are the high price and the difficulty to use in smaller children (Fig. 40.11). Ultrasonic examination of Sever's disease provides examination of the secondary nucleus of the calcaneus, the Achilles tendon, and retrocalcaneal bursa. Achilles tendinitis and retrocalcaneal bursitis may accompany Sever's disease or may be solely a cause of heel pain. Ultrasonography can demonstrate the fragmentation of the calcaneus and surrounding soft tissues (Hoşgören et al. 2005).

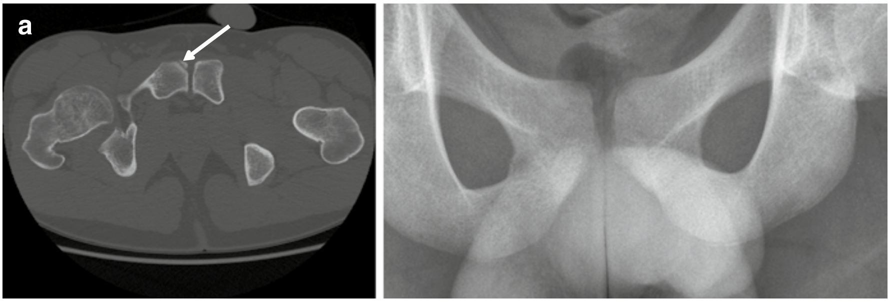

Fig. 40.12 Pelvic apophysitis radiograph and CT. Twenty-one-year-old male soccer player with chronic complaints at the right side of pubis and right tuberositas tibiae. Delayed union of tuberositas tibiae and right pelvic apophysis best demonstrated on CT (*arrow*)

40.5 Discussion Apophysitis

Girls are generally affected with overuse apophysitis at a younger age compared to boys. Apophysis is found to ossify at a younger age in girls compared to boys. At the extensor apparatus of the knee, it is common knowledge that this growth cartilage overuse is age related. At child age, the apex patellae are more vulnerable; at adolescent age, the tuberositas tibiae are more vulnerable. It is hypothesized that the stage of the apophyseal ossification determines the most vulnerable period. This would suppose that the vulnerable period is best determined by the bone age and not by the calendar age of the youngster. Bone age also defines the residual growth capacity of children; in specific sports, high stature is requested. Prediction of adult height in adolescent basketball and volleyball players may be requested. Other areas of apophysitis do exist but are not discussed in this chapter that focuses on apophysitis in jumping sports only (Fig. 40.12).

In the next paragraphs, methods to define bone age and height prediction in adolescent athletes are discussed.

40.6 Methods for the Assessment of Length Predictions and Bone Age in Young Athletes

40.6.1 Introduction

Within a group of children with the same chronological age (CA), there is a Gaussian variation in bone maturation that is influenced by several factors, including genes, hormonal status, and health, that determine the adult height. Determination of the development of the skeleton can be used to predict adult height in young athletes. There is indeed a relationship between bone age (BA) and the final length in children that can estimate the adult height of this individual. In this paragraph, several methods are described. In the estimation of adult height, a radiograph (x-ray) of the hand is frequently performed. The obtained radiographic image may then be electronically processed in the BoneXpert system. This system electronically reconstructs the edge of the bones in the hand and calculates the bone age (BA) of a person. Different methods are used to assess bone ages. Noë compared the Greulich and Pyle (G and P) method with the Tanner-Whitehouse (TW) method. Additionally, a comparison is made between X-ray of the hand and other techniques (DXA scan, ultrasound of the hand, X-ray of the vertebral column). These length predictions can be applied to select talented children that want to enroll to a talent academy to practice basketball or volleyball (Noë 2010; Thodberg et al. 2009; Uysal et al. 2006).

40.6.2 Radiograph of the Hand as a Method for Assessing Skeletal Maturation in Children

40.6.2.1 Skeletal Maturation and Bone Age Assessment

Skeletal maturation is marked by an orderly and reproducible sequence of recognizable changes in the appearance of the skeleton during childhood. Such changes include the timing and sequence of the appearance of the centers of ossification, specific alterations in the contours of the bones, and the timing and sequence of the ultimate closure of the growth plates (Zerin and Hernandez 1991). The use of radiographs of the hand to evaluate skeletal maturation is one of the oldest applications of diagnostic radiography. In the first report from 1898, Poland described in detail the radiographs of hands of British children (Mentzel et al. 2005). Radiographically, skeletal maturity or bone age can be assessed by comparing the radiographic appearance of elements of an individual child's skeleton with the standardized appearance in a comparable population of children at various stages in their progress toward maturity (Zerin and Hernandez 1991).

40.6.2.2 Atlas to Assess Bone Ages

To obtain BA of an individual, an atlas was developed by Greulich and Pyle in 1950 based on the "Atlas of Skeletal Maturation of the Hand" published by T Wingate Todd in 1937 (Noë 2010). The holistic method of Greulich and Pyle (G and P) involves a direct comparison of the radiograph of a child's hand to the pages of the G and P atlas (Thodberg 2009). This atlas is used as the standard to be compared with the X-ray of the hand and wrist of an individual. In the atlas, these standard radiographs are ranked according to CA. Thus, the holistic method can be described as intuitive or experience based (Thodberg 2009).

There is a significant time difference between the development of the bones in boys compared to girls. Girls develop earlier and more quickly than boys do. Thus, the atlas is classified by gender. Most often, a radiograph of the left hand is used, but comparison of left- and right-hand BA showed on average no difference (Martin et al. 2010).

Another method is the Tanner Whitehouse (TW) method. In this method, also a radiograph of the hand and the wrist is used, but the determination of BA is established in a different way. In this analytic method, each bone is considered in sequence, and the rater applies formal criteria to classify the maturity of each bone into a discrete stage. The TW2 method depends on individually scoring the stage of bony development of 20 bones in the hand and wrist by comparison with a series of scored standards. These individual scores are added up to a total score from which a skeletal age may be read directly from tables (Mentzel et al. 2005). The most recent version is the TW3 method, in which the bones of the fingers and the carpal bones are rated separately (since they have a total different character of development). The ultimate definition of the stage is the verbal description. Thus, bone age assessment using the analytical method is regarded as abstract reasoning about features, and the analytic method can, therefore, be described as a rule-based method (Thodberg 2009).

Generally, the G and P method is preferred over the T and W method. Currently, up to 76 % of pediatricians use the G and P method to assess skeletal age (Mentzel et al. 2005). The reported 95 % confidence interval for bone age from hand radiographs ranges from 0.6 to 0.9 years for early childhood (toddlers – 6 years) and 2.1–2.8 years for later childhood (6–12 years) to 1.8–2.5 years for adolescence (12–18 years) (Ontell et al. 1996). The main problem with manual bone age rating is rater variability. Such variability occurs because maturation is an inherently continuous change in bone morphology, which is difficult for the human mind to quantify. Although the atlas or the stage prototypes are meant to serve as "tick marks" on the "maturity ruler," the interpretation is ambiguous because the morphological change associated with maturation is entangled with the biological variation among individuals. Therefore, repeated rating of the radiograph a few days later by the same rater exhibits a certain intra-rater variability, different raters exhibit an even larger inter-rater variability, and they are also likely to be biased relative to each other (Thodberg 2009).

40.6.2.3 Predicting Adult Height

The most easy but unreliable method to make an estimation of a child's adult height is the height of the parents. Therefore, new models have been proposed to establish a more correct prediction of the final height of an individual (Noë 2010). Nancy Bayley published in 1946 a method based on the relationship between skeletal age and the proportion of the adult height. She assumed that two normal children of the same CA and BA, but of different height, have the same fraction left to grow or growth potential (G and P). Bayley-Pinneau's scaling law then states that the growth potential can be predicted (gp_{pred}), to a good approximation, as a function solely of BA and CA – BA. From this expression, the so-called *raw* prediction of adult height (H_{raw}) is formed (Thodberg et al. 2009a, b):

$$H_{raw} = h / \left(1 - gp_{pred}\right) \left(h = \text{current height}\right)$$

This is a cruder representation than desired, but their work was conceived before computers were available (Thodberg et al. 2009a, b). On the other hand, this

Fig. 40.13 Radiograph of left hand with BoneXpert computer analysis. Screenshot of BoneXpert method with radiograph of the left hand of a seven-year-old female adolescent with actual height of 124.5 cm illustrating electronic bone age calculation of seven years with adult height prediction of 165.5 cm. Contour of the metacarpals and phalanges is automatically drawn

method is the basis of new computerized methods, for instance, the BoneXpert system (Fig. 40.13). It is an extension of the classical Bayley-Pinneau method. This system is based on an automated determination of bone age, which is obtained by the G and P method. In addition, it predicts adult height of a child using the information from bone age, chronological age, and current height. The calculator can still be used with manual G and P bone age, but the uncertainties of the predictions are then larger due to the rater variability of manual rating [Thodberg]. One of the major limitations is that the TW and G and P method is restricted to Caucasian children. Other limitations are its restricted use for healthy, untreated children, and it still uses an ionizing radiation to assess bone age (Noë 2010).

40.6.2.4 Other Methods for Assessing Bone Age and Predicting Adult Height in Children

Dual-Energy X-Ray Absorptiometry (DXA)

The main problem in the classical method to asses bone age is the exposure to a certain amount of irradiation involved in X-ray procedures. The lifetime attributable risk of cancer due to one single X-ray exposure in childhood approximates 15 % per sievert. Dose reduction is therefore particularly important in childhood. DXA is currently widely used to measure bone mineral density for the assessment of osteoporosis. When applied to assess bone age, a hand-wrist scan by DXA (0.0001 mSv) produces a tenfold lower effective dose than a hand-wrist X-ray (0.001 mSv). This is the major advantage of this method compared with the classical method (Heppe et al. 2012).

When comparing DXA to X-ray of the hand using the Greulich and Pyle atlas, there is a very strong correlation between bone age results, indicating agreement of bone age assessment based on DXA and radiographic images (Pludowski et al. 2004). Both methods assess bone age with a very small difference, and 95 % of all coupled assessments do not differ by more than one year. According to this level of agreement, the DXA method produces similar results to the common X-ray method (Heppe et al. 2012). The major drawback of using the DXA scan in bone age assessments is that it is a more time-consuming procedure. The scan lasts 66 s, whereas an X-ray examination takes less than 1 s. This is relevant for movement artifacts in children. Further studies are needed to investigate the cost-effectiveness (Heppe et al. 2012).

Ultrasound

A sonographic evaluation using the BonAge method is performed in the region of the distal radius. This method is based on the observation that maturation of an epiphysis, by virtue of enchondral ossification, is strongly related to systemic bone development. Exact positioning of the wrist during the scanning process is necessary to avoid mistakes in evaluation. Especially, for follow-up investigations, it seems necessary to have a consistent point of measurement; this is one of the critical features of the sonographic BonAge system (Mentzel et al. 2005). The BonAge device demonstrates the ability of ultrasound to produce an accurate assessment of skeletal age. There is a good correlation between the data from this system and the analysis according to the G and P method. The difference between CA and BonAge was the same as the difference between CA and the conventional G and P method for skeletal age evaluation (Mentzel et al. 2005). Advantages of the ultrasound device are objectivity, lack of ionizing radiation, and easy accessibility. A disadvantage is that investment in a dedicated apparatus is needed reducing its cost effectiveness and practical use. Thus, the sonography-based technique may be an alternative to the conventional method for the assessment of skeletal age (Mentzel et al. 2005).

Ultrasound of the hip for assessing bone age is not accurate (Castriota-Scanderbeg et al. 1998).

Lateral Radiograph of the Cervical Spine (Cephalogram)

The cervical vertebrae may be a good indicator of maturity. A lateral cephalometric radiograph is taken. The radiograph is obtained with the X-ray beam perpendicular to the head of the patient. The best morphological vertebral parameter to estimate maturation is the concavity of the lower border of the vertebral body (San Roman et al. 2002). The effective radiation dose from a lateral cephalogram is 0.003–0.007 mSv. Results suggest that this method to determine skeletal maturation is reliable. This new simple method can be used instead of the hand-wrist radiograph to evaluate maturation stages but at a three- to sevenfold higher radiation dose (San Roman et al. 2002).

Magnetic Resonance Imaging

In a study by Dedouit et al., an MRI was taken of the knee. Both distal femoral and proximal tibial epiphyses were separately evaluated using a staging system based on five MRI development stages. They could not compare this method to the G and P method, but demonstrated that bone maturation at the tibial epiphyses of the knee on MRI is correlated to the age of males and females (Dedouit et al. 2012). Dvorak et al. performed bone age estimation on the basis of grading of fusion of the distal radius using MRI in 14–19 year old football players. They showed that it can be developed as a tool to determine bone maturation and may offer an alternative as a noninvasive-nonradiographic method of age determination (Dvorak et al. 2007). MRI might be developed as an alternative noninvasive method of bone age estimation without exposure to radiation. However, since the costs of MRI are high compared to radiographs, MRI is not further developed for this indication.

40.6.2.5 Alternative Methods to Predict Adult Height

Midparent Height (MPH)

The growth of a child is largely influenced by its genetic background. Therefore, the height of the parents is used as the basis for a formula developed by the University of Brussels (Roelants and Hauspie 2004):

$$\text{For Boys}: \text{MPH} = \left(\left(\text{father s height} + \text{mother s height}\right)/2\right) + 6.5$$

$$\text{For Girls}: \text{MPH} = \left(\left(\text{father s height} + \text{mother s height}\right)/2\right) - 6.5$$

The target range of this method is MPH ±10 cm for boys and MPH ±9 cm for girls.

Beunen-Malina/Beunen-Malina-Freitas Method

The Beunen-Malina method consists of a noninvasive method for predicting adult stature using five predictors (CA, current stature, sitting height, subscapular skinfold, and triceps skinfold). This method is only used for predicting adult height in adolescent boys aged 12.5–16 years. When the accuracy of the Beunen-Malina method is compared to the TW method, the Beunen-Malina prediction compares favorably (Beunen et al. 1997).

A similar noninvasive method for prediction of adult height, the Beunen-Malina-Freitas method, is developed for girls. The Beunen-Malina-Freitas 1 equation is recommended. In this equation, four predictors are used at 12 and 13 years (height, sitting height/height, forearm circumference, and menarche). This method is only applicable for girls of European origin. The Beunen-Malina-Freitas equations for girls are slightly more accurate and have lower prediction errors than Beunen-Malina predictions of adult height in boys (Beunen et al. 2011). The Beunen-Malina-Freitas method and the Beunen-Malina method both provide an accurate estimation of adult height without the use of skeletal maturity. This means that there is no exposure to irradiation (Beunen et al. 1997, 2011).

40.7 Discussion

Girls are generally affected with overuse apophysitis at a younger age compared to boys. Apophysis is found to ossify at a younger age in girls compared to boys. At the extensor apparatus of the knee, it is common knowledge that this growth cartilage overuse is age related. At child age, the apex patellae is more vulnerable; at adolescent age, the tuberositas tibiae is more vulnerable. Overuse apophysitis is a clinical diagnosis, but ultrasound or MRI evaluation may be used in specific cases. It is hypothesized that the stage of the apophyseal ossification determines the most vulnerable period. This would suppose that the vulnerable period is best determined by the bone age and not by the calendar age of the youngster. Bone age also defines the residual growth capacity of children; in specific sports, high stature is requested. Prediction of adult height in adolescent basketball and volleyball players may be requested. There are several methods for assessing bone age. They all have their specific advantages and disadvantages. The quality of these methods is mostly high, but results are not easily compared. The most frequently used and most accepted method for assessing bone age in children of about 12 years old is the G and P method by evaluating a radiograph of the hand with wrist. This radiograph is then compared to an "atlas of skeletal maturation." Assessing bone age by using a hand radiograph presents a 95 % confidence interval from 2.1 to 2.8 years for later childhood (6–12). This is larger when compared to other age groups. Using this method, the BoneXpert system is a good predictor of adult height in children. This system automatically determines bone age (using G and P) and automatically predicts adult height of a child. However, it can only be applied in Caucasian children. The major disadvantage of these methods is irradiation. An alternative to predict adult height is the formula developed by the University of Brussels based on midparental height, but this is less reliable as it gives a too wide adult height target range. The Beunen-Malina method and the Beunen-Malina-Freitas method both are noninvasive methods for prediction of adult. Results suggest that these methods produce similar results compared with the G and P method. In addition, these methods don't expose the children to irradiation.

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The Female Athlete

41

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Contents

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Abstract

Women participation in sports increased dramatically in the last century, especially in the last quarter. Women are now involved more in competitive athletics and other vigorous exercise programs, and women of all ages are exercising earlier in life and with greater intensity. This mass participation in sports resulted in dramatic increase in certain sports-related musculoskeletal injuries among women which their incidences and locations differ according to the type of sports.

Abbreviations

ACJ	Acromioclavicular joint
ACL	Anterior cruciate ligament
BMD	Bone mineral density
BMI	Body mass index
CNS	Central nervous system
CPSC	Consumer Product Safety Commission
CT	Computerized axial tomography
CTA	Computerized tomographic arthrography
FDG	Fluorinated deoxyglucose
Ga-DTPA	Gadolinium
IBS	Isotope bone scanning
ITB	Iliotibial band
MDP	Methyl diphosphonate
MHz	Megahertz
MRI	Magnetic resonance imaging
MTSS	Medial tibial stress syndrome
NCAA	National Collegiate Athletic Association Injury
PET	Positron emission tomography
Q-angle	Quadriceps angle
SPECT	Single-photon emission computed tomography
TBI	Traumatic brain injury
US	Ultrasound

41.1 Introduction

Millions of people worldwide participate in different types of sports (Jones et al. 2002; Gall et al. 2008). Sports activities and exercises are known to have a positive influence on a person's physical fitness, as well as to reduce the incidence of some chronic diseases (Giladi et al. 1991; Morris et al. 1980). For some athletes, sports is a way to increase their self-esteem, a tendency toward perfectionism and a source of income (American College of Sports Medicine 1985; Bouchard et al. 1994; Pate et al. 1995; Williams 1996).

Women participation in sports increased dramatically in the last century, especially in the last quarter, not only in most industrialized countries but also in many of the developing countries (Speed 1998; Greene 1999; Niva et al. 2009; Kowal 1980). The level of participation and performance still varies greatly by country and by sports. Women are now involved more in competitive athletics and other vigorous exercise programs, and women of all ages are exercising earlier in life and with greater intensity (Gall et al. 2008; Greene 1999). This mass participation in sports resulted in dramatic increase in certain sports-related musculoskeletal injuries among women which their incidences and locations differ according to the type of sports (Gall et al. 2008; Speed 1998; Alonso et al. 2010; Arendt et al. 2003; Bennell et al. 1996). In addition, increasing participation of nonathletes in endurance sports such as marathon running has led to an increase in stress injuries among nonprofessional sports women (Giladi et al. 1991).

Although men and women may sustain the same type of injuries, females are more prone to suffer from overuse injuries such as muscle-tendon inflammation, stress fractures, and knee disorders (Jones et al. 2002; Gall et al. 2008; Alonso et al. 2010; Angus and McBryd 1976). Prospective studies of military populations participating in different entry-level programs have consistently reported higher musculoskeletal injury rates among women than men (Jones et al. 2002; Arendt et al. 2003; Knobloch et al. 2007; Hoch et al. 2005; Bennell and Brukner 1997; Shaffer et al. 2006; Bell et al. 2000; Bijur et al. 1997; Knapik et al. 2001). Many other studies of athletic female have shown that female athletes sustain more knee injuries than male athletes, specifically anterior cruciate ligament (ACL) sprains (Gall et al. 2008; Alonso et al. 2010). Anterior knee pain is more common in women athletes than men (Knobloch et al. 2007; Hoch et al. 2005). The National Collegiate Athletic Association Injury Surveillance System, in the United States, between 1997 and 2000 indicated that female college athletes experience a greater number of concussions during games than male college athletes, based on both raw numbers and per game exposure. Some authors report that females appear to have a greater likelihood of post-concussion syndrome at the 1-month follow-up, a greater incidence of depression following mild traumatic brain injury (TBI), and a greater number of persisting symptoms 1 year after mild brain injury (Broshek et al. 2005; Bazarian et al. 1999; Fenton et al. 1993; Rutherford et al. 1979).

Women have some anatomical and physiological differences from men which had been suggested as risk factors for the increase rate of sports-related injury.

Women menstruate and have a daily variation in their hormonal status; in addition many women's menstruation is affected with exercise (Speed 1998; Greene 1999; Davis et al. 1990; Barrow and Saha 1988).

Rapid and accurate diagnosis of skeletal injuries is important to prevent propagation of these injuries, and early effective treatment may reduce time away from training and participation in sports.

The discussion below will not be limited only to athletic women in sports, but it will be extended to involve nonprofessional sports women, female military recruits, dancers (e.g., ballet dancer), and cheerleaders as they are subjected to the same type of stress and encounter similar types of injury.

41.2 Why Do Women Differ from Men?

Substantial evidence points to an increased injury rate among female athletes compared to their male counterparts. This susceptibility is present in amateur and professional female athletics (Shaffer et al. 2006; Bell et al. 2000; Bijur et al. 1997; Knapik et al. 2001, 2002; Jones et al. 1993; Snedecor et al. 2000). It is not obvious why women have a higher injury rate, but women have some physiological differences from men that are incriminated as risk factors for the increased rate of sports-related injury.

41.2.1 Hormones

Some authors claimed that the risk of some of athletic injuries varies with fluctuation in sex hormones during the menstrual cycle. Estrogen level is high during ovulatory phase, and this could affect the strength of some ligaments and make them susceptible to injury (Wojtys et al. 1998; Edwards et al. 2005; Dugan 2005; Wojtys et al. 2002; Slauterbeck et al. 2002). Some studies on the impact of hormones on injuries on the ACL of the knee in female athletes revealed that more injuries occurred than expected during the ovulatory and follicular phase of the menstrual cycle when estrogen levels are high as compared to the luteal phase (Wojtys et al. 1998, 2002; Edwards et al. 2005; Dugan 2005; Slauterbeck et al. 2002).

41.2.2 Anatomy

Various studies have considered anatomic determinants of the knee and their role in the higher knee injury rates in women (Dugan 2005; LaPrade and Burnett 1994). The Q-angle (quadriceps angle) is defined as the angle between the line connecting the anterior superior iliac spine and the midpoint of the patella and the line connecting the tibial tubercle and the same reference point of the patella (Hungerford and Barry 1979). Women typically have greater Q-angles than men, which could be attributed to their wider pelvic base and shorter femoral length. Recreational basketball players who suffered knee injuries were found to have a higher Q-angle than non-injured players (Dugan 2005; Shambaugh et al. 1991).

The miserable alignment syndrome, including pronation of the feet, increased femoral anteversion, and increased genu valgum, was thought to be contributory to anterior knee pain in women, but no studies have documented this finding (Dugan 2005).

The intercondylar notch of the femur tends to be narrower in women as compared to men. Some authors suggested that this factor might affect the stability of the athlete's knee, which is reflected on the mechanical alignment of the lower extremity and predisposes the lower limb to higher rate of injury especially around the knee (LaPrade and Burnett 1994).

Numerous studies have been done to determine the relationship between the size and shape of the femoral notch and ACL injury rate (LaPrade and Burnett 1994; Muneta et al. 1997; Shelbourne et al. 1998). Some published data on ACL tears in female athletes concluded that notch dimensions and ACL injury seem to be associated with injury but that this association was not proven to be causal (Dugan 2005; Griffin et al. 2000).

41.2.3 Joint Laxity and Flexibility

Several studies have shown that joint laxity tends to be greater in women than in men (Dugan 2005; Hutchinson and Ireland 1995; Huston and Wojtys 1996). However, the relationship between ligamentous laxity and injury is not clear. Several researchers have attempted to link joint laxity with increased incidence of injury (Gall et al. 2008). While some reports have shown that football players with loose joints suffer more knee injuries than their tight joint counterparts, no sound evidence has emerged to support or dispute this claim (Gall et al. 2008). However, there is agreement that strengthening the muscles around the lax joint (quadriceps, hamstrings, and calf muscles) may counter the detrimental effects of excessive laxity (Dugan 2005; Ahmad et al. 2006; Silvers et al. 2005).

41.2.4 Muscular Strength and Neuromuscular Control

41.2.4.1 Muscle Strength

Appropriate muscular strength, muscular coordination, and timely engagement of muscle groups have been proven to sustain knee stability (Jones et al. 2002). Women have significantly less muscle strength in the quadriceps and hamstrings compared with men, even after normalizing for body weight (Hakkinen et al. 1997; Kanehisa et al. 1996). This lack of strength places the female athlete at a significant disadvantage for the muscles surrounding the joints. Conditioning exercises have imparted some protection against injury (Caraffa et al. 1996).

41.2.4.2 Neuromuscular Control

Proprioception and reaction time, postural stability, limb dominance, muscle stiffness, firing patterns, and landing biomechanics are all being studied in hope of elucidating risk factors for some noncontact joint injury in women (Dugan 2005).

The muscle activation patterns also are different between men and women (Hewett et al. 2002). The differences in landing and other movement strategies between male and female athletes have the potential to explain at least some of the disparity in noncontact injury rates. Studies have shown that women run, land, and jump differently than men when playing sports (Schultz and Perrin 1999; Rozzi et al. 1999). Women have been found to have a highly dominant leg, with significant side-to-side strength and flexibility deficits noted (Hewett et al. 1996).

Female athletes landed with greater maximal valgus angle and with significant differences between their dominant and non-dominant knees, compared with males (Gall et al. 2008; Dugan 2005; Andrews and Axe 1985). This mismatch may lead to a higher incidence of injury to the dominant knee, as it preferentially works to limit the forces of gravity, or a higher risk of injury to the non-dominant knee, as it is significantly weaker and less able to manage such forces (Gall et al. 2008; Dugan 2005).

During knee extension movements and exercises, the female athlete prefers to contract their quadriceps as a first response, whereas male athletes respond to the same movements by first contracting their hamstrings to counter the load (Huston and Wojtys 1996; Boden et al. 2000; McNair et al. 1990). This has been described as a quadriceps-dominant pattern in female athletes. Adequate strength and reaction time of the hamstring is critical in knee stability. The quadriceps and hamstrings must fire in a harmonious pattern for all sports, specifically those requiring jumping, landing, and pivoting (Dugan 2005).

To minimize the extrinsic risk factors such as muscular strength, neuromuscular control, knee stiffness, landing patterns, and postural control, research has shown that proper athletic training and conditioning can reduce the incidence of lower body injuries. Additionally, proper warm-up before sports participation will likely decrease the risk of knee injuries (Dugan 2005; Ahmad et al. 2006; Silvers et al. 2005).

41.2.5 Athletic Amenorrhea

The effects of exercise on the female reproductive cycle and on overall hormonal status are receiving greater attention (Speed 1998; Greene 1999; Davis et al. 1990; Barrow and Saha 1988; Bullen et al. 1985). Amenorrhea in athletes, sometimes called exercise-associated amenorrhea, occurs when a woman does not have a regular period either because she exercises too much, eats too few calories, or both (Greene 1999; Shangold 1984). The reported frequency of exercise-associated menstrual irregularities varies from 2 to 51 % (Greene 1999; Arendt et al. 2003; Yeager et al. 1993). This is in contrast to approximately 2–5 % in the general population (Greene 1999). If a woman has too little body fat, the ovaries stop producing estrogen, and the woman stops menstruating. Intense exercise and extremely low body weight has also been linked with lower levels of the hormone estrogen which is necessary to maintain healthy bones. Female athletes with amenorrhea have lower bone mineral density than their counterparts with normal menstrual patterns who follow the same exercise regimens (Greene 1999; Shangold et al. 1990).

The association of exercise-induced amenorrhea with few calorie consumption leads to the concept of female athletic triad which is a combination of (Greene 1999; Knobloch et al. 2007; Shangold et al. 1990; Hoch et al. 2009; Nattiv et al. 2007; Torstveit et al. 2005; Hobart and Smucker 2000):

A. Low-energy availability (eating disorders and disordered eating)
B. Menstrual irregularities (amenorrhea)
C. Reduced bone mass (increased risk of stress fractures and osteoporosis)

Patients with female athlete triad get osteoporosis due to hypoestrogenemia (De Souza and Williams 2005) or low estrogen levels which is part of amenorrhea. Low bone mineral density renders bones more brittle and hence susceptible to fracture (Greene 1999). Because athletes are active and their bones must endure mechanical stress, the likelihood of experiencing (stress) fracture is particularly high (Nattiv et al. 2007; Hobart and Smucker 2000). Additionally, because those suffering with female athlete triad are also restricting their diet, they may also not be consuming sufficient amounts vitamins and minerals which further exacerbates the problem of weak bones (Greene 1999; Torstveit et al. 2005; Sullivan et al. 1984). The triad is seen more often in aesthetic sports which requires low body weight such as gymnastics, figure skating, ballet, diving, swimming, and long-distance running (Torstveit et al. 2005; Sullivan et al. 1984; Hoch et al. 2010).

41.3 Incidence of Musculoskeletal Injury in Female Athletes

As the number of females participating in sports is increasing and with the risks inherent in a sport which combines height, speed, and precision, the number of sports injuries has increased (Gall et al. 2008; Speed 1998; Alonso et al. 2010). The increase has been in both acute and, even more, overuse injuries (Alonso et al. 2010). The incidence of musculoskeletal injures varied with each discipline (Gall et al. 2008; Alonso et al. 2010). Incidence of injuries varies among authors even for the same type of sports. These differences between studies may be explained by inconsistencies with respect to injury definition, methodologies employed, differences in age group, playing level, methods of calculating exposure time, and game-to-training ratio and may be due to regional differences.

Running has been studied the most (Jones et al. 2002; Collins et al. 1989). Several studies showed that the annual incidence of overuse injuries in track-and-field athletes is estimated to be 1.5–12 per 1,000 training hours (Gall et al. 2008; Engström et al. 1991; Giza et al. 2005; Jacobson and Tegner 2007), with a prevalence of 76 %. Another study showed that the incidence of running injuries to the lower extremities in long-distance runners varied from 19.4 to 92.4 %. Alonso et al. (Alonso et al. 2010) studied the frequency and characteristics of sports injuries and illnesses incurred during the 2009 IAAF World Athletics Championships. According to his study, the total incidence of injuries was around 14 % (Alonso et al. 2010).

There was almost a universal agreement that most of the injuries were located in the lower limb (around 80 %) (Speed 1998; Alonso et al. 2010) and the majority of injuries were caused by overuse injury (Gall et al. 2008; Speed 1998), and there was some difference in the most frequent location affected. Kowal (1980) studied a group of female military trainee and found that most common injuries were in the tibia and then in the ankle and foot followed by the knee and hip (Speed 1998). Gall et al. (2008) studied injuries in young elite female soccer players and found that most injuries were in the ankle, thigh, and knee (Engström et al. 1991; Giza et al. 2005; Jacobson and Tegner 2007). The most frequent type of injury reported was strains (Gall et al. 2008; Alonso et al. 2010; Bennell and Crossley 1996).

These studies report annual injury incidences between 61 and 76 %, with a strong dominance of overuse-related conditions such as tendinopathies and stress fractures (Jacobsson et al. 2012; Bennell et al. 1999; D'Souza 1994). Studies concerning athletes in different type of sports showed variable results (Jones et al. 2002; Alonso et al. 2010).

41.4 Risk Factors Associated with Increased Incidence of Exercise-Induced Injury in Female Athletes

Giladi et al. (1985, 1991) first proposed that specific risk factors especially for stress fractures exist in certain individuals and for specific fractures sites. Not all of these factors proved to be associated with increase rate of sports injuries but are mentioned for the sake of completion. The risk factors in females can be categorized broadly into:

(a) Anatomical and biomechanical
(b) Hormonal and body habitus
(c) Demographic factors
(d) Environmental-mechanical strain environment
(e) Activity related

41.4.1 Anatomical and Biomechanical Factors

Many authors suggested some anatomical and biomechanical factors that might predispose to musculoskeletal injuries. Many of these were not proved to increase the risk of injury, but some showed association with some types of injuries (Giladi et al. 1987; Fnberg 1982; Clanton and Solcher 1994; Pell et al. 2004; Verma and Sherman 2001; Milgrom et al. 1988) (Table 41.1).

41.4.2 Hormonal and Body Habitus

41.4.2.1 Osteoporosis and Low BMD

Low bone mineral density (BMD) values predispose an individual to those fractures caused by compressive loads, such as those seen in the vertebrae of postmenopausal, osteoporotic women (Giladi et al. 1991; Speed 1998; Davis et al.

Table 41.1 Anatomical and biomechanical factors that might contribute to the incidence of MS injuries

Anatomical organ	Comments
Pelvis (Kowal 1980; Angus and McBryd 1976)	Wide pelvis
	Appears to contribute to the increased risk of injury to the hip and the outer aspect of the knee, leg, and foot because of the varus tilt
Femur (Jones et al. 2002; Giladi et al. 1985, 1991; Speed 1998; Kowal 1980; Knobloch et al. 2007)	Femoral anteversion and high degree of external rotation of the hip
	Athletes with greater passive external rotation of the hip joint had a higher incidence of tibial stress fractures than those with lower extent of rotation
Knee (Jones et al. 2002; Speed 1998; Angus and McBryd 1976; Giladi et al. 1987)	Genu varum and genu valgum
Leg (Jones et al. 2002; Giladi et al. 1985, 1991; American College of Sports Medicine 1985; Speed 1998; Knobloch et al. 2007; Dugan 2005; Sullivan et al. 1984)	Narrow tibia and short tibial lengths
	Predispose for tibial fracture
	Leg dominance
	However, stress fractures were more likely to occur in the dominant limb
	Leg-length discrepancy (e.g., >0.5 cm.)
	Friberg (1982) found that tibial, metatarsal, and femoral stress fractures were more likely to occur in longer limbs, and fibular fractures were more likely to occur in shorter limbs
Foot morphology (Jones et al. 2002; Speed 1998; Angus and McBryd 1976; Knobloch et al. 2007; Edwards et al. 2005; Dugan 2005; Clanton and Solcher 1994; Pell et al. 2004; Verma and Sherman 2001)	Foot arch height
	Flat feet
	Overpronate
	Malleolar torsion and range of subtalar joint motion flexibility
Muscles	High quadriceps angle (Jones et al. 2002; Kowal 1980)
	Small limb girth (Jones et al. 2002; Dugan 2005)
	Muscle strength and imbalance (Jones et al. 2002; Gall et al. 2008; Kowal 1980; Dugan 2005; Clanton and Solcher 1994; Pell et al. 2004; Verma and Sherman 2001)
Ligament	Ligamentous laxity and greater joint elasticity (Jones et al. 2002; Gall et al. 2008; Shaffer et al. 2006; Dugan 2005)
Forces	Bending forces
	In a biomechanical analysis of the pathogenesis of tibial stress fractures in military recruits, Milgrom et al. (1988) concluded that bending is the most important force involved in their development, rather than torsion, tensile, and compressive forces
	Reaction time (Jones et al. 2002; Speed 1998; Dugan 2005)
	Postural stability (Jones et al. 2002; Gall et al. 2008; Dugan 2005)

1990). It was suggested that athletes with osteoporosis are more likely to have fractures (Barrow and Saha 1988; Bennell et al. 1995; Myburgh et al. 1990); others did not find this correlation (Giladi et al. 1991). However, no relationship has been found between BMD and tibial stress fractures (Giladi et al. 1991; Speed 1998; Greene 1999).

41.4.2.2 Menstrual Irregularity

A history of amenorrhea and menstrual irregularity are risk factors for injuries (Shaffer et al. 2006). The longer the duration of amenorrhea, the more likely female athletes suffer from injury (Bennell and Brukner 1997; Greene 1999; Knobloch et al. 2007; Shaffer et al. 2006; Davis et al. 1990; Barrow and Saha 1988; Myburgh et al. 1990). It was found in one study that incidence of fracture is inversely proportional with the number of menses per year (Jones et al. 2002; Knobloch et al. 2007; Barrow and Saha 1988; Edwards et al. 2005; Bennell et al. 1995). Females with "female athlete triad" (Greene 1999; Shaffer et al. 2006; Knobloch et al. 2007; Shangold et al. 1990; Hoch et al. 2009; Nattiv et al. 2007; Torstveit et al. 2005; Hobart and Smucker 2000) have a higher incidence of stress fractures (45 % compared with 29 % of runners with normal menstrual cycles).

Female runners who were taking oral contraceptives were half as likely to get stress fractures over the course of a year as those who were not taking oral contraceptives (Jones et al. 2002; Knobloch et al. 2007). Other investigators did not support this theory (Bennell et al. 1995; Myburgh et al. 1990).

41.4.2.3 Low Body Mass Index (BMI)

Female athletes with a BMI of 20–25 have a lower risk of stress fracture than those with low BMI (Jones et al. 1993, 2002; Shaffer et al. 2006).

41.4.2.4 Eating Disorders

Athletes with eating disorders and weight fluctuations participating in sports, in which leanness is emphasized, have an increased incidence of stress fractures (Speed 1998; Greene 1999; Barrow and Saha 1988; Edwards et al. 2005; Bennell et al. 1995). It has been previously demonstrated that dietary calcium intakes more than 800 mg/day may be protective against stress fracture in athletes (Myburgh et al. 1990). Risk of stress fracture was not associated with current calcium intake by other studies (Bennell et al. 1995).

41.4.3 Demographic Characteristics

41.4.3.1 Age

An athlete with a developing skeleton is more susceptible to musculoskeletal injuries (Speed 1998). Although some studies have found a younger age to be a possible risk factor for musculoskeletal injuries, others have found older age increases the risk of injuries (Jones et al. 2002; Gall et al. 2008; McBryde 1985; Winfield et al. 1997; Peterson et al. 2000).

41.4.3.2 Race

White and Asian women have increased risk of fractures compared to black women. In one study it was found that Hispanic women were almost twice as likely to incur a stress fracture as black women. Lowest rates of stress fractures are among black women (Jones et al. 2002; Giladi et al. 1991; Speed 1998; McBryde 1985; Brudvig et al. 1983).

41.4.3.3 Height

The shorter women were at significantly greater risk than the taller women for fracture and overuse injuries. Some studies did not find this association (Kowal 1980; Jones et al. 1993).

41.4.3.4 A History Musculoskeletal Injury

History of previous injury (Gall et al. 2008; Alonso et al. 2010) is considered as a risk factor for musculoskeletal injury by some authors; other studies from the military studies did not find a relationship between prior injury and the risk of stress fracture during basic training (Jones et al. 2002; Bennell et al. 1995; Chang and Harris 1996; Ross and Woodward 1994; Shaffer et al. 1999).

41.4.3.5 Military Recruits (Speed 1998; Chang and Harris 1996; Shaffer et al. 2006)

A major factor in the development of injuries in this group is believed to be the rapid onset of training which did not allow for a progressive exposure to stress and the development of tolerance.

41.4.3.6 Personality (Speed 1998)

Another factor contributing to injuries in women may be their inability to differentiate between pushing themselves beyond the pain threshold and exposing themselves to undue risk of injury (Gall et al. 2008; Kowal 1980; Edwards et al. 2005; Clanton and Solcher 1994; Pell et al. 2004; Verma and Sherman 2001).

41.4.3.7 Other Factors

Many factors including family history of stress fracture (Milgrom et al. 2003) and smoking (Jones et al. 2002; Giladi et al. 1991) have been investigated with variable results.

41.4.4 Mechanical Strain Environment

- Running field and hard training surfaces (Speed 1998; Bennell et al. 1995)
- Weather
- Footwear: army boot has proved quite satisfactory for men during basic training; women report that the heel width is too great even in the narrow sizes used by them. This is further aggravated by the apparent lack of heel stability inherent in the army boot used by the women during basic training. The resulting heel

instability aggravates existent ankle weakness or foot disorder. Non-fitted shoes lead to foot and ankle pain and injuries, and high heels often lead to hammer toe, ingrown nails, sesamoid injuries, Morton's neuroma, back pain, and other problems (Speed 1998; Clanton and Solcher 1994; Pell et al. 2004; Verma and Sherman 2001).

41.4.5 Activity Related

41.4.5.1 Type of Sports

All activities are not equal in the risk and sites of stress fracture. Ten percent of running injuries seen in sports injuries clinic are stress fractures (Brukner et al. 1996), particularly affecting the tibia, fibula, and metatarsals (Angus and McBryd 1976; Giladi et al. 1985; Blair and Hanley 1980). Basketball, gymnastics (pars interarticularis), and aerobic dance (e.g., tibial shaft) are also frequently involved (Speed 1998; Field et al. 2011). Upper limb stress fractures are relatively rare but are particularly seen in repetitive throwing activities (Speed 1998). Stress fractures of the pubic rami seem to be particularly common among long-distance running athletes. Military studies indicate that different types of units and different types of training may place military personnel at different degrees of risk (Jones et al. 2002).

41.4.5.2 Aerobic Fitness and the Rate of the Loading

Aerobic fitness and the rate of the loading applied to the limb appear to have an important effect on the potential for the subsequent development of a stress fracture. Low levels of aerobic fitness before recruit training have been consistently identified as a risk factor among women in the military (Giladi et al. 1991; Speed 1998; Shaffer et al. 2006; Bell et al. 2000; Jones et al. 1993; Winfield et al. 1997). Women who rated their current fitness as fair or poor were twice as likely to incur a stress fracture as were women who rated their current fitness as excellent or very good (Jones et al. 2002; Giladi et al. 1991; Speed 1998; Kowal 1980; Edwards et al. 2005; Clanton and Solcher 1994; Pell et al. 2004; Verma and Sherman 2001).

Other factors have been suggested including:

- Mismatch between strength and skill and lack of previous experience (Jones et al. 2002; Gall et al. 2008).
- Competitive sports and level of competition (Jones et al. 2002; Gall et al. 2008; Giladi et al. 1991).
- Contact versus noncontact sports (Gall et al. 2008; Alonso et al. 2010).
- Training versus match's activity (Alonso et al. 2010; Gall et al. 2008).
- Inadequate recovery/rest periods and training with fatigued muscle (Kowal 1980).
- Continued hard training after onset of symptoms (Kowal 1980).
- Intensity of exercise (Jones et al. 2002; Gall et al. 2008; Giladi et al. 1991; Edwards et al. 2005; Bennell et al. 1995; Myburgh et al. 1990), mileage (Jones

et al. 2002; Harrast and Colonno 2010), and number of training cycles (Edwards et al. 2008; Lappe et al. 2001); the risks of musculoskeletal problems associated with high-intensity physical activity exceed those associated with moderate physical activity.
- Training errors, training regimen (Gall et al. 2008; Speed 1998; Clanton and Solcher 1994), and lack of supervision.
- Equipment failure and weather condition (Alonso et al. 2010).

41.5 Common Injuries in Female Athletes

The type and site of female injuries varies widely with type of the sport. Some sports are associated with high rate of injuries with variable site and severity (Jones et al. 2002; Gall et al. 2008; Speed 1998; Alonso et al. 2010). Any part of the body can be affected. In girls, most injuries are caused by playground activities, basketball, cycling, and general exercise (Gall et al. 2008; Knobloch et al. 2007; Freeman and Corley 2003). The most frequent diagnoses include strains/sprains followed by fractures. Many authors reported the lower limb as the commonest site for female athletic injuries (Gall et al. 2008; Engström et al. 1991; Giza et al. 2005; Jacobson and Tegner 2007), but still there were some difference in the distribution of these injuries in the lower limb (Gall et al. 2008; Kowal 1980).

41.5.1 Head Injuries

Although sports injuries contribute to fatalities infrequently, the leading cause of death from sports-related injuries is traumatic brain injury (TBI). Many sports have been associated with a variety of neurological injuries affecting the central nervous system (CNS), with some injuries specific to that sport (Gall et al. 2008; Alonso et al. 2010; Lindsay et al. 1980; McCrory et al. 2009; Collie et al. 2001; Hinton-Bayre et al. 1999; Toth et al. 2005). TBI can be seen in basketball, water sports, soccer, gymnastics, dance, and cheerleading (Gall et al. 2008; Morris et al. 1980; Toth et al. 2005; Boden et al. 2003; Noguchi 1994; Mueller and Cantu 1990). Women who participate in sports such as scuba diving or high-altitude climbing are at risk of brain injury through other mechanisms of brain damage (ischemia, nitrogen narcosis, and hypoxia) (Fothergill et al. 1991; Regard et al. 1989). The National Collegiate Athletic Association Injury (NCAA) Surveillance System between 1997 and 2000 indicated that female college athletes experience a greater number of concussions during games than male college athletes (Broshek et al. 2005; Covassin et al. 2003). Some authors report that women appear to have a greater likelihood of post-concussion syndrome at the 1-month follow-up, a greater incidence of depression following mild TBI, and a greater number of persisting symptoms 1 year after mild brain injury (Broshek et al. 2005; Bazarian et al. 1999; Rutherford et al. 1979). Younger players were more at risk for concussion than older one (Gall et al. 2008). According to cheerleading data from the United States (Consumer Product Safety Commission (CPSC) in the United States) in 2007, head and neck injuries accounted for 15.1 % of total cheerleading injuries (Broshek et al. 2005).

Head injury can result in brain concussions, contusions, skull fractures, and internal injuries, coma, and death. Brain imaging includes computerized axial tomography (CT scan) and magnetic resonance imaging (MRI) (Lindsay et al. 1980).

41.5.2 Spinal Injuries

One of the most catastrophic injuries in sports is spinal injury (Silver 1993). Spinal injuries are less common in women than men, and this could be either as a result of more aggressive behavior or a higher degree of competitiveness or possibly because the disciplines are different – women's gymnastics emphasizes agility, grace, and dance, whereas men's is more dependent on strength (Silver 1993).

Repetitive bending and twisting put athletes at risk for spinal injuries. The lumbar vertebrae are more prone to injury especially during sports participation. Neck muscle strains, ligament sprains, and disk and vertebral injuries are common (Silver 1993). Difficult maneuvers involving "flight" account for most spinal injuries. During these activities, the athlete is airborne and lands on a hard surface, such as the floor in gymnastics or the water in diving maneuvers. Spondylolysis and spondylolisthesis can result from repetitive hyperextension of the lower back, such as excessive back bends by gymnasts (Silver 1993; Kruse and Lemmen 2009). Disk herniation most commonly results from repetitive trauma to the back from heavy lifting or from participation in sports that require very strenuous training, such as gymnastics. Fractures can result from a blow to the back and certain parts of the vertebrae. Activities in which the athlete can get hit in the back or can fall from a great height can lead to spinal fractures (Silver 1993). Women participating in gymnastics and horse riding might be affected with spinal injury (Silver 1993; Kruse and Lemmen 2009).

Plain radiographs with multiple views should be performed. Those patients who are symptomatic despite a normal plain radiograph require further investigation in the form of a bone scan, single-photon emission computed tomography (SPECT) scan, or magnetic resonance imaging.

41.5.3 Shoulder Injuries

Shoulder injury happens frequently in sports because overuse, collision, or a fall can be the source. While tennis, baseball, swimming, and football generate many of these incidents, accidental shoulder trauma can occur in relation to nearly any athletic activity (Gall et al. 2008; Alonso et al. 2010). Common injuries include muscle strains and tears of the rotator cuff tissue or tendinopathy and shoulder fractures and dislocation. Overuse problems can be perceived as pain, shoulder instability, and scapular dysfunction, which in many cases will influence an athlete's performance (Myklebust et al. 2011; Bahr 2009; Fahlström and Söderman 2007).

An acute dislocation of the shoulder is an extremely painful injury. It usually occurs as a result of a fall onto an outstretched hand. Traumatic anterior shoulder dislocation injuries have shown high incidents of the sudden tearing of the labrum and ligaments from the bone of the socket (Gall et al. 2008; Alonso et al. 2010). This type of injury is common in snowboarders and skiers and might be associated with fracture-dislocation of the glenohumeral joint.

The clavicle is the commonest site of fracture of the shoulder joint. Shoulder injury to the clavicle occurs in contact sports, such as football, or may result from the transmission of force in a fall up the arm or due to landing on a shoulder, or receiving a blow to the collarbone itself during a fall can also result in a fracture. The most common site of fracture is at the junction of the middle and outer third (Gall et al. 2008; Alonso et al. 2010).

Rotator cuff injuries represent shoulder injury to the muscles and tendons of the rotator cuff. Tendon and muscle strain to the rotator cuff may be most well known among baseball pitchers, tennis players, and swimmers (Jobe et al. 1989; Gomoll et al. 2004; Holtby and Razmjou 2004). Impingement syndrome is also known as thrower's shoulder due to the prevalence of the condition among athletes who compete in throwing events. Impingement syndrome is often caused by rotator cuff tendinitis and occurs when the swollen tendons become trapped in the subacromial space. This injury is commonly caused by overuse; in this instance it is caused by the repeated throwing action (Gohlke et al. 1993; Barr 2004).

Acromioclavicular joint (ACJ) sprains usually result from a fall with direct impact on the outside of the upper arm and may lead to damaged and tearing to this ligament, causing subluxation or complete dislocation (Gall et al. 2008; Alonso et al. 2010).

Fractures of the upper and middle third of the humerus usually result from direct trauma to the humerus. Lower third supracondylar fractures occur as a result of upper transmission of force resulting from a fall onto an outstretched hand (Gall et al. 2008; Alonso et al. 2010).

41.5.4 Elbow Injuries

Athletic injuries of the elbow are common especially in throwing sports such as baseball and tennis (Frostick et al. 1999). Most injuries in the athlete are chronic overuse injuries (Alonso et al. 2010) as a result of repetitive overload resulting in micro-tears of the soft tissues. Elbow injuries are typically seen in baseball players and tennis players because of repetitive throwing or swinging motions and can be seen in gymnasts and swimmers (Frostick et al. 1999).

Tennis elbow, or lateral epicondylitis, is the general term for an overuse injury to the extensor muscles of the forearm. When these tendons become inflamed, it causes pain on the outside of the elbow. This injury occurs from excessive flexion or rotation of the elbow, and pain is located on the inside of the elbow (Frostick et al. 1999; Maylack 1988; Nirschl 1986; Stockard 2001).

The elbow is susceptible to sprains while playing certain sports. Elbow hyperextension sprains occur when the elbow is forcibly straightened past its normal range of motion, and this type of sprain happens most frequently in contact sports and in martial arts (Frostick et al. 1999).

Elbow dislocations occur when either the radius or ulna or both are forced out of the joint capsule. Most elbow dislocations occur posteriorly. A hard fall on an outstretched hand while the elbow is flexing and twisting can cause this type of injury (Frostick et al. 1999).

Tendinopathy or inflammation of the muscle that attaches to the bone of both the triceps and biceps tendons leads to pain at the elbow joint. Posterior elbow pain that worsens with elbow extension is associated with triceps tendinopathy, while anterior elbow pain that worsens with repeated elbow flexion may indicate biceps tendinopathy. Sports which involve repetitive hyperextension of the elbow, such as tennis, can lead to posterior impingement (Frostick et al. 1999; Maylack 1988; Nirschl 1986; Stockard 2001).

41.5.5 Wrist

Wrist injuries are common in athletes. They may result from a single, traumatic force or are a result of repetitive loading activity and more common in younger age group.

Three percent to 9 % of all athletic injuries involve the hand and wrist (Peters and Eathorne 2005; Rettig 2003). This number is as high as 46–87 % of gymnasts suffering wrist injuries (Manusov 2002; De Smet et al. 1994; Webb and Rettig 2008).

Injuries of the wrist can be divided into acute traumatic injuries and overuse injuries.

Acute wrist fractures are common injuries among athletes (Peters and Eathorne 2005). Distal radius metaphyseal and physeal fractures are common in skating, football, basketball, and snowboarding. The scaphoid is the most commonly injured carpal bone, accounting for 70 % of carpal fractures (Rettig and Patel 1995). An athlete falling on an outstretched hand with the wrist dorsiflexed is a common mechanism (Webb and Rettig 2008).

Reportedly, up to 87 % of elite gymnasts sustain distal radial physeal injuries (Manusov 2002). Stress fractures occur in athletes whose sports requires repetitive motion involving wrist compression or twisting as gymnastics (Webb and Rettig 2008).

Hook of hamate fractures have been seen in baseball, golf, and tennis players from the repetitive stress of the bat, club, or racquet, respectively (Webb and Rettig 2008; Stark et al. 1977). Repetitive stress is also thought to be a cause of avascular necrosis of the lunate or Kienböck's disease (Stark et al. 1977; Mirabello et al. 1992).

Soft tissue injuries may either be due to acute trauma or overuse. Overuse syndromes such involving many tendons around the wrist are also common (Mirabello et al. 1992). Carpal dislocation typically requires significant force, such as a fall from a height in cheerleading (Peters and Eathorne 2005; Webb and Rettig 2008).

Radiographic examination is routinely used in the initial evaluation of a suspected acute wrist fracture (Russin et al. 2003). However, because of overlapping structures, many fractures are not found at initial radiographic examination (Welling et al. 2008). Radiography has 70–80 % sensitivity for detecting wrist fractures (Welling et al. 2008). Because of this, other imaging methods such as bone isotope scan and CT are also used both in the primary evaluation of suspected wrist fractures and in the assessment of bone healing after fracture (Kiuru et al. 2004; Metz and Gilula 1993).

41.5.6 Thoracic Injuries

Chest injuries in contact and collision sports are relatively rare, particularly those that are life-threatening. These injuries mostly occur with blunt trauma to the chest/thorax (Amaral 1997; Scott and Scott 1993).

Potential life-threatening injuries and conditions that may be encountered include flail chest, open chest wounds, pneumothorax, tension pneumothorax, hemothorax, myocardial contusion, cardiac tamponade, and diaphragmatic rupture. Each of these conditions is a possible occurrence in injuries sustained while participating in collision/contact sports (Gregory et al. 2002; Scott and Scott 1993).

Stress fracture is most likely to occur in the first rib (Gregory et al. 2002; Scott and Scott 1993). Overhead athletes such as basketball or tennis players are typically at risk here. Acute rib fractures are the result of direct injury. Fractures of the first and second ribs suggest a very significant transfer of energy and can be associated with underlying injuries to the thoracic aorta. Fractures are easily overlooked on a chest X-ray but are useful to detect associated abnormality like pneumothorax. Bone isotope scan is helpful in detecting occult fractures in the ribs (Gregory et al. 2002; Scott and Scott 1993). Fracture of the costal cartilage is a rare cause of chest pain in athletes. Cross-sectional techniques such as CT, sonography, and MRI have been shown to be useful in muscle and soft tissue injury and more sensitive than radiography (Griffith et al. 1999; Miller 2006; Malghem et al. 2001).

Sternal fractures are the result of direct high-energy trauma and rare in sports. Sternoclavicular dislocation usually results from a fall or blow to the front of the shoulder or a fall onto an outstretched hand.

41.5.7 Hip and Pelvis Injuries

The most common injuries of the hip and groin region in athletes are myotendinous strain injuries. They occur when a muscle is stretched beyond a tolerable length causing it to tear (Palmer et al. 1999; Marcantonio and Cho 2000). The most common location for a muscular strain to occur is where the muscle attaches to its tendon; they can also occur within the muscle belly themselves (Jones et al. 2002; Alonso et al. 2010; Marcantonio and Cho 2000; Brittenden and Robinson 2005).

Avulsion fractures of the apophyses and spines of the pelvis are usually considered uncommon injuries, seen almost exclusively in adolescent athletes mainly as a result of the sudden, forceful, or unbalanced contraction of the attached musculotendinous unit in sporting events such as kicking a ball, running, or jumping (Knobloch et al. 2007; Tehranzadeh 1987; Kujala and Orava 1993; Veselko and Smrkoly 1994; Fernbach and Wilkinson 1981; Metzmaker and Pappas 1985). This lesion is observed in soccer players and observed in women's gymnastics. For example, injuries to the ischial tuberosity are seen in gymnastics (Tehranzadeh 1987; Kujala and Orava 1993; Veselko and Smrkoly 1994; Fernbach and Wilkinson 1981; Metzmaker and Pappas 1985). Inflammation of the bursa outside the hip joint, the so-called trochanteric bursitis, can cause pain with hip movement. The labrum can be torn by a twisting or slipping injury or over time by repetitively compressing the labrum between the femoral head and cup (Fernbach and Wilkinson 1981).

Osteitis pubis is thought to be due to the repetitive pull of muscles over the front of the hip joint. Usually pain is activity related and often seen in runners, soccer players, and hockey players. Complete dislocation of the hip joint is a very unusual, but subluxation is more common and might result in avascular necrosis of the hip (Brittenden and Robinson 2005; Kujala and Orava 1993).

A hip pointer is a bruise to the iliac crest of the pelvis. Hip pointers occur from a direct blow to the iliac crest. Because of the superficial location of the iliac crest, it is very susceptible to impact injuries. Hip pointers frequently occur during football but can occur in any sport where the iliac crest is at risk to direct impact (Brittenden and Robinson 2005).

Stress fractures of the hip are usually seen in long-distance runners (Knobloch et al. 2007) and much more common in women than in men (Major and Helms 2000; Spitz and Newberg 2002; Deutsch et al. 1997). The muscles and soft tissues of the pelvis protect the skeleton from the effects of repeated stress explaining the greater incidence of pelvic stress fracture in female athletes, with their relatively reduced muscle bulk. They are more common in sports that involve jumping and landing on hard surfaces, such as distance running, ballet, basketball, and gymnasts. Running athletes are most commonly affected with the femoral neck and the inferior pubic ramus most frequently involved although sacral fractures (Knobloch et al. 2007; Johnson et al. 2001) are not unknown (Veselko and Smrkoly 1994; Major and Helms 2000).

41.5.8 Knee Injuries

Injuries to athlete knees can result from contact or noncontact injuries.

Athletes in all different sports are susceptible to overuse injuries in the knee, primarily due to repetitive movements such as jumping, cutting, and sudden starts and stops. Soccer, ice hockey, volleyball, basketball, alpine skiing, and judo are the sports with a high proportion of knee injuries (Gall et al. 2008; Backx et al. 1991). There is growing evidence on the higher vulnerability of the knee in females (Gall et al. 2008; Alonso et al. 2010; Arendt and Dick 1995; de Loe et al. 2000). Ligament injuries to the knee are very common in sports that require stopping and starting or quickly changing directions. These extreme forces on the knee can result in torn ligaments (Gall et al. 2008). The anterior cruciate ligament (Gall et al. 2008) and the medial collateral ligament are the most often injured, but the posterior cruciate ligament and the lateral collateral ligament can also be injured. The anterior cruciate ligament injuries usually affect female more than male (Wojtys et al. 1998; Dugan 2005; Arendt and Dick 1995; Backx et al. 1991).

Cartilaginous injury usually affects either the medial meniscus or lateral meniscus. Meniscus tears are often the result of twisting, pivoting, decelerating, or a sudden impact.

Osteoarthritis is another cause of knee pain in athletes and results in a gradual loss of joint cartilage due to prolonged repetitive trauma (Niva et al. 2006). Jumper's knee, also known as patellar tendinopathy, refers to damage of the patellar tendon which connects the knee cap to the tibia.

Complete dislocation of the knee is an uncommon trauma. Because of the potentially severe neurovascular damage, knee dislocation can be limb threatening (Peltola et al. 2009; Robertson et al. 2006).

Stress fracture is common around the knee and can affect either the lower femur, upper tibia, or patella especially if the latter is weakened by osteoporosis or chondromalacia (Edwards et al. 2005; Niva et al. 2006; Mason et al. 1996).

Iliotibial band syndrome is another cause of pain around the knee (ITB syndrome). The iliotibial band runs from the pelvis to the knee and serves to protect and support the knee joint. ITB syndrome occurs when the band repeatedly rubs against the lateral femoral condoyle; it consequently becomes irritated and inflamed; this is usually due to overuse. Iliotibial band syndrome is also a common injury found among female runners and triathletes (Edwards et al. 2005).

Chronic exertional compartment syndrome of the lower leg generally is induced by exercise that impairs neuromuscular function within the involved compartment. In young athletes, it often presents in bilateral form, with equal incidence in male and female athletes. Nerve entrapment and popliteal artery entrapment syndrome are other causes of lower leg pain in athletes (Edwards et al. 2005; Clanton and Solcher 1994; Styf 1988; Touliopolous and Hershman 1999).

41.5.9 Tibia

Although complete fracture of the tibia might happen in case of severe contact trauma, the tibia is a common site of noncontact overuse stress fracture (Boden et al. 2000).

A very common overuse injury affecting players of all sports is the medial tibial stress syndrome (MTSS) or what is called shin splints. Shin splints result from inflammation of the tissues surrounding the tibia (Edwards et al. 2005). This is caused by a number of factors such as a rapid increase in training, poor flexibility, or repetitive contact (jumping or running) on hard surfaces. Stress fracture of the fibula is less common but was described by some authors

(Angus and McBryd 1976; Edwards et al. 2005; McBryde 1985; Blair and Hanley 1980; Brukner et al. 1996).

The highest incidence of MTSS occurs in runners; MTSS also may develop in athletes involved in jumping sports, such as basketball, tennis, and volleyball (Edwards et al. 2005; Clanton and Solcher 1994).

41.5.10 Ankle Injuries

The most common of all athletic injuries are ankle injuries, ranging from 17 to 20 % of injuries in most sports (Gall et al. 2008; Alonso et al. 2010; Toth et al. 2005; Bahr and Reeser 2003). Ankle sprains are the most common foot and ankle injuries seen in athletes (Gall et al. 2008; Alonso et al. 2010; McKeon Pk and Mattacola 2008). Muscle weakness and muscle imbalances have been implicated in persistent ankle pain and recurrent ankle sprains. The lateral ligaments are most commonly injured (Jobe et al. 1989; Gohlke et al. 1993).

Osteochondral lesion of the talus is defined as the separation of a fragment of the articular cartilage, with or without subchondral bone (Myklebust et al. 2011; Bahr 2009). The misdiagnosis or delayed diagnosis of osteochondral lesions of the talus occurs in up 81 % of patients presenting with chronic ankle pain (Toth et al. 2005; McKeon Pk and Mattacola 2008).

Achilles tendinosis is caused by repeated micro-tears to the Achilles tendon, leading to damage and loss of healthy tissue. Achilles tendinitis can progress either rapidly over a couple of days or gradually over several months (Cook and Purdam; continuum tendinopathy *BJSM* 2009). Usually the area 4–6 cm proximal to the calcaneus is especially predisposed to tendinopathy and subsequent tearing (Milgrom et al. 1992). Full-thickness tears usually occur in diseased tendons. Areas of friction, impingement, and force concentration during contraction are important in the development of chronic mechanical damage and tendinopathy. Some authors believe that areas of relatively poor vascular supply (e.g., the mid-Achilles tendon) also are predisposed to tendinopathy owing to impaired tendon healing (Milgrom et al. 1992).

Anterior impingement of the ankle may occur secondary to either an osseous or soft tissue lesion. Osseous impingement is due to osteophyte formation in the talus or anterior tibia. As well as being common in kicking sports, this condition is also seen in ballet dancers as it occurs in activities that involve forced dorsiflexion of the ankle joint. Soft tissue impingement is due to fibrous connective tissue formation and impingement in the anterolateral or anteromedial ankle following a sprain (Gall et al. 2008; Speed 1998; Alonso et al. 2010).

41.5.11 Foot Injuries

These fractures are a result of chronic stress due to vertical loads on the proximal third of the metatarsal shaft. Stress fracture of the fifth metatarsal, in particular, is not an uncommon injury in basketball players. Metatarsal stress fractures can occur in any sport that has repetitive jumping, landing, and cutting maneuvers, but basketball players has highest incidence of metatarsal injuries (Speed 1998; Alonso et al. 2010; McBryde 1985; Brukner et al. 1996).

Midfoot sprains usually are caused by a sudden rotation of a planted foot or an axial load on a plantar flexed foot. The classic mechanism involves a football player whose foot is planted with the toes extended and ankle plantar flexed.

Base of the fifth metatarsal fractures is subjected to fracture. This could be due to direct trauma, avulsion fracture, or diaphyseal stress fractures (Knobloch et al. 2007). Most of these fractures are non-displaced; they may be managed symptomatically.

Plantar fasciopathy is degenerative tendinopathy of the plantar fascia, which runs from the heel to the middle of the foot. This condition is common in long-distance runners and walkers (Milgrom et al. 1992).

41.5.12 Stress Fractures

Fatigue stress fracture was first described in military recruits (Jones et al. 2002; Speed 1998; Matheson et al. 1987; Gilbert and Johnson 1966). Stress fractures are overuse injuries often seen in athletes who perform high-repetition, low-impact activities, such as running, jumping, and swimming (Fahlström and Söderman 2007; Knobloch et al. 2007; Clanton and Solcher 1994; Pell et al. 2004; Chang and Harris 1996). The fractures occur when the normal bone is subjected to a frequent repetition of repetitive subthreshold forces, and the natural reparative mechanism is overloaded (Jones et al. 2002; Speed 1998; Knobloch et al. 2007; Giladi et al. 1987). Those particularly affected are military recruits and athletes (e.g., runners, dancers, and basketball players) (Jones et al. 2002; Speed 1998). Fractures usually occur during or up to 4 weeks after the commencement of preseason training (Knobloch et al. 2007; Giladi et al. 1985).

41.5.12.1 Pathophysiology of Fatigue Stress Fractures

When the bone is subjected to stress, it attempts to become stronger by remodeling its internal architecture (Jones et al. 2002; Speed 1998). Initially there will be an early osteoclastic resorption of the bone at the area of mechanical stress causing weakening of the bone (Matheson et al. 1987; Belkin 1980; Dugan and D'Ambrosia 1983). This will be followed by another phase in which osteoblastic activity increases to balance the resorption and improve strength along the stress line (Jones et al. 2002). However, during the lag time between these two phases, the bone is also more susceptible to fracture. If excessive stress continues during this remodeling, then "stress reactions" occur, involving plastic deformation of the bone (Jones et al. 2002; Matheson et al. 1987; Belkin 1980; Dugan and D'Ambrosia 1983; McBryde 1985).

41.5.12.2 Incidence of Stress Fracture in Female Athletics

Reporting of stress fractures among female athletes is increasing, predominately because of the ever-increasing mass participation in sporting and increasing the number of female recruitment in the military (Jones et al. 2002; Speed 1998; Arendt et al. 2003; Knobloch et al. 2007; Hoch et al. 2005; Bennell and Brukner 1997).

Studies of military recruits report an incidence varying from 2 to 64 % in different countries (Speed 1998; Slauterbeck et al. 2002). In one report, estimates of stress fracture rates of 5–12 % have been reported among women undergoing various entry-level military training programs, rates that are about 1.5–5 times higher than those reported for men undergoing similar training (Arendt et al. 2003; Bennell and Brukner 1997; Jones et al. 1993). More important, pelvic and femoral stress fractures, more common among women than among men in military settings, have a higher frequency of complications (Campbell and Warnekros 1983; McKenzie et al. 1985; Frnsztajer et al. 1990). Stress fractures may comprise as much as 10–15 % of all sports injuries (Arendt et al. 2003; Bennell et al. 1996) and between 4.7 and 20 % of injuries to runners (Arendt et al. 2003; Bennell et al. 1996; James et al. 1978).

41.5.12.3 Risk Factors for Stress Fracture

Risk factors for stress fracture do not differ from those for other overuse injuries. Biomechanics and alignment are important factors in the etiology of stress fracture (Matheson et al. 1987; James et al. 1978). The rigid pes cavus foot was found to be more common in stress fractures of the metatarsal and femur (Matheson et al. 1987). Tarsal bone stress fractures were also common in individuals with pronated feet (Matheson et al. 1987; Campbell and Warnekros 1983; McKenzie et al. 1985). Low aerobic fitness was strongly associated with consequent stress fracture injury (Beck et al. 2000).

Military recruits have higher rate and different patterns of stress fractures from those found in athletes (Matheson et al. 1987). Military recruits often have a lower degree of musculoskeletal fitness at the time of injury and are required to march in hard footwear, train on cement or asphalt surfaces, and have a markedly emphasized heel strike (Matheson et al. 1987). The rate of loading of the musculoskeletal system in military recruits is rapid, and the pattern of loading associated with marching is distinct. It is likely that military recruits have specific patterns of injury, which reflect these factors (Matheson et al. 1987).

41.5.12.4 Site of Athletic Stress Injuries

Stress fracture can almost affect any bone in the body (Jones et al. 2002). Stress fractures of the lower extremity account for 80–95 % of all stress fractures (Jones et al. 2002; Knobloch et al. 2007; Boden et al. 2001; Sterling et al. 1992). Running, however, appears to be the most commonly reported sport or exercise activity associated with the occurrence of stress fracture (Jones et al. 2002). Stress fractures account for 4–16 % of running injuries (Jones et al. 2002; Speed 1998). Stress fractures may be associated with a specific sport such as the humerus in throwing sports, the ribs in golfers and rowers, the spine in gymnastics, the lower extremity in running activities, and the foot in gymnastics and basketball. Stress fractures in athletes differ clinically from stress fractures in the military population (Verma and Sherman 2001; Brukner et al. 1996). The radiographic and pathologic findings do not differ. The most striking clinical differences are in the incidence and site (Angus and McBryd 1976).

The majority of stress fractures involve the tibia (Jones et al. 2002; Knobloch et al. 2007) (Fig. 41.1) (around 50 %) mainly in the proximal metaphyseal (Fig. 41.2) or upper diaphyseal (Fig. 41.3) (Wojtys et al. 1998; Touliopolous and Hershman 1999; Boden et al. 2001; Sterling et al. 1992) followed by the metatarsal bones

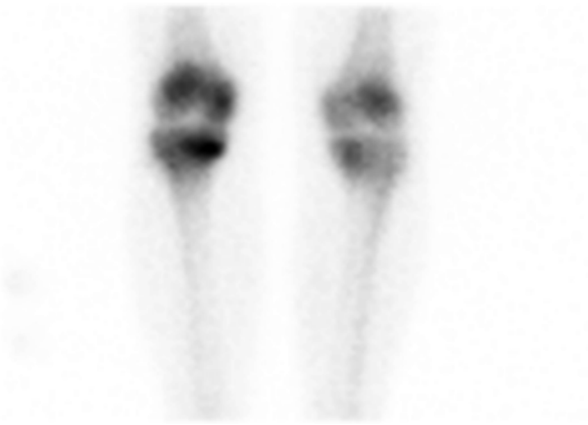

Fig. 41.1 Medial plateau stress fracture in a female military recruit

Fig. 41.2 Metaphyseal stress fracture in a female military recruit

(occurring in about 10–20 % of athletes, particularly runners) and then the fibula and the tarsal navicular bone (Fig. 41.4) (Speed 1998; Knobloch et al. 2007).

Stress fractures are far less common in the upper extremity than in the lower extremity, but fractures have been described in athletes participating in throwing sports, tennis, and swimming (Wojtys et al. 1998; Adolfsson and Lysholm 1990; Farquharson-Roberts and Fulford 1980; Murakami 1988).

Currently two types of stress fractures are classified regarding their risk (Knobloch et al. 2007): High-risk stress fractures occur in the superolateral femoral neck, anterior tibial shaft, tarsal navicular, proximal fifth metatarsal, and talar

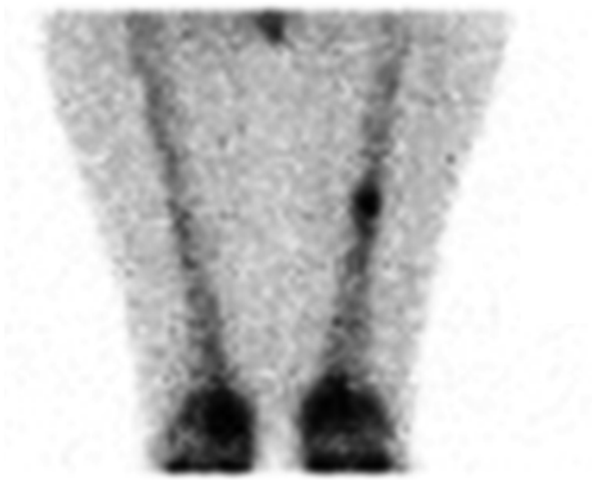

Fig. 41.3 Diaphyseal stress fracture in a female military recruit

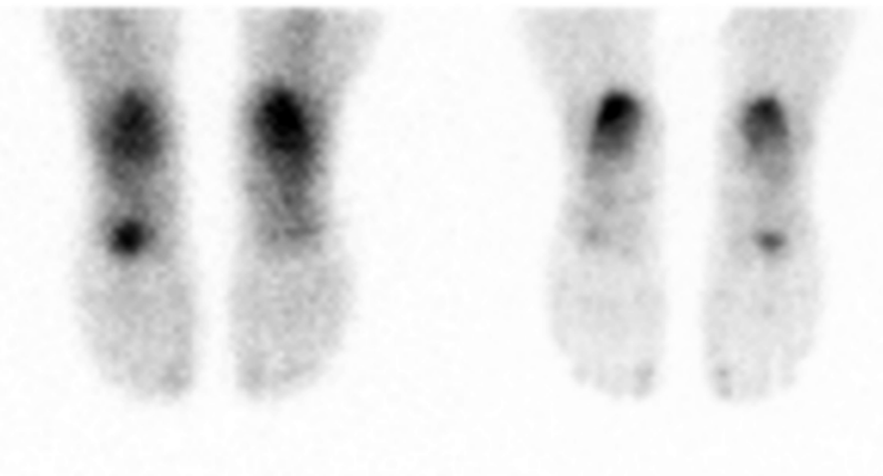

Fig. 41.4 Navicular stress fracture in a female military recruit

neck leading often to prolonged and complicated recovery. The femoral neck (Fig. 41.5) is considered a high-risk area because of the potential for displacement and can be complicated by osteonecrosis of the femoral head (Pihlajamaki et al. 2006).

Low-risk stress fractures occur in the lateral malleolus, calcaneus, and second through forth metatarsals, and the femoral shaft usually heals within 4–6 weeks without any complications (Knobloch et al. 2007; Bono 2004; Kaeding et al. 2005).

Table 41.2 lists some of the commonest stress fractures encountered in athletic females.

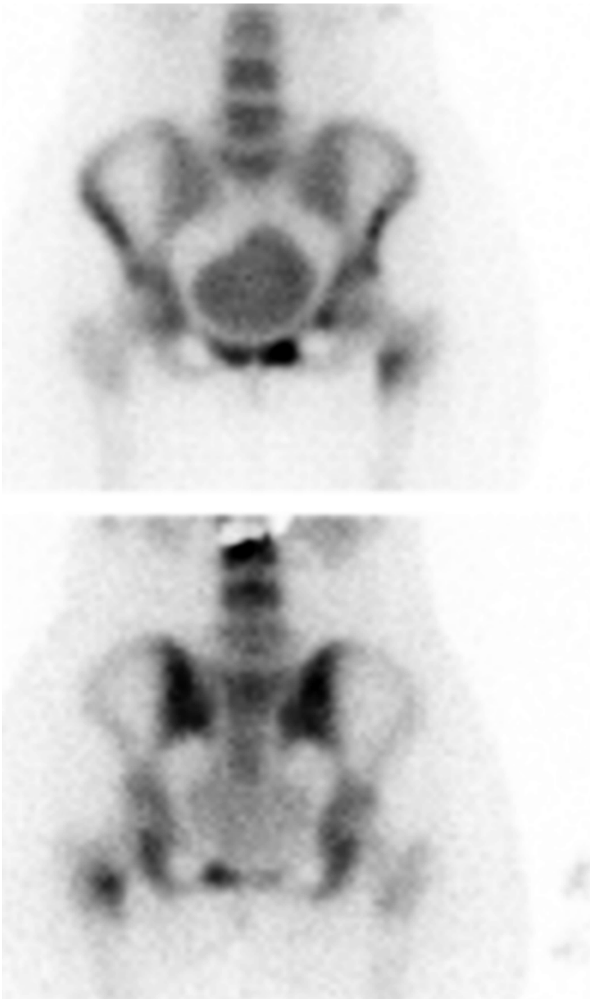

Fig. 41.5 Lesser trochanteric and pubic bone stress fracture in a female military recruit

Table 41.2 List of some of the commonest stress fractures encountered in athletic female

Bone affected	Site of fracture in the bone	Type of sport	Mechanism
Humerus	Occur in the shaft in adults	Throwing sports, baseball (Bijur et al. 1997) Cricket	Repetitive torsional forces and opposing muscular contractions during the throwing maneuver
	Proximal growth plate in skeletally immature athletes	–	–
Ulna		Tennis (Bijur et al. 1997)	
Ribs	First rib	Basketball players	Repetitive upper extremity activity
	Middle ribs	Basketball players Golfers and elite rowers Gymnasts, tennis players, and swimmers	–
Metacarpal		Tennis, handball (Bijur et al. 1997)	
Spine	Pars interarticularis resulting in spondylolysis and spondylolisthesis. Most common in L5, L4, and L3	Gymnastics, diving, wrestling, weight lifting, water skiing	Repetitive hyperextension or extension and rotation place the spine
Pelvis	Sacrum	–	Usually elderly women with osteoporosis
	Pubic rami, usually inferior	Long-distance runners Military recruits, fencing (Bijur et al. 1997) Hiking	–
Femur	Neck, shaft, and supracondylar and condylar regions	Runner, jumping Military recruits	–
Tibia	Shaft (posteriomedial), anterior cortex of the mid tibia and the medial malleolus	Runners, basketball (Bijur et al. 1997) Soccer, aerobics (Bijur et al. 1997) Military recruits, ballet dancers (Bijur et al. 1997)	–
Fibula	Proximal fibula	Military recruits	Result of a combination of muscle traction and torsional forces
	Distal fibula (more common)	Distance runners training on hard surfaces, skating, aerobics (Bijur et al. 1997)	Rhythmic contraction of the long toe flexors

Table 41.2 (continued)

Bone affected	Site of fracture in the bone	Type of sport	Mechanism
Patella		Basketball (Bijur et al. 1997)	
Calcaneus	Adjacent to medial tuberosity	Long-distance runners Military recruits Osteoporotic people	–
Metatarsals	Neck of the second (most common), third, and fourth metatarsals, and base of fifth is the least	Base of the second metatarsal in female ballet dancers	–
	Metatarsal shaft	Military recruits (march foot) Distance runners Ballet dancers	Abrupt increase in training exercises on a hard surface predisposes to injury

41.6 Clinical Approach for Athletes with Suspected Overuse Injuries

A systematic approach should be followed for athletes presented with suspected sports-related injury as early diagnosis through correct imaging will help to avoid unnecessary time-out from training or participation in sports and reduce the rate of further complication. Symptoms and clinical findings in sports injuries are often nonspecific; still some sports injuries may be diagnosed solely on history and physical examination. In questionable cases diagnostic imaging may be required for accurate diagnosis and optimal treatment planning. Plain radiography, radioisotope bone scanning (IBS), magnetic resonance imaging (MRI), and computed tomography (CT) and ultrasound (US) are used most commonly in the diagnosis of sports injury.

41.6.1 History

Patient usually presents with pain (Jones et al. 2002; Speed 1998; Wojtys et al. 1998) which is nonspecific and common in all athletics. An insidious onset of pain with a concurrent reported change in activity is a typical presentation. Pain initially occurs as a mild ache after a specific amount of exercise and then subsides. As the condition progresses, pain may become severe and occur during earlier stages of exercise (Jones et al. 2002), as well as after cessation of activity (Wojtys et al. 1998; Clanton and Solcher 1994; Pell et al. 2004; Verma and Sherman 2001). It is important to locate the pain to help the radiologist interpret any investigations. A comprehensive history should include patient medical history, nature of physical activity, and a review of the training program (Table 41.3), which can help the clinician to assess the likelihood of skeletal injury (Speed 1998).

41.6.2 Physical Examination

Clinical examination of the affected limb or body region will usually show localized palpable tenderness. In most of cases, local examination to the area affected can lead to the diagnoses (Giladi et al. 1991). In some cases a more comprehensive examination might be needed (Table 41.4) especially in the event of severe trauma or a suspicion of underlying or associated pathology (Giladi et al. 1991; Wojtys et al. 1998; Clanton and Solcher 1994; Verma and Sherman 2001).

Table 41.3 Points to be clarified in the history

Patient data	Patient's general health
	Medications
	Diet
	Occupation
	History of menstrual abnormalities such as "female athlete triad"
	Related activity
	Eating disorders
	Family history of stress fracture
	History of bony injury
Physical data	Type of physical activity or sport, sports in which leanness is emphasized
	Any recent increases in activity level (Jones et al. 2002; American College of Sports Medicine 1985)
	Details regarding training regimens
	Surface conditions
	Shoe wear

Table 41.4 Tips to be considered in the examination

Local examination	Assessment for local tenderness (Jones et al. 2002; American College of Sports Medicine 1985)
	Evidence of external erythema, laceration, bruises or swelling, and warmth (Jones et al. 2002)
	Evidence of deformity around the joints
	Range of motion of the joint (American College of Sports Medicine 1985)
	Evaluation of limb biomechanics for leg-length discrepancies, malalignment, muscle imbalance, or weakness should be performed
General examination	Neurological examination which can help in excluding any nerve injury or entrapment and rule out referred pain to the area
	Vascular examination to exclude vascular entrapment or damage
	Obtaining the height and weight, with calculation of the percentage of body fat, also may be helpful in assessing a potential eating disorder (American College of Sports Medicine 1985) BMD for patient suspected with osteoporosis (American College of Sports Medicine 1985)

41.6.3 Plain Radiographs

Plain radiographs should be performed as the first imaging step. Plain radiography is useful in the initial evaluation of patients with acute or chronic musculoskeletal pain and in the assessment of bone healing after fracture (Angus and McBryd 1976). Radiographic results may be normal for 3–4 weeks (Jones et al. 2002; Angus and McBryd 1976; Knobloch et al. 2007) after symptoms begin until the development of a periosteal reaction or cortical thickening 2–4 weeks after the onset of symptoms (Jones et al. 2002; Speed 1998). Characteristic radiographic abnormalities associated with stress fractures are a radio-transparent line interrupting cortical continuity, local periosteal reaction with addition of new bone (at 6 weeks), and endosteal sclerosis (Jones et al. 2002; Speed 1998; Angus and McBryd 1976; Wilson and Katz 1969).

A radiographic examination demonstrates a visible fracture on a plain radiograph of the affected limb which is diagnostic (Jones et al. 2002; Angus and McBryd 1976), and further imaging is usually needed only for operative planning in fractures at high risk of nonunion. Radiographs are mandatory to confirm the results after internal or external fixation with reduction of dislocations and alignment of displaced fracture fragments, for monitoring the progress of fracture healing with callus formation or detection of soft tissue calcification after severe muscle trauma (e.g., myositis ossificans). In certain pathologies where radiography is normal (e.g., medial tibial stress syndrome and impingement syndrome), plain X-ray is still helpful as it can exclude abnormalities associated with other conditions, including stress fractures, detection of bone spurs, tumors, the presence of loose bodies, or degenerative join changes (Angus and McBryd 1976).

If radiographic examination demonstrates evidence of a stress fracture, no further imaging is necessary (Clanton and Solcher 1994).

Because of overlapping structures, possible suboptimal positioning and technique, lack of dedicated special radiographic views, and other problems inherent to radiographic analysis, many fractures are not found at initial radiographic examination. Occult fractures are difficult to see, and radiographs are initially normal. The lack of soft tissue contrast resolution is a well-recognized limitation of plain radiography, but when present, soft tissue changes can be used as indirect signs of osseous pathology.

When complications of fracture healing process occur, such as infection or avascular necrosis, or there is a high suspicion of joint or soft tissue pathology, the role of plain radiography may be limited, and other imaging techniques, such as bone scintigraphy and/or MRI, may be useful for confirming the diagnosis.

41.6.4 Computerized Tomography (CT) Scans

The use of CT in bone traumatic injury allows visualization of anatomic structures without the overlap of other structures that confounds radiographic interpretation (Knobloch et al. 2007; Gaeta et al. 2005; Bensch et al. 2011; Shah and Tung 2009).

Current multidetector CT scanners can obtain slice thicknesses of less than 1 mm, which allows imaging and high-resolution reformation in any plane to obtain a high diagnostic yield. Furthermore, CT had the advantage of a wider availability and a very fast image-acquisition time of large volumes with submillimeter section thickness (Bensch et al. 2011).

CT scan can be used in the primary evaluation of suspected injuries particularly in complex bony structures such as the wrist and pelvis. CT scan may often show post-traumatic changes not shown by radiography and in the assessment of bone healing after fracture (Bensch et al. 2011; Shah and Tung 2009). Due its higher soft tissue contrast, CT scan can be used in the investigation of soft tissue and joint injuries (Bensch et al. 2011). The images should be assessed using both bone and soft tissue window settings.

Computed tomography has limited usefulness in the diagnosis of stress fracture because it has a lower sensitivity than bone scintigraphy and MRI. It may be used for patients with contraindications to MRI or those with claustrophobia. Multidetector CT arthrography is a valuable alternative to MR imaging for the assessment of internal derangement of the joints (Shah and Tung 2009).

41.6.5 Radioisotope Scintigraphy: ^{99m}Tc-MDP Bone Scan

41.6.5.1 Planer Imaging Radionuclide

Imaging has traditionally been the standard means for confirming clinically suspected stress fractures in patients with negative bone radiographs because of its high sensitivity for stress fracture detection before they are manifested radiographically (Speed 1998; Knobloch et al. 2007; Johnson et al. 2001; Drubach et al. 2001; Anderson and Greenspan 1996). Bone scan can be used in the primary evaluation of suspected fractures and in the assessment of bone healing after fracture (Speed 1998; Roub et al. 1979). The scintigraphic pattern indicative of a stress fracture is a discrete, localized area of increased uptake on all three phases of a ^{99m}Tc diphosphonate bone scan (Giladi et al. 1991). The scintigrams can be used to differentiate soft tissue injury from osseous injury with considerable accuracy and may be positive within 6–72 h of onset of pain (Speed 1998; Matin 1983). The use of the triple-phase bone scan provides quantification of an angiogram, blood pool, and delayed static image (Martire 1987).

Normal skeletal scintigraphy is used to exclude stress fracture. Its sensitivity for this diagnosis approaches 100 % (Drubach et al. 2001; Anderson and Greenspan 1996).

Stress fracture scintigraphic patterns were classified into four grades of bone response according to dimension, bone extension, and tracer concentration in the lesions (Sharma 2010):

- Grade I: small, ill-defined lesion with mildly increased activity in the cortical region
- Grade II: larger than grade I, well-defined, elongated lesion with moderately increased activity in the cortical region

Table 41.5 Indication for bone scintigraphy in sports injuries

Assessment of stress avulsion and occult fracture
Spontaneous or idiopathic osteonecrosis of the femoral condyle
Assessment sites of pathological accumulations of calcium phosphate, such as heterotopic ossifications and soft tissue calcifications
Assessment of back pain
Common insertional injuries such as shin splints
Patellofemoral syndrome
Impingement syndromes
Symptomatic subtalar coalitions
Post-traumatic arthritis
Reflex sympathetic dystrophy syndrome
Assessment of chondral and osteochondral lesions
Osteonecrosis
Osteochondroses related to sports activity, such as Osgood-Schlatter disease
Evaluation of some soft tissue lesions such as rhabdomyolysis and myositis ossificans

Table 41.6 Advantages and disadvantages of bone scintigraphy

Advantages	Disadvantages
High sensitivity	Low specificity
It is possible to visualize the whole skeleton in a short period of time	Lack of anatomical details
Early diagnoses of stress fracture	No immediate results
Useful in the assessment and early diagnosis of avulsion injuries not show by radiograph	The radiation dose for a bone scan is 75 times the dose of a normal chest radiograph
Detect occult fracture not seen by X-ray	Low special resolution

- Grade III: wide fusiform lesion with highly increased activity in the corticomedullary region
- Grade IV: wide extensive lesion with intensely increased activity in the transcorticomedullary region

Table 41.5 lists some indication of bone isotope scan in sports injuries, and Table 41.6 lists some of the advantages of bone scintigraphy.

41.6.5.2 ^{99m}Tc-MDP SPECT

The development of single-photon emission computed tomography (SPECT) has enhanced the contrast resolution of scintigraphic images by eliminating the surrounding soft tissue. This tomographic procedure allows one to examine with greater contrast and with accurate anatomical localization the lesion in the spine, hips, and knees. SPECT increases the diagnostic yield of planar BS by 20–50 %.

Improvement of the spatial resolution of the image may be achieved by using pinhole collimation. SPECT special resolution is still inferior to planar bone scintigraphy (Nathana et al. 2012; Milgrom et al. 1985; Even-Sapir et al. 2007; Mohan et al. 2010; Van der Wall et al. 2001; Matin 1979; Connolly and Treves 1998; Holder et al. 1995).

For this reason, SPECT complements but does not replace planar bone scintigraphy.

41.6.5.3 Hybrid Imaging

A major limiting factor of planar bone scintigraphy is poor specificity due to low spatial resolution and lack of anatomical markers. This is of particular importance in complex anatomical structures such as the peripheral extremities. This suggests that an imaging modality that combines the high sensitivity of functional imaging (SPECT) with the high specificity of structural imaging (CT/MRI) could overcome these limitations. The advantages of combining SPECT with CT are primarily due to the anatomical referencing and the attenuation correction capabilities of CT. These new modalities provide anatomical detail not only of bony structures but also of surrounding soft tissues. SPECT/CT can be used in the primary evaluation of suspected fractures and in the assessment of bone healing after fracture.

Hybrid positron emission tomography (PET)/computed tomography (CT) and single-photon emission computed tomography (SPECT)/CT systems provide accurate co-registration of sequential, near-simultaneous acquisition of PET or SPECT and CT.

The fusion of anatomic and molecular images obtained with integrated PET/CT or SPECT/CT systems, sequentially in time but without moving the patient from the imaging table, allows optimal co-registration of anatomic and molecular images, leading to accurate attenuation correction and precise anatomic localization of lesions.

The new PET/CT system allows the use of 18F-fluoride in the assessment of bony pathology with its superior resolution compared to planer and SPECT/MDP bone scan (Fig. 41.6). The role of 18F-fluoride imaging has been evaluated in many studies and showed promising results. Still its cost is a prohibited factor (Even-Sapir et al. 2009).

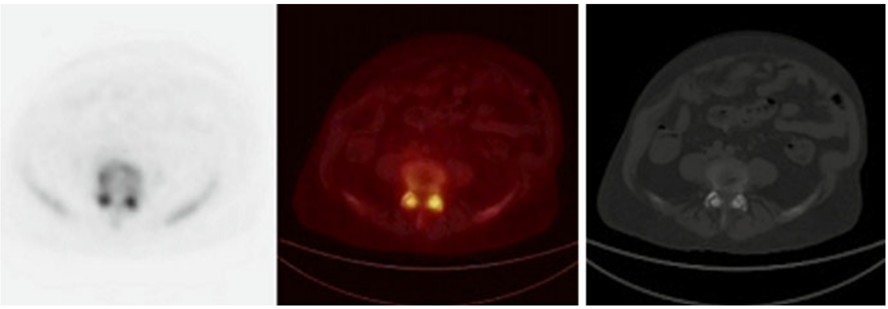

Fig. 41.6 Bilateral facet joint disease seen by ^{18}F-FDG PET/CT (for illustration)

Numerous traumatic causes of FDG uptake in the musculoskeletal have been reported including fractures and degenerative disk disease; additionally muscular uptake due to overuse due to altered mechanics is also seen (Costelloe et al. 2009).

41.6.6 Magnetic Resonance Imaging (MRI)

MR imaging has become the dominant imaging modality in the assessment of sports-related injury (Gaeta et al. 2005; Nathana et al. 2012; Mohan et al. 2010). MRI, providing excellent sensitivity and specificity, is very accurate for grading soft tissue injuries, bone injuries, and joint problems (Knobloch et al. 2007; Johnson et al. 2001; Atlan et al. 1986; Soder Ro et al. 2011; Johal et al. 2005).

MR examinations most frequently requested are of the knee and shoulder (Johal et al. 2005; MacMahon and Palmer 2011). MRI can be used in the primary evaluation of suspected fractures and in the assessment of bone healing after fracture (Speed 1998; Knobloch et al. 2007; Johnson et al. 2001). It was shown that magnetic resonance imaging is a valuable tool in identifying stress fractures. Typical MRI findings are diminished signal intensity within the fracture lines surrounded by a bone marrow edema (Speed 1998; Knobloch et al. 2007; Johnson et al. 2001; Schweitzer and White 1996). The use of gadolinium-DTPA contrast medium may allow further differentiation from pathological fractures (Speed 1998). MRI of the knee is a valuable and accurate tool for diagnosing ligamentous and meniscal tears especially in patients with sports-related knee injuries (Soder Ro et al. 2011; Johal et al. 2005; MacMahon and Palmer 2011).

Furthermore, important information about muscle biomechanics, muscle energetics, and joint function may be obtained (Soder Ro et al. 2011; Johal et al. 2005; MacMahon and Palmer 2011). Table 41.7 summarizes some of the advantages and disadvantages of MRI examination.

Table 41.7 Advantages and disadvantages of MRI examination

Advantages	Disadvantages
It provides the evaluation of an entire anatomical area including the bone	Good for the study of a limited part of the skeleton
More sensitive and specific than scintigraphy	Not always accepted by patients (claustrophobia)
Provide information about surrounding soft tissue	Incompatible with dynamic maneuvers
No exposure to ionizing radiation	Cost
Less imaging time than three-phase bone scintigraphy	
Detect bone changes earlier than X-ray	

41.6.7 Arthrography

The conventional X-ray arthrography has now been largely replaced by cross-sectional imaging techniques and is only performed as part of CT or MR arthrography (Amaral 1997).

MR arthrography is mainly used in the shoulder, wrist, ankle, knee, and hip joint. Two different techniques are described – direct and indirect MR arthrography (Johal et al. 2005; MacMahon and Palmer 2011; Shah and Tung 2009). During the direct technique, intra-articular injection of contrast medium of gadolinium-DTPA is performed, while with indirect technique, contrast medium of gadolinium-DTPA is injected intravenously (Soder Ro et al. 2011; Johal et al. 2005; Shah and Tung 2009).

Multidetector CT arthrography (CTA) (Vande Berg et al. 2002) showed to be sensitive in the studying joints. CTA has become a valuable alternative to MR imaging for the assessment of internal derangement of joints. Potential advantages of spiral CTA with respect to MR imaging are the short examination time, the availability at short notice, and limited degree of imaging artifacts related to the presence of metallic objects. Limitations of CTA include its invasiveness, possible allergic reaction, use of ionizing radiation, and poor soft tissue contrast resolution. Another major limitation of CTA imaging of the cartilage is its complete insensitivity to alterations of the deep layers of the cartilage.

41.6.8 Ultrasound

Since approximately 30 % of sports injuries deal with muscle and tendon injuries, ultrasound (US) plays a major role in sports traumatology (Nathana et al. 2012; Mohan et al. 2010). The major tendons are predominantly superficial and can be assessed (Torriani and Kattapuram 2003). High-frequency linear-array probes (9–17 MHz) are used to perform musculoskeletal US examinations (Robinson 2009; Bianchi and Martinoli 2007; Jacobson 2009).

US plays an important role in the study of muscle injuries owing to their ability to identify lesions effectively, which is closely related to the presence of edema in the damaged muscle (Takebayashi et al. 1995; Jacobson 2009).

Due to the excellence of spatial resolution and definition of muscle structure, US is considered the imaging technique of first choice for the diagnosis of muscle lesions, both in the initial phase for recognition of a lesion and during the follow-up period. The addition of color-power Doppler imaging to US has allowed for the noninvasive study of blood flow and vascularity within anatomic structures and lesions (Jacobson 2009). Ultrasound evaluation for peripheral nerve abnormalities, such as nerve entrapment disorders and nerve dislocation, is now common at many institutions as part of musculoskeletal imaging (Jacobson 2009). Furthermore, US provide image guidance for interventional procedures such as drainage of fluid collections and cysts. The usefulness of ultrasound in diagnoses of stress fracture is limited to superficial bones where there is little overlying soft tissue (Matheson

Table 41.8 Advantages and disadvantages of US examination in musculoskeletal injury

Advantages	Disadvantages
Low cost	Limited depth of penetration
Availability	Small static scan field
Ease of examination	Limited field of view
Lack of radiation exposure	Operator dependency
	Inability to penetrate osseous structure
	Subjective

et al. 1987). Early investigation into the usefulness of ultrasound in the diagnosis of metatarsal stress fractures suggests that it may have a place as an alternative to MRI (Robinson 2009; Bianchi and Martinoli 2007).

Advantages and disadvantages of ultrasound examination in sports traumatology are listed in Table 41.8.

41.6.9 Thermography

Although thermography has held promise in diagnosing stress fractures at selected sites with less cost and radiation than scintigraphy, its overall accuracy has proven to be too low to allow their use independently. Thermography is limited by its inability to distinguish conclusively soft tissue from osseous injury (Matheson et al. 1987; Goodman et al. 1985).

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Muscle Strains: Pathophysiology and New Classification Models

42

Nicola Maffulli and Angelo Del Buono

Contents

Abstract

Muscle strains occur most often at the musculotendinous junction as a consequence of an indirect trauma. Very common in sprinters and jumpers, they usually arise from an indirect trauma, from application of excessive tensile forces. Two-joint muscles, muscles contracting eccentrically and with a higher percentage of type II fibers, are most predisposed to be injured. However, the coordination and

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balance between agonist and antagonist muscles, a previous injury, inadequate rehabilitation, and warm up have to be considered as predisposing them. Since structural and biochemical changes occur after the initial insult, the overall goal is to assist the body with its natural healing process, respecting the inflammatory, repair, and remodeling phases. In an attempt to better define acute muscle strain injuries, we describe an imaging (magnetic resonance or ultrasound) nomenclature, which considers the anatomical site, pattern, and severity of the lesion in the acute stage. This system must be assessed with multiple joints to determine its utility, and additional studies are needed prior to its general acceptance.

42.1 Introduction

Muscle lesions, a high percentage of all acute sports injuries, are frequent in high-demand athletes (Jarvinen et al. 2005). Hamstrings, rectus femoris, and medial head of the gastrocnemius are the most commonly involved. They all contain a great percentage of type II fibers, a pennate architecture, cross two joints, and are injured during the eccentric phase of muscle contraction (Garrett et al. 1989). This chapter describes the pathophysiology of acute muscle strain injuries. These lesions have a significant impact on the athletes and their teams, but it is often difficult to predict short-term outcome and long-term prognosis (Best 1995). Predisposing factors and mechanisms of injury are described, and a new model of classification is showed. The object is to aid in the prevention, proper diagnosis, and management of these lesions.

42.2 Muscle Injury Classification

Acute injuries may result from direct and indirect trauma. When the insult to the muscle is direct, it produces a contusion at the point of contact; if the injury is indirect, without any contact, some myofibers are disrupted. Indirect injuries are passive or active. Specifically, passive injuries are the result of tensile overstretching forces without contraction; active lesions occur after eccentric overloads on the muscle (Garrett 1990). Contusions and strains account for more than 90 % of all sports-related skeletal muscle injuries; lacerations are uncommon (Jarvinen and Lehto 1993). Contusions occur in contact or combat sports after application of large compressive forces on the muscle. Muscle strains, very common in sprinters and jumpers, usually arise from an indirect trauma, from application of excessive tensile forces. Lacerations, rare in athletes, arise from direct blunt trauma to the epimysium and underlying muscles (Koh and McNally 2007).

In *grade I injury* (*strain*) (Fig. 42.1), the lesion involves a few muscle fibers, swelling and discomfort are complained, and strength and function are minimally impaired. Ultrasound (US) findings are often normal, with evidence of some perifascial fluid in almost 50 % of the patients. At MR imaging, a classic “feathery”

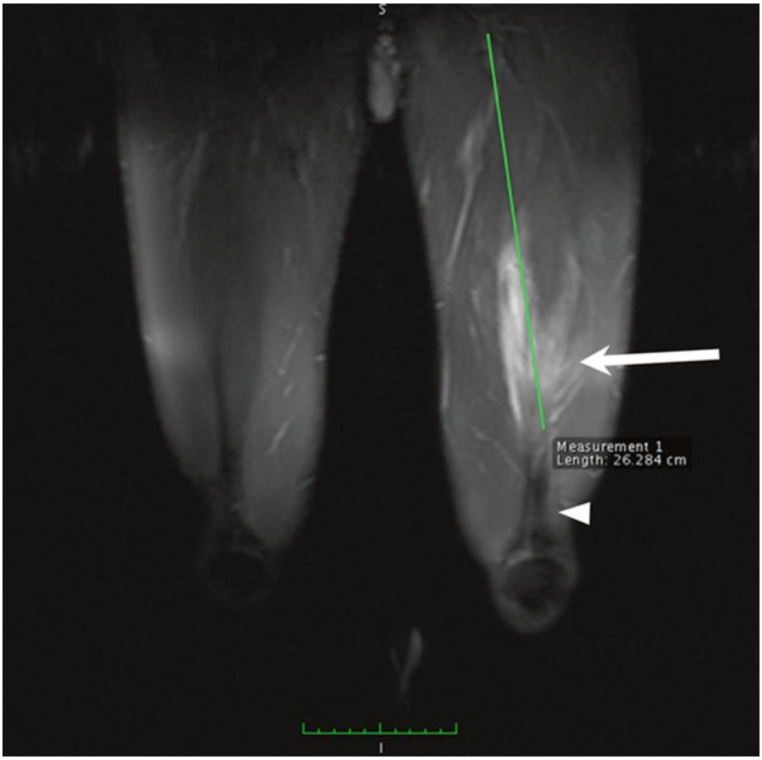

Fig. 42.1 *Grade I lesion* image of feathery edema-like pattern with intramuscular high signal on the fluid-sensitive sequences, with no discernible muscle fiber disruption (*arrow*) and adjacent to distal quadriceps tendon (*arrowhead*)

edema-like pattern may appear on fluid-sensitive sequences. Some fluid may appear in the central portion of the tendon and along the perifascial intermuscular region, without discernible disruption of muscle fibers or architectural distortion (Kneeland 1997).

In grade II injury, *a partial tear* is macroscopically evident, with some continuity of fibers at the injury site (Slavotinek 2010) (Fig. 42.2a, b). Less than one third of fibers are torn in low-grade injuries, from one third to two thirds in moderate ones, and more than two thirds in high-grade injuries. Muscle strength and high speed/high resistance athletic activities are impaired, with marked loss of muscle function. At US, muscle fibers are discontinuous, the disruption site is hypervascularized, and echogenicity is altered in and around the lesion (Lee and Healy 2004). At MRI, appearance varies with both the acuity and the severity of the partial tear, changes are time dependent, and edema and hemorrhage of the muscle or MTJ may extend along the fascial planes, between muscle groups. MRI can sometimes be predictive of the time high-performance athletes will be away from play.

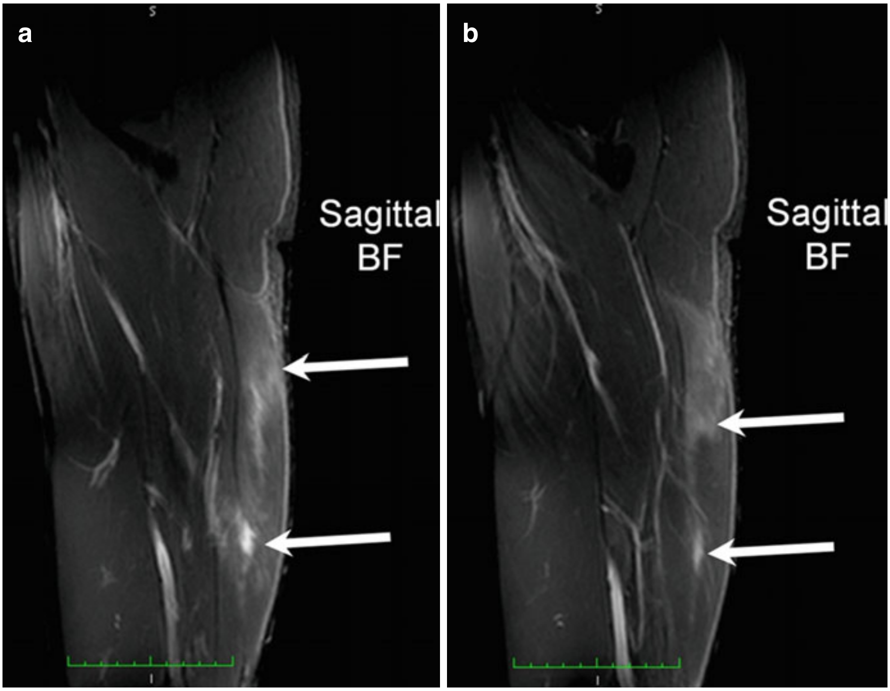

Fig. 42.2 (**a**, **b**) *Grade II tear* edema (*arrow*) and hemorrhage of the muscle or MTJ extending to the fascial planes of biceps femoris (*arrow*)

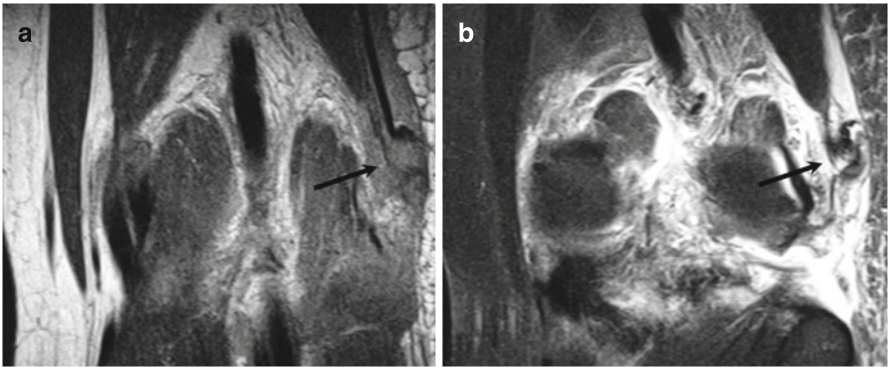

Fig. 42.3 (**a**, **b**) Grade III tear showing femoral biceps muscle and avulsed MTJ from fibula head with complete avulsion of musculotendinous junction and associated large amount of edema with complete interruption of muscle fibers and associated hematoma

A grade III injury is a complete tear (Fig. 42.3a, b). At US and MR imaging, these injuries show complete discontinuity of muscle fibers, hematoma, and retraction of the muscle ends (Lee and Healy 2004). Clinically, muscle function is lost.

When extensive edema and hemorrhage fill the defect between the torn edges, it is difficult to distinguish partial from complete tears, whereas real-time dynamic US imaging may be helpful (Koh and McNally 2007).

42.3 Predisposing Factors

Traumatic muscle injuries vary on the directions and angle movements of forces applied. Contusions, strains, or lacerations may be distinguished (Garrett 1996). Contusions and strains account for more than 90 % of all sports-related skeletal muscle injuries; lacerations are uncommon (Jarvinen and Lehto 1993). Contusions occur in contact or combat sports after application of large compressive forces on the muscle. Muscle strains, very common in sprinters and jumpers (Crisco et al. 1994, Garrett 1996), usually arise from an indirect trauma, from application of excessive tensile forces. Muscle lacerations, rare in athletes, arise from direct blunt trauma to the epimysium and underlying muscles (Koh and McNally 2007).

Three types of muscle are at possible risk for injury:

1. *Two-joint muscles*. In such instance, the motion at one joint may increase the passive tension of the muscle and lead to an overstretch injury.
2. *Muscles contracting eccentrically*. Concentric and eccentric contractions are normally performed in functional activities. Specifically, eccentric contractions, common in the deceleration phase of activity, may induce acute strains by producing specific tensions which lead to myofiber overload injury (Friden et al. 1983).
3. *Muscles with a higher percentage of type II fibers*. These are fast-twitch muscles, in which speed of contraction produced is greater than in other muscles, predisposing a muscle to injury. The fact that most of the muscle action involved in running and sprinting is eccentric, muscle strains most often occur in sprinters or "speed athletes." In these sports, the muscles more susceptible to be strained are the hamstrings, gastrocnemius, quadriceps, hip flexors, hip adductors, erector spinae, deltoid, and rotator cuff.

The coordination and balance between agonist and antagonist muscles have to be taken into account. Specifically, flexibility imbalances between agonists and antagonists may predispose to injury. Flexible muscles are most likely to be injured (Page 1995). A previous injury makes more vulnerable to reinjury, justifying that sprinters with recent hamstring injuries have tighter and weaker hamstrings than uninjured muscles (Garrett 1996).

When rehabilitation is inadequate, strength, flexibility, and endurance may not be completely restored before return to activity. Therefore, residual weakness and impairment may predispose the muscle to a new injury. From the assumption that cold or tight muscles are more predisposed to muscular strain, proper stretching exercises and warm-up may prevent muscular injury (Strickler et al. 1990). After warm-up, muscle elongation before failure is increased. In addition, since warm muscles (40 °C) are less stiff than cold (25 °C) muscles, warm-up may prevent and enhance performance (Noonan et al. 1993).

42.4 Structural Changes

The most vulnerable site for an indirect strain injury is the musculotendinous junction, the weakest link within the muscle tendon unit (Bach et al. 1987). In eccentric muscle actions, when muscle tension increases suddenly, the damage may occur in the area beneath the epimysium and the site of muscle attachment to the periosteum (Garrett 1990). In fascial injuries, common in the medial calf and biceps femoris, differential contractions of adjacent muscle bellies may produce aponeurotic distraction injuries (Koulouris and Connell 2005; Malliaropoulos et al. 2011). Hamstring strain muscle injuries, the most widely studied, typically occur in the region of the MTJ, a transition zone organized in a system of highly folded membranes, designed to increase the junctional surface area and dissipate energy. The region adjacent to the MTJ is more susceptible to injury than any other component of the muscle unit, independently from type and direction of applied forces and muscle architecture (El-Khoury et al. 1996). In this area, even a minor strain, by inducing an incomplete disruption, evident only at microscopy, may weaken it and predispose to further injury. Disruptions in the fibers cause biochemical changes both from direct injury to the fibers and from the inflammatory reaction.

42.5 Biochemical Changes

Serum creatine kinase (CK) and lactate dehydrogenase (LDH) enzyme levels are used to indirectly assess muscle damage following eccentric exercise (Stauber 1989). These biochemical markers are released after the insult. In addition, inflammatory reactions occur. Acute inflammation is designed to protect, localize, and remove injurious agents from the body and promote healing and repair (Askling et al. 2007). Chemical inflammatory mediators are present in acute muscular strain, such as histamine, serotonin, bradykinin, and prostaglandin. The capillary membrane permeability is increased, blood vessel diameter is changed, and pain receptors are stimulated. As consequence, the accumulation of proteins and transudate in the interstitial space produces edema. Therefore, swelling, heat, redness, and pain of inflammation are due to biochemical changes stimulated by chemical mediators. Inflammatory reaction and edema occur 1–2 days after a stretch-induced muscular injury (Nikolaou et al. 1987). The acute phase of inflammation lasts up to 3–4 days after the initial insult. Proliferation of fibroblasts, increased collagen production, and degradation of mature collagen weaken the tissue. In this way, stretching the tissue induces progressive irritation and limitation, up to predisposition to chronic muscle strains. When the inflammatory phase subsides, repair is started, for 2–3 weeks. Specifically, capillary growth and fibroblast activity to form immature collagen are promoted. This immature collagen is easily injured if overstressed. The final stage of healing is maturation and remodeling of collagen, occurring from 2 to 3 weeks after the insult, until patients are pain-free. In the healing phase, if fibers are not properly stressed, surrounding adhesions and scar resilient to remodeling may be formed.

42.6 Treatment of Acute Strains

Management varies on the severity of the injury, the natural healing process of the body, and the response of the tissue to new demands.

The overall goal is to assist and respect the body with its natural healing process. Therefore, the athletic trainer must not return the athlete to activity too soon. Two to three weeks of restricted activity are necessary to allow collagen formation and prevent reinjury.

42.6.1 Inflammatory Phase

Rest, ice, compression, and elevation (RICE) are indicated for at least 48 h. Rest protects the injured tissue, but immobilization may be detrimental to healing and uninjured tissues. Ice slows the inflammatory process and decreases pain and muscle spasm; compression and elevation reduce edema. Crutches are also recommended. When the inflammation subsides, passive range of motion (ROM) and gentle mobilization should be initiated to maintain soft tissue and joint integrity. Submaximal isometric muscle sets may be used at multiple angles to maintain strength and keep the developing scar tissue mobile. Aggressive stretching and strengthening should be avoided. Electrical stimulation and pulsed ultrasound should be used during both the inflammatory and repair phases to reduce pain and edema.

42.6.2 Repair Phase

The inflammatory and repair phases overlap during the first week after injury. An early accelerated rehabilitation program may prolong the inflammatory phase and lead to chronic muscle strain. When collagen is formed, it must be appropriately stressed in the normal lines of tension. Signs of inflammation (pain, swelling, redness, warmth) are signs of tissue overstress and allow to assess the rehabilitation program. Frequency, intensity, and duration of exercises are altered to allow for healing and to prevent inflammation for the next 1–2 weeks. Cold may be beneficial initially to allow for pain-free exercise and aid in the formation of the scar tissue. Gentle, pain-free stretching and pain-free submaximal isometrics can be incorporated into contract-relax techniques to help align collagen fibers. A cardiovascular conditioning program should be incorporated for any athlete not capable of full athletic participation.

42.6.3 Maturation and Remodeling Phase

When collagen is mature, tension should be applied in the line of normal stresses to remodel properly. This stage presents at about 2–3 weeks after injury and is characterized by: (1) the absence of inflammation, (2) full, pain-free ROM, and (3) pain after tissue resistance (passive ROM). The athlete is progressed as tolerated with limited participation in his/her sport. More vigorous stretching, closed- and open-chain strengthening, cardiovascular training, and sports-specific activities are allowed. Muscles must be stressed and overloaded in the manner in which they are used functionally, following the principle of specificity. Specifically, type of contraction (eccentric vs. concentric), metabolism (aerobic vs. anaerobic), and functional pattern (diagonal vs. cardinal plane) of the muscle should be respected. Eccentric exercise is functional in most athletic activities, develops greater tension than concentric exercise, and may be more comfortable in the early stages of rehabilitation (Page 1995).

Proprioceptive and endurance training are used in the advanced stages of rehabilitation. After the athlete has regained full, pain-free active ROM and over 90 % strength bilaterally, full participation is allowed. Maintenance programs should be continued to avoid any dysfunctional adaptation or compensation.

42.7 Prevention of Acute Strains

Prevention of acute muscular strains implies adequate preseason screening of flexibility and strength balances in major joints (knee, shoulder, and ankle). Flexibility, strength, endurance, and proprioception should be also assessed. Adequate agonist/antagonist ratios for strength and flexibility should be attained for major muscle groups, and muscles must be strengthened in the mode in which they are used functionally. Warm-up and stretching before activity are recommended. Specifically, active warm-up such as jogging or biking should be helpful before specific muscle stretching, especially in two-joint muscles at high risk for strain, muscles with high percentages of fast-twitch fibers (hamstrings, gastrocnemius, quadriceps, biceps), and those with high incidence of strain (hip flexors, hip adductors, erector spinae, rotator cuff). Muscles which contract eccentrically or decelerate in functional high-speed activities, such as the posterior rotator cuff in throwing athletes or the hamstrings in sprinters, should be stretched for 15–20 s and repeated four times (Taylor et al. 1993).

42.8 New Concepts

We have proposed a recent anatomic classification of acute muscle strain injuries (Table 42.1). We propose to distinguish muscular, MTJ (proximal and distal), and tendon injuries (proximal and distal). Considering the anatomy, muscular lesions can be further classified as intramuscular, myofascial, myofascial/perifascial, musculotendinous, or a combination (Chan et al. 2012; Maffulli et al. 2014). With regard

Table 42.1 Proposed classification system

Site of lesion		
1. Proximal MTJ		
2. Muscle	A. Proximal	(a) Intramuscular
	B. Middle	(b) Myofascial
	C. Distal	(c) Myofascial/perifascial
		(d) Myotendinous
		(e) Combined
3. Distal MTJ		

MTJ musculotendinous junction

to the site of injury, we classify muscular injuries as proximal, middle, and distal (Chan et al. 2012; Maffulli et al. 2014). The severity of the muscular and musculotendinous injuries is classified according to a three-grade classification system from MRI and US (Koh and McNally 2007).

Conclusion

Clinical assessment, site of injury, and pathophysiology can all provide prognostic information regarding convalescence and recovery time following both an acute muscle strain injury. The anatomical system we proposed must be assessed with multiple joints to determine its utility. Well-planned appropriately powered clinical research should be performed to determine whether the classification system put forward in the present article can be applied in clinical practice and be of greater value than current systems.

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Musculoskeletal Injuries in Dancers and Musicians

43

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Contents

Abstract

Both dancers and musicians present with specific injuries. Dancing is associated with a very high injury rate. Most injuries are soft tissue injuries such as sprains and tendinopathies. Dancers mainly present with injuries of the lower limb,

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usually localized at the ankle and foot such as dancer's toe or dancer's heel. Knee and back injuries are also common. Musicians on the other hand often suffer from injuries of the upper limb. Most frequent are the musculoskeletal problems of the wrist and hand. In this chapter an overview is given of the common injuries seen in dancers and musicians and their approach.

43.1 Musculoskeletal Injuries in Dancers

43.1.1 Introduction

Dance is a highly demanding physical and mental activity with an artistic component where flexibility, mobility, strength, condition, proprioception and coordination are extremely important. Dancers have specific injuries and a higher tolerance for pain compared to non-dancers, and treatment may differ from traditional sports medicine (Tajet-Foxell and Rose 1995; Anderson and Hanrahan 2008).

Dancing is associated with a very high injury rate. Several studies have shown an injury rate varying from 42 to 95 % of dancers injured during a 5-year follow-up period, with an incidence between 0.8 and 2.5 injuries per dancer per year (Nilsson et al. 2001; Solomon et al. 1999; Liederbach et al. 2008; Arendt and Kerschbaumer 2003; Gamboa et al. 2008). Approximately 60–76 % of dance-related injuries are microtraumatic in nature, characterized as 'overuse injuries' (Solomon et al. 1999; Kennedy and Baxter 2008). Most musculoskeletal injuries are soft tissue injuries such as sprains, strains and tendinopathies (Jacobs et al. 2012; Hincapie et al. 2008; Wanke et al. 2012). This is due to the endless repetition of movements that dancing requires to achieve perfection.

Ballet dancers frequently develop problems at the lower extremity, mainly located at the ankle and foot. This is followed by injuries of the knee, hip and back. Neck and shoulder pathology is less common (Nilsson et al. 2001; Liederbach et al. 2008; Gamboa et al. 2008; Jacobs et al. 2012; Hincapie et al. 2008; Negus et al. 2005; Leanderson et al. 2011).

Most of the scientific literature concerns ballet dancers. For this reason, the typical injuries of ballet will be in the main topic of this chapter.

43.1.2 Injuries of the Foot

Dancer's toe is an overuse tendinopathy of the flexor hallucis longus tendon (FHL), related to repetitive plantar flexion to achieve 'en pointe' (Fig. 43.1). Another common cause of FHL tendinopathy is hyperpronation in the midfoot as a result of a natural malalignment or a faulty technique. The symptoms are pain posterior to the medial malleolus that is aggravated by active flexion or passive full dorsiflexion of the first toe. 'Clicking' or 'locking' can occur in more severe cases. Adhesions may mimic an arthritic condition of the MTP joint of the great toe, by not allowing dorsiflexion of the great toe (therefore named pseudo hallux rigidus). The flexor hallucis longus tendon runs through a fibro-osseous tunnel

Fig. 43.1 (**a**) 'Demi pointe', (**b**) 'en pointe', (**c**) 'turnout', (**d**) 'fifth position'

posterior to the malleolus (Richard Drake 2009). Risk factors for impingement are an abnormally low insertion of the muscle belly or enlargement or medial displacement of the os trigonum. Although the history and examination are the most important contributors to the diagnosis, ultrasound or MRI may identify a tendinopathy and/or tendovaginitis. Only MRI is able to show bone marrow oedema in a large os trigonum.

Treatment consists of ice application, anti-inflammatory medication in the acute phase, physical therapy and limiting 'turnout' (Fig. 43.1) and working 'en pointe' during the recovery period. Furthermore, the dance technique should be improved, especially the 'jumps' and 'turnout'. During physical therapy, ice massaging, stretching and strengthening of the FHL tendon could be beneficial. Insoles can be effective in the dancer who has a naturally pronated foot. A steroid injection can be given, but weakness and rupture of the tendon may occur. Relapse after corticoid infiltrations is common (Hamilton et al. 1996). Explorative surgery and a release of the tendon sheath may be required if conservative treatment fails (Sammarco and Cooper 1998).

The most common fracture among dancers is the *dancer's fracture*. This is a spiral fracture of the shaft of the distal fifth metatarsal. It usually occurs secondary to an inversion sprain from the 'demi-pointe' position where a maximal dorsiflexion of the metatarsophalangeal (MTP) and an ankle plantarflexion is required (Garrick and Lewis 2001). The dancer will complain of immediate pain and swelling. A radiograph confirms the diagnosis. In displaced or malrotated fractures, surgery is indicated and in other cases management consists of immobilization of the fracture. During 4–6 weeks, a rocker-bottom shoe is essential, followed by 4–6 weeks of rehabilitation. The physical therapy consists of proprioception training, strengthening exercises and mobilization of the ankle.

Because of repetitive movements, dancers are vulnerable to *stress reactions and stress fractures*. The second metatarsal is the most common site for occurrence of stress fractures in dancers (Garrick and Lewis 2001). The onset is often insidious and gradually worsens until dancing is almost impossible. Risk factors specific to ballet are a faulty dance technique, gender (female > male), irregular or absent menses and malnutrition. Early diagnosis with a bone scan or MRI is possible before radiographs demonstrate the problem. Treatment is the same as in the general population.

Hallux valgus is a deviation of the great toe towards the lateral side of the foot. This is frequently seen in dancers as a result of forcing 'turning out', where excessive pronation increases valgus stress of the hallux (Quirk 1994). In early phases it is often asymptomatic, but when a deformity develops, pain and restriction of movement of the first MTP joint may occur. Radiographs reveal the severity of the pathology. Bony exostoses and a bursitis develop around the first MTP joint. Bunion means an area of swelling and refers to the prominent medial portion of the first metatarsal head. This can be the bursa or osteophyte. Footwear to reduce friction over the bunion is necessary. Correction of the valgus position of the first MTP joint by surgery is the final option of treatment.

Hallux rigidus is a term for restricted mobility of the big toe due to exostoses or osteoarthritis of the MTP joint. Symptoms are pain and restriction of dorsiflexion during demi pointe (Fig. 43.1). In an early stage, it is called hallux limitus and in young dancers the term juvenile hallux rigidus is used. It is more frequently seen in female dancers. The degree of degeneration is shown on radiographs. Initial treatment involves relative rest, NSAIDs, cortisone injection, physiotherapy and a correction of biomechanical factors with insoles. Arthrodesis is not performed in this population because surgical fixation of the MTP joint will end their career. If conservative treatment fails, cheilectomy (Roukis 2010; Wagenmann et al. 2011; Rietveld and van de Wiel 2011) or arthroplasty of the first MTP joint can be required.

Morton's interdigital neuroma is usually located between the third and fourth metatarsals (third web space). It is a swelling of the nerve and scar tissue and can be palpable in some cases (Kennedy and Baxter 2008). During compression typical pain radiating into the toes with paresthesia will be noted. Ultrasound may confirm the diagnosis. Ice application in acute phases, insoles to spread the load over the metatarsals and intrinsic foot muscle strengthening exercises are all part of the initial treatment. A corticosteroid injection can be given and in chronic cases surgical excision is indicated. Ultrasound-guided alcoholization is recently developed as an alternative to surgery.

Pain and tenderness in the metatarsal region is called *metatarsalgia*. If the second metatarsal is longer than the first, metatarsalgia is more frequent (Rietveld and van de Wiel 2011). In the ideal dance, foot metatarsal one and two are of equal length. Custom-made insoles in ballet shoes are a good solution and if this fails an osteotomy of the second metatarsal may be indicated.

The plantar fascia or the thick connective tissue which supports the arch of the foot. The inflammation tendinopathy of the plantar fascia (PF) is mostly due to repetitive microtrauma. Improper footwear, plantar fascia laxity or tightness, excessive pronation of the foot, pes planus and pes cavus are also risk factors. *Plantar fasciitis* (*fasciopathy*) gives pain at the medial calcaneal tuberosity and is aggravated with the toes dorsiflexed to tighten the PF (Woolnough 1954). Ultrasound confirms the diagnosis. Radiographs may show a calcaneal spur that is not related to the fasciitis, this in contradistinction with common thoughts. Pathology resembles that of tendinosis and it is also treated this way. Dancers may dance 'en pointe' (Fig. 43.1) but must avoid the 'demi-pointe' (Fig. 43.1) position.

Sesamoids are isolated intratendinous bones. In general, there are two sesamoids at the first MTP joint located in the flexor hallucis brevis tendon under the first metatarsal head. During 'en pointe', stress increases on the sesamoids. Injuries usually occur at the medial sesamoid.

Numerous pathological processes can occur: (stress) fracture, osteoarthritis, osteochondritis, sprain of a sesamoid, sprain of the sesamoid-metatarsal articulation, tendinopathy of the flexor hallucis brevis and ganglion cyst between the sesamoids (Mellado et al. 2003). Clinical features are pain during forefoot weight bearing and tenderness and swelling at the sesamoid. Testing the functional range of motion of the first MTP joint is usually painful and often restricted. Radiographs may rule out a fracture. However, radiographs in a stress fracture can be negative for several weeks and an isotopic bone scan or MRI is needed to clarify the diagnosis. Without treatment sesamoid problems can lead to chronic pain and disability. The initial treatment of sesamoid inflammation involves rest, ice, compression and elevation (RICE), NSAIDs and avoidance of flexion of the MTP joint as well as contraction of the flexor hallucis brevis. A sesamoid pad (padding) can distribute weight away from the sesamoid bones, and insoles are required if foot mechanics are abnormal. Corticosteroid injections may be effective. Sesamoid stress fractures are treated with 6 weeks of non-weight-bearing and are prone to non-union. Sesamoid problems should be treated non-surgically, as sesamoidectomy can create imbalance especially during 'en pointe' and may cause a hallux abducto valgus deformity. Rehabilitation can take a long time and gradual increase in weight bearing after resolving of symptoms is necessary.

43.1.3 Injuries of the Ankle

Common overuse injuries of the ankle are a posterior and anterior impingement syndrome. *Posterior impingement syndrome* is also known as *dancer's heel*. During movement of 'demi pointe' or 'en pointe', the dancers note pain at the posterior ankle. In full ankle plantarflexion, there is compression between the posterior tibia and posterior talus. On radiographs an enlarged posterior tubercle of the talus or an os trigonum may be present (Moser 2011; Russell et al. 2010).

Athletes with *anterior impingement syndrome* usually have pain at the anterior side of the ankle during movements of dorsiflexion such as ‘plié’. This is most often seen in dancers with pes cavus and an anteromedial osteophyte or in dancers with an exostose secondary to a traction injury of the joint capsule of the ankle. This injury occurs whenever the foot is repeatedly forced into extreme plantarflexion. Radiographs may show exostoses and abnormal tibiotalar contact.

If further information is required, an MRI (or bone scan) may be useful in both cases. Early management with physical therapy, relative rest and NSAIDs can be very useful. A corticoid infiltration can be given when improvement is insufficient. In anterior impingement syndrome, a heel lift to minimize the impingement can also be helpful. Surgery may be necessary if conservative treatment fails and this can be performed arthroscopically or by an open procedure.

Ankle sprains and especially sprains of the lateral ligaments are frequently seen in dancers. The anterior talofibular ligament is most commonly involved. Diagnosis and treatment are similar to those of the general population. Immediate care should include RICE. A radiograph to exclude a fracture should be done. Most of the time, sprains can be treated symptomatically with an ankle brace followed by rehabilitation involving physiotherapy during 4–6 weeks. In recurrence of ankle sprains and ankle instability, formerly radiographs in valgus and varus stress were indicated; these are now replaced by ultrasound or MRI. In chronic ankle instability, surgical stabilization could be necessary.

Achilles tendinopathy is a common injury among the general population and dancers alike. Posterior tendon irritation is secondary to the repetitive dorsiflexion and plantar flexion motions. ‘Demi pointe’ (Fig. 43.1a) places more stress on the Achilles tendon than ‘en pointe’ (Fig. 43.1b). Symptoms, diagnosis and treatment are the same as in other patients.

43.1.4 Injuries of the Lower Leg and Knee

Stress fractures of the tibia can be located at the posteromedial side of the tibia or at the anterior edge of the tibia. The last one is more resistant to treatment and is more at risk to develop non-union. The focal pain gradually increases and is provoked by movements. With palpation there is tenderness along the tibia. Bone scan or MRI is the golden standard to establish the diagnosis.

Treatment is equivalent to the ‘ordinary’ patient. It is necessary to identify which factors precipitated the stress fracture.

Periostitis, medial tibial stress syndrome or medial tibial traction periostitis gives diffuse pain at the medial border of the tibia. Dancing is possible, but pain gradually increases after dance and is worse the following morning. Radiographs are routinely negative and an isotopic bone scan may show diffuse areas of increased uptake along the cortical bone of the tibia. This is in contrast to stress fractures, which should show focal uptake. Treatment is based on symptom relief, identification of risk factors and treating the underlying pathology.

Patellofemoral pain is the preferred term used to describe pain in and around the patella. Knee problems are most often caused by patellar problems (>50 %). Overuse, abnormal Q-angle, laxity, increased range of motion of the knee and neighbouring joints (Steinberg et al. 2012), poor technique and variations in anatomic alignment of the lower extremities can give patellar problems in dancers. Dancers with excessive femoral anteversion can have compensatory faulty technique with the knee and the ankle when there is lack of turnout at the hip. Tight iliotibial bands (ITB) are also associated with patellofemoral pain in dancers (Winslow and Yoder 1995). The symptoms are diffuse anterior knee pain that is exacerbated by dance activities such as plié, knee bends, stairs or prolonged sitting (movie sign). Quadriceps or vastus medialis obliquus (VMO) hypotrophy gives the feeling of 'giving way'. Weak external rotator muscles of the hip and quadriceps, tightness in the ITB and pronated feet may be found and have to be treated. Strengthening of VMO, stretching TFL and correcting a faulty technique are indicated. Taping or bracing can be associated. Radiographs are routinely negative and surgery is rarely needed.

Subluxating and dislocating patellae occurs more in adolescent dancers with shallow trochlear grooves, abnormal Q-angles, excessive ligamentous laxity, abnormal lateral patellar movements and hyperextended knees. Subluxation can occur without any damage. Severe acute pain and hydrops is due to patella dislocation. Extension of the knee along with the quadriceps muscles pulls the patella back into position. Treatment consists of RICE. Radiography to exclude a fracture is necessary; MRI can diagnose fracture fragments and a tear of the medial patellofemoral ligament or retinaculum. Knee immobilization for a few weeks is indicated. Rehabilitation consists of strengthening the vastus medialis obliquus, which is the key to patellar control (Pattyn et al. 2011; Lin et al. 2008). Stretching the lateral structures (mainly the ITB) should be added if tight lateral retinacular structures are present. Hamstring strengthening is recommended to prevent hyperextension. Wearing a brace during class is helpful but cannot be used during performance most of the time. In case of relapse, surgery to restore the medial patellofemoral ligament is indicated.

Patellar tendinopathy (*jumper's knee*) is like other tendinopathies an overuse injury. Symptoms, diagnosis and treatment are in accordance with the classical protocol of tendinopathy.

Hyperextension of the knee or improper landing of a jump can cause *ligament injury* (MCL, LCL or ACL). In dance these injuries are not frequently seen; they more occur often during contact sports and unexpected movements. Dance movements are choreographed and therefore predictable. Symptoms, physical examination, diagnostics and treatment are the same as in the standard young and active population. Anterior cruciate ligament (ACL) reconstruction is recommended to stabilize the knee. Rehabilitation with strengthening the hamstrings and quadriceps and proprioceptive exercise to practice turning and changing direction are necessary before returning to dance.

Medial meniscal tears are caused by increased turnout; lateral meniscus is at risk during 'plié'. In *meniscus injuries* symptoms, physical examination, diagnosis and treatment are according to a meniscal tear in the general population. If the knee locks or pain and effusion persist, arthroscopy is necessary. Quadriceps setting exercises are recommended to avoid atrophy. A faulty technique has to be corrected. Exercises to encourage the use of short hip external rotators for turnout and abdominal muscle strengthening and stretching of the hip flexors to control the pelvis are useful to decrease torsion of the knee.

43.1.5 Injuries of the Hip

M. piriformis is responsible for external rotation and flexion of the hip and stabilization of the pelvic girdle. Different piriformis conditions are seen in athletes, but the diagnosis remains controversial. *Piriformis muscle strain* gives deep buttock pain that is exacerbated by sitting, prolonged standing and movement that requires external rotation and abduction of the hip. Clinical factors are chronic muscle shortening, tenderness and reduction of passive internal hip rotation. In both cases conservative stretching and strengthening of the piriformis and surrounding muscle groups or trigger point injections can be helpful.

'*Snapping*' *hip* is seen in 91 % of the dancers and in 80 % on both sides (Winston et al. 2007). It is also named coxa saltans and is divided into external (lateral) and internal snapping hip. External snapping hip is due to the posterior iliotibial band or anterior edge of the gluteus maximus muscle sliding across the greater trochanter. Internal snapping hip is described as rubbing of the iliopsoas tendon over the anterior ridge on the femoral head, the iliopectineal ridge or a portion of the iliacus muscle belly; the latter is probably the most prominent cause (Wahl et al. 2004). The iliopsoas is the most frequently involved anatomical structure in snapping hip (Winston et al. 2007). Most of the time, this snapping is asymptomatic. If pain occurs bursitis or tendinopathy should be excluded. Physical examination can show local tenderness. Moving the flexed and internally rotated hip passively to an extension and externally rotated hip may provoke 'snapping'. Ultrasonography is used to confirm the diagnosis and can show tendinosis or bursitis. Initial treatment consists of relative rest, NSAIDs for a short period, physiotherapy and attention to ballet technique. Peripelvic stretching and strengthening exercises particularly of the iliopsoas are indicated. Occasionally surgical release may be required.

43.1.6 Injuries of the Back

Due to repetitive or acute hyperextension of the spine dancers are at risk for back injury. The majority of back injuries in dancers involve the lumbar region.

Spondylolysis refers to a defect in the pars interarticularis of the vertebra without displacement of the vertebra. It is more common in the adolescent dancer and is due to repetitive extension of the lower back. The pain increases by lumbar hyperextension and the dancer notices pain with movements such as 'cambré backwards' (Fig. 43.2). The dancer will note lumbar spine stiffness, gradually worsening dull back pain that radiates into the buttock. Physical examination shows hyperlordosis and tightness of the hamstrings. Radiographs may confirm the diagnosis. Bone scan is more sensitive and indicated if radiographs are negative. The athlete with early-stage defects is best treated with a hard brace in the acute situation (Rietveld and van de Wiel 2011; Sairyo et al. 2012). Decreased activity and an anti-lordotic rehabilitation programme are necessary in acute and chronic conditions.

Spondylolisthesis is defined as the forward slippage of a vertebra in relationship to an adjacent vertebra and may be due to bilateral spondylolysis. Management is conservative and consists of lumbar bracing, avoiding lumbar hyperextension and

Fig. 43.2 'Cambré backwards'

physical therapy. Surgery could be necessary if there is severe pain, neurologic findings or in stage three (>50 %) and four (>75 %) spondylolisthesis.

Scoliosis is a sideways curvature of the spine. Scoliosis is significantly more common in dancers than in the general population. During physical examination children bend forward to 90° at the hips with the knees straight. An asymmetric prominence of one side of the thoracic or lumbar region compared to the other side is an early sign of scoliosis. Other signs such as asymmetry of shoulder height or scapular prominence, unequal arm height and waistline or lower limb length can be noted. Radiographs of the spine have to be taken to assess the severity of the curve and for follow-up. In most cases specific treatment is unnecessary but observation until completion of growth is required. A well-balanced scoliosis, even if large, does not necessarily exclude a successful dancing career.

Facet joint osteoarthritis is seen in the older dancers. Repetitive lumbar hyperextension (Fig. 43.3) causes stress on the facet joints and may result in degenerative changes. This progress occurs over years, but the symptoms can appear in a relatively short period of time. Radiographs shows facet joint osteoarthritis and a bone scan may show an area of increased activity.

Relative rest, anti-inflammatory drugs and most importantly anti-lordotic exercises are the treatment of choice. Facet infiltration or facet denervation can decrease the pain. Rarely, surgery may be considered if non-operative treatment fails.

Disc herniation is more often seen in male dancers because of lifting the partner (Fig. 43.4). Lifting with hyperlordosis of the lumbar spine and a poor lifting technique with outstretched arms away from the body may increase herniation risk. Symptoms, clinical research, diagnosis and treatment are similar as in the general population.

Fig. 43.3 Lumbar hyperextension causes stress on the facet joints. Injuries of the upper limbs occur more often in male dancers

43.1.7 Injuries of the Upper Back, Neck and Shoulder

Injuries to the bone and discs at the upper back and neck are unusual. Most of the time, it consists of muscle strains, tendinopathy or ligament sprains. They may occur during lifting as a result of muscle weakness or being off balance. These problems are more common in male than in female dancers (Figs. 43.3 and 43.4).

43.1.8 Conclusion

Musculoskeletal injuries are frequently seen in dancing, especially overuse injuries of the lower extremity. Older age, fatigue, higher intensity and frequency of training, menstrual dysfunction and psychological factors like stress and anxiety make the dancer prone to injury.

Specific injuries occur due to dancing and treatment differs from the general population. Taking a mandatory break for recovery or treatment is frustrating for many dancers and this ‘taboo’ is often enhanced by the expectations of the entourage. Finding alternative methods to keep an injured dancer active and preventing deconditioning are important. Taping and bracing are most of the time not possible during performance, not only because of the fact that full range of motion is mandatory but also because of aesthetics. Prevention is the key to decrease the incidence of injuries (Ojofeitimi and Bronner 2011). Stabilization exercises, neuromuscular control training, improving technique, a healthy diet, proper footwear, aerobic training and respecting physiologic and psychological limits play an important role in this prevention (Kiefer et al. 2011; Lee et al. 2012; Zulawa and Pilch 2012; Pearson and Whitaker 2012).

Fig. 43.4 Lifting technique is important to avoid injuries

43.2 Musculoskeletal Injuries in Musicians

Musicians, instrumentalists in particular, are prone to musculoskeletal injuries. They suffer a lot from dynamic and static stress while playing their instrument. In this chapter only injuries that occur due to instrumental playing will be described.

It is obvious that also for professional players and music students, a minor injury can threaten their career or playing level. Instrumentalists practice for hours at a time, especially before auditions and performances. This is very demanding for their muscles, joints, tendons and spine. Playing in a competitive environment, as students and professionals do, also means a lot of psychological stress.

It is mandatory for physicians to keep in mind the importance of playing an instrument for this particular population and understanding the concerns regarding these problems (Zaza and Farewell 1997; Zaza et al. 1998).

The prevalence of musculoskeletal playing injuries varies from 32 to 87 % (Paarup et al. 2011), depending on the adopted definition and the population included in the studies.

Instrumentalists suffer mostly from musculoskeletal disorders (64 %), peripheral neuropathies (20 %) and focal dystonia (8 %) (Lederman 2003; Brandfonbrener 2003). Musculoskeletal disorders consist mostly of pain syndromes or 'overuse' syndromes. In only one third of the cases, a specific diagnosis such as tendinopathy, tenosynovitis or bursitis is made. The upper body is affected most, especially the hand, forearm and wrist. Brass and wind players can also suffer from mouth or lip problems.

Females are more prone to playing injuries than men, except in the group of focal dystonias.

43.2.1 Mechanisms of Developing Injuries

The mechanism of developing an injury or musculoskeletal disorder depends on the instrument played. There are several risk factors predisposing to specific injuries or pain syndromes. Roughly, these factors consist of characteristics of the person (intrinsic factors: for example, size, physical condition, strength, joint flexibility, playing technique, etc.), extrinsic characteristics regarding the instrument – also in relationship with the characteristics of the instrumentalists – and of the repertoire played.

A sudden increase in hours of practice, or changes to the instrument or teacher, may cause problems as well.

Playing an instrument causes static stress, due to holding an instrument or keeping the body in a fixed position while playing. In an orchestra, this also includes playing in a narrow space, sitting on less ergonomical chairs and being in a position to keep an eye on both the music and the conductor.

Playing an instrument involves repetitive movement, hence causing dynamic stress.

In a symphony orchestra, string players are most at risk, especially the high strings (violists, violinists), while brass players are at the lowest risk of developing a musculoskeletal injury. When looking further into the general musical population, keyboard, guitar and harp are the instruments with the highest incidence. The lowest incidence is seen with the bassoon, brass and oboe (Paarup et al. 2011; Lederman 2003; Brandfonbrener 2003; Leaver et al. 2011; Joubrel et al. 2001).

43.2.2 History Taking and Examination

43.2.2.1 History

It is important for a physician, who looks after this kind of patients, to know about basic music terms, instruments and specific demands in relation to music type and repertoire. For example, jazz music has a different playing style in comparison to the repertoire played by a symphony orchestra.

The physician should be familiar with the importance of injuries and the specific concerns of instrumentalists.

In addition to the general history, one should focus on the music-related history. The following questions serve as an example (Dommerholt 2009, 2010a, b):

- First of all the physician should ask about the instrument they play at the moment:
  - Do they play several instruments? Which one is played most of the time? Did they play other instruments before?
  - How long have they been playing this instrument or these instruments?
  - At which level do they play? (Musical student, professional, amateur, etc.)

  - Do they play in an ensemble, symphonic orchestra or others? What kind of repertoire do they usually play?
  - How long do they practice? Are there enough rest periods?
  - Has there been a sudden change in number of hours of practice, repertoire, technique, instrument or teacher?
- One should ask about previous playing related injuries:
  - Did they already suffer from the same injury? Did they suffer from other injuries? Were there other injuries, not playing related?
  - What intervention has been taken? What was the result?
  - Are there other medical problems?
  - Are there other hobbies? Are they doing any kind of sports?
- Concerning the current problem:
  - What is the complaint?
  - When did it start?
  - When does it occur? Does it only occur when playing? Does it occur after playing?
  - Does it interfere with daily activities? Does the complaint persist at night or at rest?
  - Has there been any deterioration or change of the complaint over time?
  - Has help from other medical workers or physiotherapists been sought? Has an intervention or medication already been tried?
- A physician should also keep in mind the psychosocial stress that playing at high level can induce:
  - Do they suffer from performance anxiety? Do they suffer from other psychological problems? Is there stress in daily life?

One should always ask the patient/musician about technique, repertoire or anything else, when in doubt.

43.2.2.2 Examination

In addition to the classical clinical musculoskeletal and neurological examination, an investigation should be performed with and without the instrument. Playing the instrument in the presence of the physician may be the only way to provoke the symptoms and gain insight in the inducing factor. Ask the patient to undress the upper body in order to reveal asymmetric posture and muscle tone while playing the instrument. Consider the length of the limbs in relation to the instrument. Watch the technique while the patient is playing. Observe any tension, joint positions, body posture, how they support the instrument and excessive movements (Dommerholt 2010a, b).

43.2.3 Risk Factors

The risk factors can be divided in musician-related (intrinsic) and extrinsic instrument-related and repertoire-related risk factors. It is important to assess these factors, not only because they can give a clue to the cause but also because they require attention during interventions as they may form the base and subject for prevention strategies (Paarup et al. 2011; Lederman 2003; Brandfonbrener 2003; Leaver et al. 2011; Joubrel et al. 2001; Dommerholt 2009, 2010a).

- Intrinsic musician-related factors are:
  - Female gender
  - Older age
  - Posture
  - Size of hands/fingers/arms in relation to the measures of the instrument
  - Physical condition
  - Flexibility of the joints, especially the fingers
  - Playing technique
- Extrinsic instrument-related risk factors include:
  - Weight/size of the instrument
  - How it is played
  - How it has to be held
- Extrinsic repertoire-related factors:
  - Fast notes, long notes
  - String: playing with finger, plectrum or bow

Any change in rehearsing time, playing method, instrument, teacher or repertoire is also an important risk factor. Psychosocial stress may cause more tension and therefore plays a role in developing a playing-related problem. Often more than one risk factor is needed to cause a playing-related problem.

43.2.4 Injuries

43.2.4.1 Musculoskeletal Problems

Regional Pain Syndromes: Overuse Syndromes (Lederman 2003; Brandfonbrener 2003)

Two thirds of the musculoskeletal problems are regional pain and overuse syndromes. This term is used when no other specific diagnosis, for instance, a tendinopathy, can be made. The patient describes pain or tenderness along a muscle, tendon or muscle group related to overuse. The muscles affected are performing a lot of repetitive motions; they are used for posture and holding or playing the instrument.

The most common symptoms are pain or tenderness. It can be limited to one muscle or felt across a region of the body. There can also be signs of tightness, stiffness, cramping, fatigue or a swollen muscle. Sometimes there is numbness.

On examination the physician can get the impression of weakness of the affected muscle against resistance. This decreased strength is caused by pain. There is no muscle atrophy and neurologic examination reveals normal sensitivity and reflexes. There is local tenderness over a muscle or muscle group when palpating. There is pain while stretching the muscle. Ultrasonographic examination of the affected site is normal.

Cervical Spine, Shoulder (Lederman 2003; Brandfonbrener 2003)

Cervical spine or shoulder problems can occur as primary or secondary problems. Muscles of the cervical spine take care of posture while holding the instrument and playing. Often musicians are in poor physical condition; when holding heavy instruments the cervical spine is more at risk in these musicians.

Playing with a poor or incorrect posture may also cause problems of the neck and shoulder.

This is often seen in musicians playing the high strings, violin and viola, where there is a rotation of the cervical spine while holding the instrument. This position can also cause problems of the left shoulder and jaw while pressing the instrument between these body parts. Degenerative cervical changes may occur after time. Keyboard players are also prone to cervical problems as they bend forward to look at their hands while playing. These degenerative changes can be identified on radiographs. To exclude compression of a nerve root or other causes of cervical complaints, MRI may be done.

A thoracic outlet syndrome (TOS) can be related to a specific posture while playing an instrument. When this is the case, only a symptomatic TOS and not a real neurologic TOS is found. A symptom may be pain in the forearm and is more frequent at the ulnar side than the radial side. Sometimes pain can occur in the upper arm or in the hand. Sensibility disturbances may consist of numbness, paresthesia or a burning sensation, mostly at the ulnar side of the forearm. Symptoms can be provoked in specific positions or activities such as hyperabduction of the shoulder while playing the violin or viola, an abducted extended arm or downward traction with an endo-rotated shoulder, while carrying heavy instrument cases. Neurological examination, strength, sensitivity and reflexes can be completely normal. Violists and violinists are at risk for TOS. The left arm is most affected because of the playing position in hyperabduction.

Elbow, Forearm (Lederman 2003; Brandfonbrener 2003; Sakai 2002)

Most commonly elbow and forearm problems are caused by overuse or a regional pain syndrome as mentioned above. These complaints are related to repetitive motions while playing the instrument.

In most cases the flexors of the forearm are much stronger than the extensor muscles. They are used when playing strings or keys or maintaining grip while holding the instrument.

Extensive use of the forearm flexors, mostly seen in pianists, violists and violinists, can cause overuse syndromes at the medial epicondyle or even epicondylitis.

On the other hand, this flexion against resistance of the keys and strings causes more strength in the flexors, resulting in relative shortening compared to the extensor muscles. Extensor muscles prepare the wrist and digits for the next note to be played, by lifting the hand and fingers. This imbalance between flexors and extensors, results in increased stress of the extensor muscles at the forearm and pain over the extensor muscle compartment and the lateral epicondyle.

Lateral epicondylitis and tendinopathy of the extensor muscles, when affecting not only the insertion on the bone, may also exist. Diagnosis and staging of these conditions can easily be made with ultrasound.

Fig. 43.5 Hyperabduction of the fifth digit reaching for the keys

Fig. 43.6 Asymmetric posture can cause asymmetric development of the proximal muscle groups

Problems at the lateral epicondyle or lateral epicondylitis can also be caused by playing with hyperabducted fifth digit. This occurs, for example, while playing chords or octaves on the piano and reaching for the keys (Fig. 43.5).

Poor posture can be due to muscle weakness, imbalance or poor condition of the proximal muscle groups, the para-scapular and shoulder muscles. It can also cause pain syndromes of the forearm and elbow. Look for asymmetric development of the proximal muscle groups and bad body position (Fig. 43.6).

Fingers, Hand (Sakai 2002)

Problems in the region of the hand are mostly seen in pianists, violists and violinists. Hyperabduction of the first and fifth digit is seen while playing these instruments.

Fig. 43.7 Extensive wrist flexion; pressing the strings which causes strong and short flexor muscles; extension of the metacarpophalangeal joints; an arched finger position; and hyperabduction of the fifth digit

In addition striking or pressing keys or strings can cause problems along the thenar and hypothenar muscles of the hand. Extensive wrist flexion causes problems at the insertion of the flexor carpi ulnaris and flexor carpi radialis muscle. Tenosynovitis of the flexors is seen in the digits due to excessive finger flexion while striking keys or playing strings. As mentioned above flexor muscles have more strength than extensor muscles. The extensor digitorum communis tendon is at risk while extending the metacarpophalangeal joints followed by flexion in an arched finger position. Also the interosseous muscles are prone to pain syndromes (Fig. 43.7).

De Quervain tenosynovitis is related to playing with hyperabducted first finger. It is mostly seen in pianists, caused by playing octaves and chords. Ultrasound is helpful to diagnose and stage these conditions.

Pain in the proximal interphalangeal joints or metacarpophalangeal joints may develop. There can also be pain over the extensor region of the digits. A risk factor is joint laxity of these finger joints. The muscles will try to compensate for this reduced stability; given the imbalance of flexors and extensors, the extensor muscles will be most vulnerable to develop muscle pain in the hand and forearm.

While playing with hyperabducted fifth and fourth digit, mostly in pianists, there is increased valgus stress on the radial collateral ligaments of the proximal interphalangeal joints.

Basic Principles of Therapy (Lederman 2003; Brandfonbrener 2003; Warrington 2003)

First of all, there should be a period of relative rest. Only in severe cases full rest is necessary, and only for a short period of time. The use of anti-inflammatory drugs should be restricted. It might be helpful in a tendinopathy with concomitant paratenonitis, tenovaginitis or bursitis and only for a short period. The use of ice is also favoured, especially after exercises or playing.

When the pain is under control, one can start physical therapy.

Thorough examination with and without the instrument reveals muscle imbalances, bad posture, restricted range of motion or simply the muscles needed for playing and holding the instrument. Based on these observations, an exercise program can focus on impairments. Supportive muscles, spine and shoulder muscles, should be trained. The muscles used for playing should be trained for endurance and not for force. They need to be practiced with light resistance and many repetitions. Stretching of the muscles to prevent shortening and mobilization of the joints should be done.

If there are restrictions, based on the anatomy of the musician in reference to the instrument, modifications or attachments to the instrument can be necessary. Extended keys, for example, on a flute, neck straps to hold the instruments, a modified chin hold for the violin, etc.

Sometimes the playing posture needs to be corrected or more ergonomical seats are used.

When hyperlaxity of the fingers is seen, isometric exercises of the muscles around the specific joints are advised. Ring splints can be used temporarily or permanently while playing.

Intermittent splinting during daily activities and while playing may be considered in De Quervain tenosynovitis.

43.2.4.2 Peripheral Nerve Injuries

These problems mostly consist of compression neuropathies seen at predilection sites. They are frequently seen in the general population and have the same characteristics.

Ulnar Nerve Neuropathy (Brandfonbrener 2003)

A compression of the ulnar nerve at the cubital tunnel of the elbow may cause pain at the elbow, radiating downwards along the ulnar side of the forearm into the hand. Paresthesias with ulnar distribution may also exist. Atrophic ulnar innervated flexor muscles can be seen. A provocative test is flexion of the elbow during 1 min. Tinel at the cubital tunnel should be tested.

This problem is frequently seen in viola and violin players. The left arm is affected most because of the finger movements in an excessive flexed and supinated arm position (Fig. 43.7).

Therapy consists of changing the degree of elbow flexion while playing. Night splints can be prescribed to keep the elbow in 140° of extension at night.

During daytime unnecessary flexion of the elbow should be avoided. When this conservative treatment fails, surgical decompression or transposition of the ulnar nerve can be considered.

Sometimes the compression site is elsewhere, proximal of the elbow or at Guyon's canal of the wrist. Compression site may not always be clear. Motor problems with muscle wasting are predominant in proximal compression.

Nerve conduction studies and electromyography should be performed. They confirm the diagnosis and assess the severity of the condition. Ultrasound can be done to exclude masses at the cubital tunnel and may demonstrate intermittent dislocation of the nerve. It may show thickening of the nerve.

Median Nerve Neuropathy (Brandfonbrener 2003)

The most common entrapment syndrome is the carpal tunnel syndrome of the wrist. Pain can occur in the hand and/or forearm. Paresthesias are present in the distribution of the median nerve. This occurs mostly at night. There can be loss of dexterity. Motor loss and muscle wasting is seen in advanced stages.

The examination may show a positive Tinel at the wrist and positive Phalen's test. These signs are not obligatory to make a confident diagnosis.

It is seen in keyboard players, bilaterally but mostly often the right hand, and in string players. It may also occur bilaterally in woodwind and brass players or in percussionists. It is caused by playing with a hyperflexed wrist. Because of the high prevalence in the general population, one must consider causes beyond the playing-related causes.

Treatment consists of reduced wrist flexion while playing, wearing night splints and stretching. Use of corticoid infiltration must be restricted because of possible side effects, especially damage to the tendons. When conservative treatment has no effect, surgery is an option. In musicians surgical treatment has to be a well-considered decision, only in case of failed conservative treatment.

Other compression sites are less common, for example, the pronator syndrome or the nervus interosseus anterior.

Again nerve conduction studies and needle electromyography are useful examinations. Ultrasound may exclude mass lesions and may show thickening of the median nerve in the carpal tunnel.

Others (Brandfonbrener 2003)

Nerve problems regarding mouth and lips are seen in brass and woodwind players. They cause difficulties with producing tones.

43.2.4.3 Focal Dystonias (Brandfonbrener 2003)

Similar to a writer's cramp it is also named a musician's cramp. Men are more affected than women. It has an insidious onset. The patient experiences difficulties to make fast movements of the hand and fingers and coordination problems may occur. There is cramping, stiffness and sometimes muscle fatigue. Usually there is no pain. It is a very task-specific condition, which may only occur while playing a specific instrument. On examination, reflexes are normal and so are nerve conduction studies with electromyography.

In string players this is most seen in the left hand, with involuntary flexion of the third and fourth digits. In keyboard players the right hand is more affected, classically the fourth and fifth fingers. Brass and woodwind players may also suffer from dystonias, especially of the jaw or mouth. In clarinetists an involuntary extension of the third finger is also seen.

Most therapeutic options are very disappointing, especially in the long term. Most effective is a change in technique and posture. There can be benefit in focal limb dystonia with toxin injections.

43.2.5 Preventive Strategies

To prevent injuries related to playing music or overuse syndromes, an increase in awareness among musicians is mandatory. They need to look for medical help as soon as possible to prevent the worsening of the injury and aim for a faster return to a pre-injury level of playing. An important focus should be on playing technique, good posture, ergonomic seats and adjusted music stands. Taking breaks every hour while practicing is necessary.

A good warm up with and without the instrument, as well as a proper cooling down, helps to prevent overuse injuries.

Taking care of one's physical condition in general can prevent muscle weakness especially postural muscles. Muscle stretching is also necessary as a part of the warm up, during playing and during breaks (Lederman 2003; Brandfonbrener 2003; Warrington 2003).

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The Heart as a Special Muscle in Athletes and Anabolic–Androgenic Steroids (Ab)use

44

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Contents

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Abstract

Adaptation of the heart muscle in response to exercise has been extensively described. Different forms of sports may imply a different strain to the heart. In this context endurance sports are considered to induce a dynamic, isotonic workload, which is accompanied by an increase in heart rate and stroke volume and a reduction in peripheral vascular resistance.

Sudden athlete death (SAD) is a widely publicised and increasingly reported phenomenon. For many, the athlete population epitomise human physical endeavour and achievement, and their unexpected death comes with a significant emotional impact on the public.

Anabolic–androgenic steroids (AAS) are abused for enhancing muscle mass, strength growth and improving athletic performance. In recent years many observational and interventional studies have shown important adverse cardiovascular effects of AAS abuse.

Imaging with nuclear medicine with or without combined CT techniques, echocardiography and CMR are promising methods to target and image certain biomarkers in the process of cardiovascular pathology that can be used for early detection of sport- and also AAS-associated adverse effects.

This book chapter discusses the physiological background of myocardial (dys)function in athletes and established and novel nuclear molecular imaging techniques, including MRI, that may serve as potential tools for early detection of sport- and AAS-associated cardiovascular disorders and reducing cardiovascular sudden deaths in athletes.

Abbreviations

^{123}I-MIBG	^{123}I-metaiodobenzylguanidine
AS	Aortic stenosis
ACS	Acute coronary syndrome
AT1	Angiotensin-1
AAS	Anabolic–androgenic steroids
RGD	Arginine–glycine–aspartate
ARVC	Arrhythmogenic right ventricular cardiomyopathy
CO	Cardiac output
CMR	Cardiovascular magnetic resonance
CPT	Cold pressure test
CAD	Coronary artery disease

CR	Coronary reserve
CTA	CT angiography
DHEA	Dehydroepiandrosterone
ECG	Electrocardiography
FFR	Fractional flow reserve
gRE	Global relative enhancement
HCM	Hypertrophic cardiomyopathy
HRV	Heart rate variability
H/M	Heart/mediastinum
BMIPP	^{123}I-beta-methyl-iodophenylpentadecanoic acid
IDC	Idiopathic dilated cardiomyopathy
LGE	Late gadolinium enhancement
LV	Left ventricle
LVEF	Left ventricular ejection fraction
LVH	Left ventricular hypertrophy
MBF	Myocardial blood flow
MDCT	Multi-detector computed tomography
MI	Myocardial infarction
MUGA	Multigated acquisition scan
MPI	Myocardial perfusion imaging
MPR	Myocardial perfusion reserve
PET	Positron emission tomography
RAS	Renin–angiotensin system
RPP	Rate–pressure product
RV	Right ventricle
RVEF	Right ventricular ejection fraction
SPECT	Single-photon emission computed tomography
SV	Stroke volume
SAD	Sudden athlete death
USPIO	Ultra-small superparamagnetic particles of iron oxide
VCAM-1	Vascular cell adhesion molecule-1
WR	Washout rate

44.1 Introduction

Sudden athlete death (SAD) is a widely publicised and increasingly reported phenomenon. For many, the athlete population epitomise human physical endeavour and achievement and their unexpected death comes with a significant emotional impact on the public. The term "sudden athlete death" (SAD) has often been used interchangeably with "sudden cardiac death". The international classification of diseases (10th revision) defines sudden cardiac death as death due to any cardiac disease that occurs out of hospital, in an emergency department or in an individual reported dead on arrival at a hospital (Goldberger et al. 2008). In addition, death must have occurred within 1 h after the onset of symptoms. Sudden cardiac deaths

Table 44.1 The incidence of death from cardiac causes from the study on sudden death in 1866 athletes in the United States and where possible comparison with reported incidence of sudden death in athletes in the Veneto region of Italy (Corrado et al. 1998; Maron et al. 2009)

	Incidence	
Cause	American study	Italian study
HCM	36.3	2.0
Coronary artery anomalies	17.2	12.2
Myocarditis	8.3	6.1
ARVD	5.9	22.4
Ion channel	4.3	
MVP	3.6	10.2
Myocardial bridge	3.5	4.1
Coronary artery disease	3.3	18.4
Aortic rupture	3.3	2.0
Aortic stenosis	2.8	
Dilated cardiomyopathy	2.5	2.0
Congenital heart disease	1.2	
Myocardial infarction	1	
Conduction system disease	2.3	8.2
Possible HCM	17.2	

HCM hypertrophic cardiomyopathy, *ARVC* arrhythmogenic right ventricular cardiomyopathy, *MVP* mitral valve prolapse

within this group are often without prior warning. This is found in the younger athletes due to underlying congenital pathology and in the older athletes with coronary artery disease (CAD) (Table 44.1). Preceding symptoms of exertional syncope and chest pain do, however, occur and warrant investigation. Similarly, a positive family history of sudden death in a young person or a known family history of a condition associated with SAD necessitates further tests. Screening programmes using medical history, physical exam and ECG aimed at detecting those at-risk individuals also exist with the aim of reducing fatalities and cardiovascular complications associated with intensive training programmes of athletes (Drezner et al. 2013).

44.1.1 Myocardial Function/Dysfunction in Athletes in Endurance and Power Sport

The heart is a striated muscle with similarities and dissimilarities compared to the striated skeletal muscle. Although both muscle cell types contain actin and myosin filaments, there is a large difference in the structural organisation of the cells. Cardiac myocytes in contrast to skeletal myocytes form a syncytium. This implies a propagation of action potentials after the activation of one of its cells.

Adaptation of the heart muscle in response to exercise has been extensively described. Different forms of sport may imply a different strain to the heart. In this context endurance sports are considered to induce a dynamic, isotonic workload, which is accompanied by an increase in heart rate and stroke volume and a reduction in peripheral vascular resistance. Strength sports on the other hand induce a static, isometric workload, which is accompanied by only a small increase in heart rate and stroke volume and a high increase in systolic and diastolic blood pressure. In short, endurance sports result predominantly in a volume load and strength sports in a pressure load for the heart. Despite the differences in load, it is generally accepted that all forms of high-level sport which result in an athletes' heart are characterised by left ventricular hypertrophy, which may be eccentric or concentric. In the eccentric form of LV hypertrophy, the LV cavity sizes tend to be larger than controls. Wall thickness in strength athletes tend however to be higher than in endurance athletes assigned as the concentric form (Prior and La Gerche 2012). Interestingly, the adaptation of the cardiac muscle in response to exercise is regarded as physiological remodelling. This means that the hypertrophy is characterised by a normal myocardial architecture with a normal myocyte–capillary ratio and without fibrosis.

The effect of strenuous exercise on the right ventricle. In contrast to LV function, RV function has long been underexposed. Maybe this was caused by the limited modalities to image and evaluate RV function. Retrospectively it is very curious that RV function was long neglected; most ventricular arrhythmias originate from the RV and an excessive increase of cardiac output (CO) is not only by an increase of the stroke volume of the LV but also of the RV. Studies of Corrado stressed the importance of arrhythmogenic RV cardiomyopathy (ARVC) as the main cause of SUD in athletes in Italy (Corrado et al. 2006). The group of La Gerche, demonstrating the development of RV dysfunction and structural remodelling, performed important work on the aetiology of RV dysfunction (La Gerche et al. 2011). Important results were generated by imaging techniques, not only echocardiography but especially with cardiac magnetic resonance imaging (CMR).

The RV is wrapped around the LV septum and is differently shaped. The shape and the thin wall make it difficult to study RV function by traditional imaging techniques. In contrast to the LV, pressure is lower and filling partly dependent on the negative intrathoracic pressure during inspiration facilitates venous return from venous (low pressure) system. Although pressure is much lower, the stroke volume (SV) is generally equal to the LV. In maximal exercise SV can increase from 60–80 cc to 100–125 cc in untrained but in athletes up to even a 200 cc (Gurtner et al. 1975). This high volume can be accommodated in the systemic circulation by arterial vasodilation especially in the muscles and the skin. Due to a decrease in afterload, the increase of LV pressure and strain on the OV wall is limited. In contrast, the capacity of vasodilation in the pulmonary circulation is limited and its maximum will be reached soon, already at submaximal exercise intensity levels. A substantial increase in pulmonary arterial pressure is a consequence of the large increase of SV during maximal exercise, leading to a substantial increase not only of preload but especially of afterload. The La Gerche group has demonstrated the consequences of this volume and pressure overload. After intense endurance exercise, they demonstrated acute dysfunction of the RV (in contrast with a persistent normal LV function) and a significant rise of serum troponin levels. With DGE-CRM, they demonstrated myocardial fibrosis of the RV in endurance athletes (La Gerche et al. 2012).

Using modern echocardiography techniques, it has become clear that the right ventricle in athletes shows a profound adaptation (La Gerche et al. 2011). Right ventricular mass as well as volumes increase especially in endurance athletes (Aaron et al. 2011). Right ventricular abnormalities found in athletes may actually mimic right ventricular arrhythmogenicity (Ector et al. 2007). All in all, left as well as right ventricular adaptations and abnormalities may develop in athletes.

44.1.2 Anabolic–Androgenic Steroids (AAS)

Anabolic–androgenic steroids (AAS) are abused for enhancing muscle mass, strength growth and improving athletic performance. In recent years many observational and interventional studies have shown important adverse cardiovascular effects of AAS abuse.

Cardiovascular adverse effects of AAS abuse have been reported sporadically as case reports of hypertension (Stergiopoulos et al. 2008), myocardial infarction (MI) and stroke (Stergiopoulos et al. 2008), dysrhythmia (Angelilli et al. 2005), cardiomyopathy (Ahlgrim and Guglin 2009) and sudden cardiac death (Fineschi et al. 2007) in bodybuilders with long-term AAS abuse in the recent years. Case reports on hard atherosclerotic end points (sudden cardiac death, MI or stroke) comprise young AAS abusers without pre-existent cardiac risk factors, suggesting that a high AAS dose imposes additional independent risk to conventional cardiovascular risk factors.

Growth hormone (GH) has also a significant role in cardiovascular function. Acromegaly, a state of endogenous GH excess, results in myocardial hypertrophy and decreased cardiac performance with increased cardiovascular mortality. Additional insight into the role of excess GH on the cardiovascular system has been gained from data collected in athletes doping with GH. Likewise, however important, GH abuse and cardiovascular risk in athletes will be beyond the scope of this chapter.

44.1.3 Imaging with Nuclear Medicine with or Without Combined CT Techniques and CMR

Imaging with nuclear medicine with or without combined CT techniques and CMR is a promising method to target and image certain biomarkers in the process of cardiovascular pathology that can be used for early detection of sport- and also AAS-associated adverse effects. A number of modalities and tracers are currently being developed that may become useful to delineate functional abnormalities in several pathways involved in sport- and AAS-induced cardiovascular injury at the preclinical and clinical level. Single-photon emission computed tomography (SPECT/CT) and positron emission tomography (PET/CT) are nuclear imaging cameras for the evaluation of several cardiovascular processes using different radiopharmaceuticals. Cardiovascular magnetic resonance (CMR) can be used for anatomical structures related to cardiovascular diseases and also for functional imaging. Important cardiovascular imaging items are myocardial ischemia, viability, left and right ventricular ejection fraction (LVEF and RVEF, respectively), myocardial innervation, atherosclerosis, valve abnormalities (CMR) and flow velocities (CMR).

This book chapter discusses the physiological background of myocardial (dys) function in athletes and established and novel nuclear molecular imaging techniques, including MRI, that may serve as potential tools for early detection of sport- and AAS-associated cardiovascular disorders and reducing cardiovascular sudden deaths in athletes.

44.2 Nuclear Medicine and CMR Imaging of Heart Disorders in Athletes

Nuclear medicine techniques such as SPECT/CT, PET/CT and gated blood pool MUGA can be used for function, perfusion, viability and molecular imaging. Myocardial perfusion imaging (MPI) SPECT using ^{99m}Tc-labelled myocardial perfusion tracers is an established imaging technique that is already an integral part of managing several heart diseases and is included in a number of professional guidelines. For instance, many studies have assessed the diagnostic accuracy of MPI for the detection of coronary artery disease using a combination of rest and (adenosine or bicycle) stress MPI SPECT (Hendel et al. 2010; Kapur et al. 2002; Koh et al. 2011). The widespread application of ^{99m}Tc-labelled myocardial perfusion tracers and the data processing capacity have made ECG-gated SPECT imaging part of the clinical routine in nuclear imaging laboratories (Germano et al. 1995). ECG-gated tracers using ^{99m}Tc-labelled perfusion tracers permit assessment of regional myocardial wall motion and wall thickening throughout the cardiac cycle, due to their high count rates and stable myocardial distribution with time. The automatic quantification of LV volumes, ejection fraction (EF), regional myocardial wall motion and thickening from gated SPECT is rapid and accurate, with minimal operator interaction, and is therefore widely used. In a large cohort of unselected patients with known or suspected ischemic heart disease, the values of LVEF routinely measured by echocardiography, gated SPECT and LV angiography were closely correlated and provided a powerful prognostic information that was incremental to clinical variables for gated SPECT (Gimelli et al. 2008). PET imaging is an established technique for absolute myocardial perfusion quantification (Slart et al. 2011; Tio et al. 2009a, b) and to distinguish viable from scarred myocardium (Slart et al. 2005, 2006); however its dependency of cyclotrons and high costs have limited the widespread use in clinical practice. PET has however several technical advantages over gamma-technique SPECT such as higher counting sensitivity, higher spatial resolution and absolute quantification of myocardial perfusion flow and metabolism by using ^{18}F-fluorodeoxyglucose (^{18}F-FDG) (Slart et al. 2004). Also LV function can be quantified by gated PET techniques, using myocardial perfusion tracers such as ^{13}N-ammonia, rubidium-82 (^{82}Rb) or the viability tracer (^{18}F-FDG). MUGA (multigated acquisition scan) is a relative old technique for LV function assessment but is highly reproducible (van der Vleuten et al. 2005). Myocardial perfusion SPECT and PET can be combined with calcium scoring angiography of the coronary arteries by adding CT technology. This can be performed on the hybrid SPECT/CT and hybrid PET/CT camera in a single procedure. Functionality (myocardial perfusion) and morphology (calcium deposition and coronary stenosis) will be combined in one session. Myocardial perfusion and calcium scoring are partly related in the diagnosis of cardiovascular disease and, combined, showed to be a strong prognostic predictor for cardiovascular events (Danad et al. 2012; Ghadri et al. 2012). Red blood cells are labelled with ^{99m}Tc-pertechnetate after the injection of stannous chloride (in vivo method most commonly used), and gamma camera acquisition is performed during ECG gating. The resulting images show that the volumetrically derived blood pools in the chambers of the heart and timed images may be computationally interpreted to calculate the ejection fraction and injection fraction of the heart.

Molecular imaging differs from traditional nuclear imaging in that probes known as biomarkers are used to help image particular targets or pathways. Biomarkers interact chemically with their surroundings and in turn alter the image according to molecular changes occurring within the area of interest. For instance, myocardial sympathetic innervation related to arrhythmias ^{123}I-MIBG can be visualised and quantified with ^{123}I-*meta*iodobenzylguanidine ^{123}I-MIBG SPECT or ^{11}C-*meta*hydroxyephedrine (^{11}C-mHED) PET and ^{11}C-CGP-12388 PET for β-adrenoceptor quantification (Bengel and Schwaiger 2004; de Jong et al. 2005; Flotats et al. 2010). There is a growing body of literature on the utility of ^{123}I-MIBG for patient risk stratification and its potential role in important management decisions such as for cardiac resynchronisation therapy and defibrillator placement (Kelesidis and Travin 2012).

Other cardiovascular targets that can be visualised and quantified with nuclear molecular imaging are angiogenesis, inflammation, proteolysis, apoptosis, fatty acid metabolism and stem cell therapy (Bengel et al. 2009; Majmudar and Nahrendorf 2012; Miyagawa et al. 2005; Stacy et al. 2012). For the assessment of cardiac function and morphology, cardiovascular magnetic resonance imaging (CMR) allows also a multifaceted approach to cardiac evaluation by enabling an assessment of anatomy, function, perfusion, viability, tissue characterisation and blood flow during a single comprehensive examination (Ibrahim 2012). Delayed-enhancement (DE)-CMR using gadolinium contrast agent provides a direct assessment of myopathic processes. This permits a fundamentally different approach than that traditionally taken to ascertaining the aetiology of cardiomyopathy, which is vital in patients with nonischemic cardiomyopathy and incidental coronary artery disease and patients with mixed, ischemic and nonischemic, cardiomyopathy. Precise tissue characterisation with DE-CMR also improves the diagnosis of left ventricular thrombus, for which it is the emerging clinical reference standard. Velocity-encoding CMR is used for measuring blood flow. Velocity-encoding images are used for evaluating the valvular and vascular conditions (Mohiaddin et al. 1991).

44.2.1 Ventricular Dysfunction

The athlete's heart is commonly characterised by an increase in left ventricular mass because of an increase in the left ventricular diastolic cavity dimensions or wall thickness or both. A previous study examined the cardiac structure and function of a unique cohort of documented lifelong, competitive endurance veteran athletes (>50 year) (Wilson et al. 2011). Twelve lifelong veteran male endurance athletes [mean ± SD (range) age: 56 ± 6 years (50–67)], 20 age-matched veteran controls [60 ± 5 years (52–69)] and 17 younger male endurance athletes [31 ± 5 years (26–40)] without significant comorbidities underwent cardiac magnetic resonance (CMR) imaging to assess cardiac morphology and function, as well as CMR imaging with late gadolinium enhancement (LGE) to assess myocardial fibrosis. Lifelong veteran athletes had smaller left (LV) and right ventricular (RV) end-diastolic and end-systolic volumes ($p < 0.05$) but maintained LV and RV systolic function compared with young athletes. However, veteran athletes had a significantly larger absolute and indexed LV and RV end-diastolic and end-systolic volumes, intraventricular septum thickness during diastole, posterior wall thickness during diastole and LV and RV stroke volumes ($p < 0.05$), together with significantly reduced LV and RV ejection fractions ($p < 0.05$), compared with veteran controls. In six (50 %) of the veteran athletes, LGE of CMR indicated the presence of myocardial fibrosis (four veteran athletes with LGE of non-specific cause, one probable previous myocarditis and one probable previous silent myocardial infarction). There was no LGE in the age-matched veteran controls or young athletes. The prevalence of LGE in veteran athletes was not associated with age, height, weight or body surface area ($p > 0.05$) but was significantly associated with the number of years spent training ($p < 0.001$), number of competitive marathons ($p < 0.001$) and ultra-endurance (>50 miles) marathons ($p < 0.007$) completed. An unexpectedly high prevalence of myocardial fibrosis (50 %) was observed in healthy, asymptomatic, lifelong veteran male athletes, compared with zero cases in age-matched veteran controls and young athletes. These data suggest a link between lifelong endurance exercise and myocardial fibrosis that requires further investigation. Another study in endurance athletes examined the influence of exercise on the RV function (Schattke et al. 2012). After exercise, the RV volumes decrease significantly when measured by CMR compared to baseline. This was confirmed by a study of la Gerche et al., in which they found that exercise induces a relative increase in wall stress of the RV which exceeds LV wall stress in athletes (La Gerche et al. 2011). Also in athletes, greater RV enlargement and greater wall thickening may be a product of this disproportionate load excess.

Athletes show a significant decrease in ventricular volumes and LV wall mass with increasing age, which probably reflects decreasing training intensity rather than the effect of age (Prakken et al. 2011). Mature athletes form a distinct group requiring separate reference values as they have significantly lower ventricular volumes and wall mass as compared to young athletes, however, still significantly higher values than mature non-athletes. Cardiac MRI reference values showed also increased ventricular volumes, diameters, wall mass and wall thickness for endurance athletes compared with non-athletes. High training hours/week and male sex resulted in an increased overlap with standard thresholds for cardiomyopathy (Prakken et al. 2010).

44.2.2 Coronary Artery Evaluation

Several causes of sudden death in athletes arise from the coronary arteries. They may be classified as either congenital or acquired. Coronary arteries can be imaged with invasive conventional coronary angiography and reveals the location and severity of obstructive lesions using contrast agent. New advances in cardiac multi-detector computed tomography (MDCT) these days mean invasive angiography is no longer the initial investigation for suspected coronary artery anomalies. Technical difficulties were encountered related to the small size and almost constant motion of the coronary vessels throughout the cardiac cycle. The high spatial and temporal resolution of current cardiac CT generations overcomes many of these challenges, allowing coronary artery evaluation. A meta-analysis by Vanhoenacker et al. (2007) found that the pooled sensitivities and specificities of 64-detector coronary CT, 16-detector coronary CT and four-detector coronary CT for detecting a significant stenosis (>50 % per segment) were 93 and 96 %, 83 and 96 % and 84 and 93 %, respectively.

These days MDCT can be combined with functional PET or SPECT imaging, using hybrid PET/CT and SPECT/CT cameras (Kaufmann and Di Carli 2009). Whereas MDCT has the advantage of detecting coronary atherosclerosis at its earliest stages, thereby allowing initiation of appropriate therapeutic measures well before development of obstructive CAD, myocardial perfusion imaging (MPI)-SPECT can clarify the hemodynamic consequences of the anatomic findings on MDCT based on a functional assessment of myocardial blood flow.

The largest of these studies using integrated PET and 64-detector CT prospectively enrolled 107 patients with chest pain with intermediate likelihood of CAD and compared hybrid ^{15}O-water PET and CT angiography (CTA) versus CTA alone in the detection of haemodynamically significant coronary stenosis (Kajander et al. 2010). Hybrid imaging was technically feasible and scan time remained short, because single 6-min PET scan during adenosine stress was used. The haemodynamic significance of stenoses was defined by quantitative coronary angiography including FFR measurement of intracoronary pressure gradient when feasible. Although both PET and CTA alone demonstrated high (97 %) NPV, CTA alone was suboptimal in assessing the severity of stenosis (PPV 76 %) and perfusion imaging alone could not separate microvascular disease from epicardial stenoses (PPV 77 %) in all patients. The use of PET/CTA significantly improved diagnostic accuracy to 98 %. Sensitivity, specificity, PPV and NPV were 93, 99, 96 and 99 %, respectively. This indicates that non-invasive hybrid PET/CTA imaging is a highly accurate diagnostic method for the detection of haemodynamically significant CAD compared with PET or CTA alone and may be beneficial in athletes.

Hybrid SPECT/CT may play also an important role in optimised risk stratification of patients with acute coronary syndrome (ACS) and providing an objective decision-making tool for tailoring the future therapeutic strategy as demonstrated in a study of Rispler et al. (Rispler et al. 2011). That study showed no negative effect on prognosis in patients with non ST-elevated ACS and also avoided unnecessary revascularisation procedures.

44.2.3 Microvascular Myocardial Perfusion in Athletes

It is possible to make quantitative measurements of myocardial blood flow (MBF) and myocardial perfusion reserve (MPR) with the use of PET. Owing to high temporal resolution and correction of photon attenuation, PET provides accurate delineation of regional tracer kinetics in the blood pool within the left ventricle cavity and myocardium, which are used in combination with tracer kinetic models to quantify MBF in mL/g/min of tissue. Recently, continued improvements in PET technology have contributed to the growing interest in translation of quantitative flow and flow reserve using PET from mainly a research tool to routine clinical practice. Routine list-mode acquisition of myocardial perfusion PET scan enables easy combination of flow quantification with the traditional MPI parameters, which facilitates implementation of quantitative analysis. Because of technical challenges, very little is known about absolute myocardial perfusion in humans in vivo during physical exercise. In the present study positron emission tomography (PET) was applied in order to (1) investigate the effects of dynamic bicycle exercise on myocardial perfusion and (2) clarify the possible effects of endurance training on myocardial perfusion during exercise. Myocardial perfusion was measured in endurance-trained and healthy untrained subjects at rest and during absolutely the same (150 W) and relatively similar [70 % maximal power output (Wmax)] bicycle exercise intensities. On average, the absolute myocardial perfusion was 3.4-fold higher during 150 W ($p<0.001$) and 4.9-fold higher during 70 %W (max) ($p<0.001$) than at rest. At 150 W myocardial perfusion was 46 % lower in endurance-trained than in untrained subjects (1.67 ± 0.45 vs. 3.00 ± 0.75 ml $\times$ $g^{(-1)} \times min^{(-1)}$; $p<0.05$), whereas during 70 %W (max) perfusion was not significantly different between groups (p = not significant). When myocardial perfusion was normalised with rate–pressure product, the results were similar. Thus, myocardial perfusion increases in parallel with the increase in working intensity and in myocardial work rate. Endurance training seems to affect myocardial blood flow pattern during submaximal exercise and leads to more efficient myocardial pump function (Laaksonen et al. 2007). In the study of Sörensen et al. (2010), ^{11}C-acetate PET applied was used at rest for measuring absolute myocardial blood flow (MBF) and oxidative metabolic rate (k(mono)) of the coronary arteries and microvascular capillaries. They evaluated the feasibility of quantitative ^{11}C-acetate PET during exercise. Five endurance athletes underwent dynamic PET scanning at rest and during supine bicycle stress. Exercise was maintained at a workload of 120 W for 17 min. The rate–pressure product (RPP) was recorded repeatedly. MBF, k(mono) in the left (LV) and right (RV) ventricular wall, cardiac output (CO), cardiac efficiency and a lung uptake value reflecting left heart diastolic pressures were calculated from the PET data using previously validated models. MBF increased from 0.71 ± 0.17 to 2.48 ± 0.25 ml min$^{(-1)}$ per ml, LV-k(mono) from 0.050 ± 0.005 to 0.146 ± 0.021 min$^{(-1)}$, RV-k(mono) from $0.023 + 0.006$ to $0.087 + 0.014$ min$^{(-1)}$, RPP from 4.7 ± 0.8 to 13.2 ± 1.4 mmHg × min$^{(-1)} \times 10^{(3)}$ and cardiac output from 5.2 ± 1.1 to 12.3 ± 1.2 l min$^{(-1)}$ (all $p < 0.001$). Cardiac efficiency was unchanged ($p = 0.99$). Lung uptake decreased from 1.1 ± 0.2 to 0.6 ± 0.1 ml g$^{(-1)}$ ($p < 0.001$). That study showed that a number of important parameters related to cardiac function can be quantified non-invasively and simultaneously with a short scanning protocol during steady-state supine bicycling. This might open up new opportunities for studies of the integrated cardiac physiology in health and early asymptomatic disease based on coronary and microvascular angiopathy (Sorensen et al. 2010).

44.2.4 Hypertrophic Cardiomyopathy

Echocardiography (echo) and CMR has a central role in the structural and functional assessment of HCM. Several parameters can be examined: (1) the presence/absence of LVH together with its extent and degree, (2) the mitral valve, (3) the left ventricular outflow tract, (4) systolic function and (5) diastolic function. Echocardiography can suffer from poor acoustic windows, incomplete visualisation of distant areas of the left ventricular wall and poor assessment of left ventricular mass in those with focal asymmetric hypertrophy. CMR can overcome these limitations and more accurately assess wall thickness, distribution of hypertrophy and ventricular mass and function. It can also utilise the diagnostic power of delayed enhancement following gadolinium contrast administration and accurately differentiate athlete's heart from HCM (Fig. 44.1). Diagnosing HCM in the athlete population poses difficulty as it needs to be distinguished from cardiac hypertrophy that usually occurs physiologically in the same population ("athlete's heart") (Maron et al. 1995). Although there is no minimum wall thickness that excludes HCM, the commonest diagnostic criterion of HCM is a left ventricular wall thickness of ≥15 mm (Maron et al. 2003). In the majority of athletes, wall thickness is normal or less than 12 mm, while in a small few it can be up to 16 mm (Spirito et al. 1994). Of the population of patients who have HCM, an important minority has mild hypertrophy of 13–15 mm. This area of overlap leads to a diagnostic dilemma as to whether the observed wall thickness is pathological HCM or physiological (Maron 1986). Clinical information, echocardiography and, in particular, CMR have an important role to play in answering this question (Maron et al. 1995; Petersen et al. 2005). The pattern of hypertrophy in the cardiac wall is important. In trained athletes, thickening of all wall segments are similar (within 1–2 mm) with the dominant area being the anterior septum (Maron et al. 1995). HCM can sometimes be distinguished from athlete's heart purely on the end-diastolic volume of the ventricles (Maron et al. 1995). An enlarged end-diastolic cavity (greater than 55 mm) is present in a third of elite athletes (Spirito et al. 1994), while, in contrast, in HCM, the cavity is usually

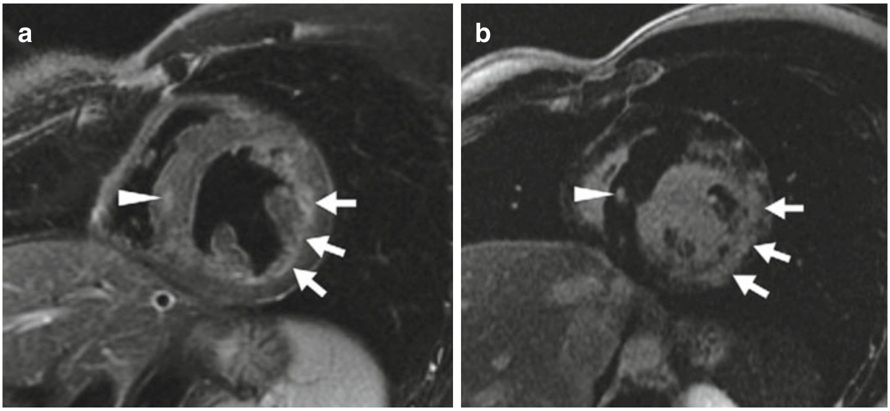

Fig. 44.1 Hypertrophic cardiomyopathy. A 58-year-old man presented with worsening chest pain. Coronary angiography showed non-obstructive coronary artery disease but systolic obliteration of the distal and apical portions of the left ventricle. (**a**) A vertical long-axis view from cardiac CMR image demonstrates hypertrophy of the apical ventricular segments (*arrows*) with (**b**) demonstrating corresponding delayed gadolinium enhancement within the same region (*arrows*) compatible with myocardial fibrosis. Such fibrosis depiction on CMR has been shown to have prognostic implications for patients with HCM (Arrigan et al. 2011)

small (less than 45 mm) unless in the end stages of heart failure where dilatation occurs (Maron et al. 2009). CMR has been demonstrated in a single-centre study to be able to differentiate between athlete's heart and other causes of ventricular hypertrophy (Petersen et al. 2005). In an eloquent study using a variety of geometric measurements from CMR, Petersen et al. (2005) determined that left ventricular diastolic wall thickness divided by left ventricular end-diastolic volume was the best parameter to distinguish athlete's heart from HCM. A ratio of <0.15 was 80 % sensitive and 99 % specific for identifying athlete's heart with a positive predictive value of 95 % and a negative predictive value of 94 %. No single geometric index was 100 % accurate in identifying athlete's heart. However, using all volumetric and geometric parameters recorded (nine in total) in multiple logistic regression analyses, CMR could identify athlete's heart with 100 % accuracy (Petersen et al. 2005). An important aspect in the evaluation of athlete's heart is the importance of the particular sport engaged in as the type and degree of changes in ventricular parameters vary greatly between sports (Baggish et al. 2008; Pelliccia et al. 1991, 1993). Baggish et al. (2008) examined cardiovascular changes observed in those involved in endurance training (rowing) or strength training over 90 days. Their findings in the endurance-training group showed left and right ventricular dilation, enlargement of both atria and enhanced left and right ventricular diastolic function (Baggish et al. 2008). Those involved in strength training showed increased left ventricular thickness (all less than 12 mm) and reduced left ventricular diastolic function (Baggish et al. 2008). Pelliccia et al. (1991) in a study of 1.000 athletes in Italy demonstrated that only 2 % had left ventricular thickness of greater than 12 mm of which all except one case were attributable to rowing or canoeing (the remaining case was a cyclist). Absolute increases in wall thickness were not beyond 12 mm in any other disciplines including those involving strength training, such as weight lifting (Baggish et al. 2008; Pelliccia et al. 1993). Patients with HCM might have epicardial coronary artery disease, and many HCM patients with chest pain undergo stress perfusion SPECT imaging to detect ischaemia. Treadmill, bicycle exercise, atrial pacing, dipyridamole and adenosine were examined in this population. Defects, both reversible and fixed, were noted from 10 to 100 % of the patients imaged. Most defects involve the septum but can occur in other walls. Although the general principles of SPECT interpretation apply to HCM patients, cardiologists should be cautious of "hot spots". These have increased count activity and are most frequently noted in the septum in patients with asymmetric LVH. The increased count activity might be related to LVH and/or increased regional blood flow. Irrespective of the aetiology of "hot spots", if the tomographic slices are normalised to this area of increased count activity, regions adjacent to and distinct from the "hot spot" will appear relatively less intense, thereby creating spurious perfusion defects. Inaccurate image interpretation can be avoided by paying attention to the location and type of perfusion defects. The lateral wall is most frequently involved, and perfusion defects are usually fixed. Furthermore, on gated SPECT images, normal regional function will be noted despite the apparently reduced perfusion (Nagueh and Mahmarian 2006). Abnormal myocardial perfusion in HCM patients, despite normal coronary angiography, has been linked to sudden cardiac death (Dilsizian et al. 1993). Anterior and inferior wall defects are so common in healthy athletes with physiological LVH that the specificity of myocardial SPECT for the detection of CAD, in contrast to exercise ECG, seems to be too low for evaluation of chest pain in this group. The mechanism of anterior and inferior defects may be related to hot spots (papillary muscles) in the lateral wall. The specificity of SPECT for the detection of CAD is maintained in athletes without LVH (Bartram et al. 1998).

More recently, worse prognosis was noted with microvascular dysfunction as determined by myocardial blood flow and coronary flow reserve measured by ^{13}N-labelled ammonia (Cecchi et al. 2003). Impaired coronary reserve (CR) with angiographic coronary arteries has been demonstrated in patients with left ventricular hypertrophy (LVH) in response to valvular heart disease or hypertension. To determine if adaptive LVH induced by intensive training may alter myocardial blood flow (MBF) and CR, 8 highly trained endurance triathletes (29.6 ± 4.0 year, with echographic LVH) were compared with 6 control subjects (33.0 ± 7.9 years, with a normal echographic examination). Triathletes entered the study if they had a left ventricular mass >120 g/m^2 at 2-D echocardiographic measurements (mean = 148.6 ± 19.8 g/m^2). MBF was assessed using positron emission tomography (PET) with ^{15}O-water. Subjects underwent an intravenous bolus of 17–25 mCi of ^{15}O-water at baseline and after intravenous infusion of 0.80 mg/kg of dipyridamole; ^{15}O-water examination was followed by an (^{18}F-FDG) myocardial imaging. CR was determined as the ratio of maximal to basal myocardial blood flow. In comparison with controls, triathletes with LVH showed normal MBF values (0.74 ± 0.1 vs. 0.8 ± 0.2 ml/ml/min, $p = 0.2$) but an increased CR (3.8 ± 0.7 vs. 6.1 ± 1.9, $p < 0.05$). In contrast with other forms of LVH, CR is not altered in LVH due to intense physical training. These results suggest that LVH due to intensive physical training is associated with an increase in coronary blood flow capacity (Toraa et al. 1999).

Aside from perfusion defects, additional abnormalities have been reported, including increased washout rates of ^{99m}Tc-tetrofosmin, which is positively correlated with New York Heart Association functional class and wall thickness (Buyukdereli et al. 2005). A number of interesting observations were made with cardiac metabolic and (^{123}I-BMIPP) neurotransmission imaging. ^{123}I-beta-methyl-iodophenylpentadecanoic acid, a marker of fatty acid metabolism ^{123}I-BMIPP, imaging was investigated in Japanese patients with HCM. BMIPP uptake was decreased, whereas its washout was increased in HCM (Zhao et al. 2003), with regional BMIPP dynamics related to regional function and perfusion. Intriguing observations were noted with ^{123}I-MIBG, which tracks the presynaptic uptake and storage of neurotransmitters. In one study, HCM patients with ventricular tachycardia had a significantly higher MIBG global washout rate, which was the most powerful predictor of ventricular tachycardia on multiple, regression analysis (Terai et al. 2003a). Interestingly, a progressive decrease in ^{123}I-MIBG uptake and an increase in its washout rate are noted in HCM patients, as LV size increases and EF decreases (Terai et al. 2003b). Other studies (Lefroy et al. 1993; Schafers et al. 1998) have explored changes in beta-adrenergic receptor density, with the radioactive tracers ^{11}C-mHED and ^{11}C-CGP-12177. These studies demonstrated the presence of reduced beta-adrenergic receptor density with reduced norepinephrine reuptake by presynaptic terminals. The reduction in beta-adrenergic receptor density seems to be particularly prominent in patients with heart failure (Choudhury et al. 1996a, b). Collectively, the aforementioned findings suggest that autonomic dysfunction might play a role in sudden death, disease progression and the development of heart failure in HCM. However, additional studies are needed in a larger number of patients to corroborate these observations.

44.2.5 Idiopathic Dilated Cardiomyopathy

Diagnostic criteria on echo for idiopathic dilated cardiomyopathy (IDC) are (1) left ventricular ejection fraction <45 % and/or fractional shortening of <25 % (both of which correspond to two standard deviations from the mean) and (2) left ventricular end-diastolic diameter of 117 %, predicted for age and body surface area (corresponds to two standard deviations +5 % from the mean) (Pelliccia et al. 1999). The features of dilated cardiomyopathy can also be clearly shown by CMR. Compared with echocardiography, CMR provides improved visualisation of the right ventricle and low amounts of variation between functional measurements. CMR can also be of assistance in determining whether the underlying cause is acquired or idiopathic. In one prospective study, McCrohon et al. (2003) showed that CMR with gadolinium delayed enhancement had a superior ability to differentiate between heart failure associated with dilated cardiomyopathy and a previous ischaemic event in comparison to coronary angiography. In that study of 90 patients labelled as having IDC based on a negative coronary angiogram, they found gadolinium-enhanced

CMR demonstrated a subendocardial pattern of enhancement in 13 patients consistent with subendocardial infarction.

SPECT and PET imaging is predominantly used in the area of differentiation between ischaemic and non-ischaemic dilated cardiomyopathy rather than diagnosis of the presence of dilated cardiomyopathy itself. Studies have demonstrated that where the underlying aetiology is unclear, ^{99m}Tc-sestamibi or ^{13}N-ammonia PET imaging can accurately differentiate between the underlying causes through perfusion scores and segmental wall motion abnormalities (Danias et al. 1998; Tio et al. 2009b). Those patients with ischaemic disease have the most severe focal regional wall motion abnormalities (Tio et al. 2009b). This compares with non-ischaemic disease where there is uniform systolic dysfunction and uniform mild reductions in perfusion (Danias et al. 1998). It is known that in patients with IDC the increased sympathetic activity owing to chronic congestive heart failure leads to an imbalance of cardiac autonomic tone, as reflected by decreased heart rate variability (HRV). ^{123}I-MIBG, which has the same affinity for sympathetic nerve endings as norepinephrine, can be used to assess the integrity and function of the cardiac sympathetic nervous system. In the study of Lotze et al. (1999), they measured the cardiac sympathetic activity assessed by ^{123}I-MIBG uptake compared with HRV in patients with ^{123}I-MIBG, IDC. In 12 patients with IDC and mild to moderate heart failure, myocardial ^{123}I-MIBG uptake was calculated from the myocardial (M) to left ventricular cavity (C). A significant correlation between the M/C ratio and mean RR interval ($r = 0.52$; $p = 0.016$) or M/C ratio and HRV triangular index ($r = 0.76$; $p = 0.003$), respectively, was found. Thus, the significant correlation between the M/C ratio and HRV indicate that they are both suitable non-invasive methods for evaluating cardiac sympathetic activity in patients with IDC. Long-term treatment with beta-blockers in IDC causes also a recovery of the cardiac adrenergic nervous system concomitantly with a clinical and haemodynamic improvement (Lotze et al. 2001).

44.2.6 Valvular Abnormalities

Aortic stenosis (AS) and mitral valve prolapse make a combined contribution of over 6 % to the cause of sudden athlete cardiac death (Maron et al. 2009).

The standard assessment of aortic stenosis is with echocardiography and Doppler analysis. Classification of the disease is according to aortic valve area with mild >1.5 cm^2, moderate 1–1.5 cm^2 and severe <1 cm^2. Multisection CT studies have shown good correlation with echo for the evaluation of AS. A study of 30 patients demonstrated a sensitivity of 100 % and specificity of 93.7 % in identifying AS. Measurement of the mean aortic valve area by CT was 0.94 cm^2 compared with 0.90 cm^2 by echo using the continuity equation; this gave a correlation coefficient of 0.89 (Vanhoenacker et al. 2007).

A comparison of CMR with echo and cardiac catheterisation in the assessment of aortic valve area in a group of 40 patients found a mean aortic valve area of

0.91 cm^2 by CMR compared with 0.89 cm^2 by echo with a correlation coefficient of 0.96 ($p < 0.0001$). Valve area measurement by catheterisation was calculated using the Gorlin equation and was 0.64 cm^2, giving a correlation of 0.44 which, although less favourable, was comparable to that between echo and catheterisation (0.47), leading the authors to conclude that CMR was an accurate alternative to invasive techniques and echocardiography in the assessment of aortic stenosis (John et al. 2003).

The prevalence of mitral valve prolapse has been reported at approximately 2.5 % of the population (Freed et al. 1999). It is most commonly caused by myxomatous degeneration of the valve. When leaflet thickening of greater than 5 mm occurs, it is known as "classic" mitral valve prolapse and is associated with a greater risk of sudden death (Hayek et al. 2005). Leaflet thickness less than 5 mm is known as "non-classic" (Hayek et al. 2005). The mechanism of sudden cardiac death in mitral valve prolapse is unknown and there is no evidence of increased atrial or ventricular arrhythmias on ECG monitoring (Grigioni et al. 1999). However, when mitral prolapse occurs in association with mitral regurgitation, there is an increase in ventricular arrhythmias and the risk of sudden death is increased further, especially if the associated mitral regurgitation is severe and associated with a flail leaflet (Grigioni et al. 1999).

Notably, however, more recent studies suggest that CMR may be just as valuable (Grigioni et al. 1999). However, a recent study of 25 patients found that compared with echo, CMR had a sensitivity and specificity of 100 % each in detecting leaflet incursion of greater or equal to 2 mm into the left atrium and that it also accurately identified greater leaflet thickness in those patients with MR than controls (Grigioni et al. 1999).

44.2.7 Myocarditis

Myocarditis has been found in a number of studies to be a moderate contributor to sudden athlete cardiac death in the range of 6–8 % (Corrado et al. 1998; Maron et al. 2009). Sudden death from myocarditis results from atrial or ventricular arrhythmias, complete heart block or an acute myocardial infarction-like syndrome (Cooper 2009).

Several diverse and non-specific findings have been found on echocardiography in biopsy-proven myocarditis. These include findings which are consistent with associated cardiomyopathies including hypertrophic, restrictive, dilated and ischaemic forms (Cooper 2009; Skouri et al. 2006). Wall motion abnormalities (hypokinesia, akinesia and dyskinesia) simulating acute ischaemia also occur. Echocardiography can also be used to investigate for right ventricular dysfunction, ventricular thrombi and pericardial effusions (Pinamonti et al. 1988). Progression in echocardiographic technology allowing measurement of strain rates, tissue characterisation and the detection of low-level diastolic dysfunction has also increased its role.

CMR is likely to become the non-invasive standard in the investigation of myocarditis (Magnani and Dec 2006). Different CMR sequences have the ability to

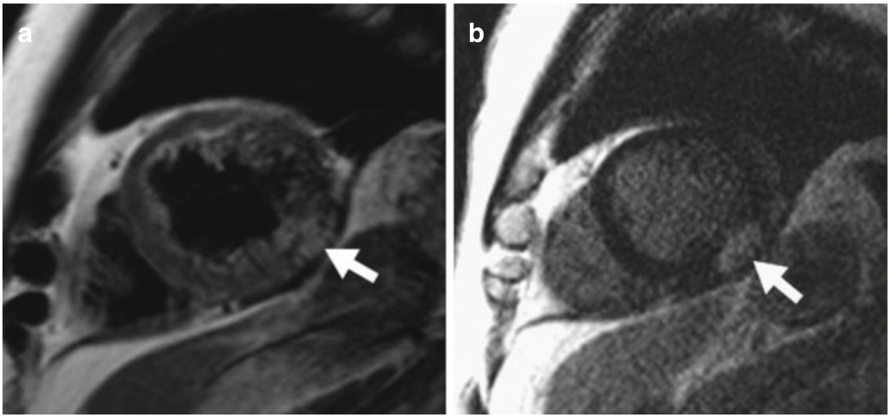

Fig. 44.2 Myocarditis. A 22-year-old man presented with central chest pain following recent viral infection. (**a**) T2-weighted cardiac magnetic resonance short-axis view shows epicardial and mid-wall high signal consistent with myocardial oedema. (**b**) Delayed, enhanced CMR image short-axis view demonstrated subepicardial and mid-wall enhancement typical of myocarditis (Friedrich et al. 2009)

identify different components of the pathophysiology of the disease. Myocardial global relative enhancement (gRE) and late gadolinium enhancement (LGE) are reflective of hyperaemia and increased capillary permeability, myocyte necrosis and increased extracellular space (Friedrich et al. 2009). T2-weighted sequences detect myocardial oedema (Fig. 44.2). Friedrich et al. (2009) pooled data from multiple studies (130 patients) and found that the most accurate methodology for diagnosing myocarditis was by using any two of gRE, LGE and T2-weighted imaging. This combined approach had sensitivities and specificities of 67 and 91 %, respectively, and a diagnostic accuracy of approximately 80 % (Friedrich et al. 2009). Anti-myosin antibodies are directed against the contractile myosin filaments within the cardiac myocyte. Cellular necrosis enables antibody binding to the protein, and detection of indium labelling of the antibody allows non-invasive assessment of myocarditis (Magnani and Dec 2006). A cohort study by Dec et al. (1990) of ^{111}Indium-labelled anti-myosin uptake in suspected myocarditis showed a sensitivity and specificity of 83 and 53 %, respectively, and a negative predictive value of 92 %. A more recent study by Margari et al. (2003) examining anti-myosin antibody imaging in conjunction with a non-dilated left ventricle found a sensitivity and specificity of 45 and 88 %, respectively, in suspected cases of active myocarditis. Myocarditis may also be identified at (^{18}F-FDG) PET by the presence of increased metabolic activity in the myocardium. Diffuse increased metabolic activity in the right and left ventricles may be seen at (^{18}F-FDG) PET (James et al. 2011). This condition must be differentiated from congestive heart failure, right ventricular strain and hypertrophy due to elevated pulmonary artery pressure, which also can lead to increased (^{18}F-FDG) uptake in the right ventricular myocardium.

44.2.8 Arrhythmias

Arrhythmogenic right ventricular cardiomyopathy (ARVC) is a substantial contributor to sudden athlete cardiac death. It is characterised by fibrofatty replacement of the myocardium, which progresses from the epicardium or mid-myocardium to become transmural (Basso et al. 2009). This leads to thinning and aneurysm of the cardiac wall classically evident in the triangle of dysplasia that involves the inferior, apical and infundibular walls (Basso et al. 1996; Thiene and Basso 2001). The left ventricle may be involved usually limited to the postero-lateral subepicardium (Basso et al. 1996; Thiene and Basso 2001). Echocardiographic examination is of great importance in the assessment of ARVC and findings can be used in the assessment of severity of disease (Nava et al. 2000). The largest study of familial ARVC by Nava et al. (2000) classified the disease as mild, moderate or severe according to right ventricular end-diastolic volume (ranging from <75 ml/m^2 for mild to >120 ml/m^2 for severe) and the extent of hypokinesia or akinesia (localised in mild, increasing to widespread in severe).

CMR has progressively developed, and its use as part of the non-invasive workup of ARVC is now strongly supported (Sen-Chowdhry et al. 2006). A diverse range of imaging findings on CMR are associated with ARVC, including right ventricular dilatation and systolic impairment, segmental or localised dilatation, regional wall motion abnormalities, right ventricular aneurysms and intramyocardial fat, and the presence of delayed enhancement (Calkins 2008; Sen-Chowdhry et al. 2006). Chowdhry et al. assessed the accuracy of CMR in the diagnosis of ARVC by comparison with task force guidelines, extended diagnostic criteria and gene-carrier status. They studied 232 patients undergoing investigation for suspected ARVC with CMR (Sen-Chowdhry et al. 2006). CMR was positive in 100 % of patients meeting the task force criteria (64 patients) and specificity was 29 %.

ARVD can also be evaluated with ^{123}I-MIBG for the assessment of sympathetic innervation disturbances. Lerch et al. (1993) evaluated 25 patients with ARVD; sympathetic innervation of the left ventricle was assessed ^{123}I-MIBG SPECT. In addition, thallium-201 SPECT was performed. The diagnosis of ARVD was made by an electrophysiological study and right and left heart catheterisation including right ventricular endomyocardial biopsy. Ischaemic heart disease was excluded by coronary angiography. A group of seven patients without any evidence of heart disease served as a control group. Twenty-two of the 25 patients showed reduced uptake of ^{123}I-MIBG. The abnormal areas were located predominantly in posterior and posteroseptal segments of the heart. No focus of increased ^{123}I-MIBG activity could be demonstrated. No patient had signs of left ventricular involvement on left ventricular angiography. In contrast to the results of the ^{123}I-MIBG SPECT, those of ^{201}T1 SPECT were normal in 16 patients. The remaining nine patients showed areas of slight hypoperfusion not correlated with the reduced ^{123}I-MIBG uptake. ^{123}I-MIBG scintigraphy allows detection of left ventricular adrenergic dysinnervation in ARVD patients without morphological or functional abnormalities of the left ventricle. Ordinary endurance exercise may induce cardiovascular adaptations, including increased vagal tone. The sympathetic function can be evaluated in athletes as in a previous study with ^{123}I-MIBG imaging obtained 15 (early) and 180 (late) min after the injection of ^{123}I-MIBG (Matsuo et al. 2001). The ratio of heart/mediastinum count (H/M) and the washout rates of ^{123}I-MIBG (WR) were calculated in 25 consecutive patients who were athletes (aged 52 ± 13 years) and 23 normal subjects. There was a significant difference in the H/M between the athletic and normal hearts (2.3 ± 0.3 vs. 2.6 ± 0.3, $p < 0.01$). An increased WR was observed in the athletes group when compared with the normal group (34 ± 4 vs. 28 ± 3, $p < 0.01$), and there was a significant correlation between WR and the left ventricular mass index ($r = 0.58$, $p < 0.01$). Prolonged exercise, training may alter cardiac sympathetic nerve function, which can be detected by ^{123}I-MIBG imaging.

44.3 Cardiovascular Effects of Anabolic Steroids in Athletes

The term "anabolic–androgenic steroids (AAS)" refers to a group of compounds that are structurally related to testosterone and exert two main physiological effects including muscle growth and masculinisation (van Amsterdam et al. 2010). Since the 1940s, AAS therapy has been advocated as substitution therapy of testosterone deficiency and hypogonadism (van Amsterdam et al. 2010). Moreover, AAS in high doses have been abused with the purpose to enhance muscle mass and improve athletic performance.

Cardiovascular adverse effects of AAS abuse have been reported sporadically as case reports of hypertension (Stergiopoulos et al. 2008), myocardial infarction (MI) and stroke (Stergiopoulos et al. 2008), dysrhythmia (Angelilli et al. 2005), cardiomyopathy (Ahlgrim and Guglin 2009) and sudden cardiac death (Fineschi et al. 2007) in bodybuilders with long-term AAS abuse in the recent years. Case reports on hard atherosclerotic end points (sudden cardiac death, MI or stroke) comprise young AAS abusers without pre-existent cardiac risk factors, suggesting that a high AAS dose imposes additional independent risk to conventional cardiovascular risk factors.

As late as 1975, AAS abuse was classified as doping. According to the world anti-doping agency report in 2008, AAS were the most commonly identified prohibited drugs among all. Therapeutic use of AAS has been shown in many studies to affect the individuals' lipid profile. A meta-analysis including 19 studies and comprising 272 hypogonadal men showed that substitution therapy with intramuscularly administered testosterone results in a decrease in plasma HDL cholesterol levels which amounted to 0.10 mmol/l (Whitsel et al. 2001). Moreover, high-dose AAS abuse has been demonstrated to exert unfavourable direct and indirect effects, through AAS-associated hyperhomocysteinaemia (Graham et al. 2006), on plasma lipid levels. In a non-blinded investigation on 19 bodybuilders, short-term (8 weeks) and long-term (>14 weeks) high dosages of AAS administration markedly reduced HDL cholesterol (Hartgens et al. 2004). The suppressive effects of AAS administration on HDL plasma levels are dose dependent and, depending on the type of AAS and route of administration, can result in decrement of 40–70 % (Hartgens et al. 2004; Hartgens and Kuipers 2004). The adverse effects of high AAS dosages on plasma levels of LDL cholesterol have been shown in animal and human studies (Fontana et al. 2008).

Lipid profile impairment is causally implicated in vascular wall injury by promoting inflammatory processes in the arterial wall, macrophage recruitment and uptake of LDL and oxidised LDL by macrophages which results in foam cell formation (Tabas et al. 2007).

44.3.1 Vascular Imaging: Imaging Early Atherogenesis

The aforementioned processes, which contribute to the establishment and progression of atherosclerotic plaques, can be depicted by molecular imaging techniques. ^{18}F-fluorodeoxyglucose (^{18}F-FDG) positron emission tomography (PET) has been studied in a notable number of investigations and has been shown to correlate with the macrophage density in atherosclerotic plaques in humans and in animal models (Chen et al. 2009). Additionally, ^{18}F-FDG PET depicts myocardial infarction subsequent to coronary atherosclerosis. Figure 44.3 shows a whole-body cardiac-gated ^{18}F-FDG PET/CT image of a male bodybuilder with abdominal aortic calcification (Fig. 44.3a) with more extensive ^{18}F-FDG uptake in aortic plaques (Fig. 44.3b) and an inferolateral myocardial infarction (Fig. 44.3c) as a result of right coronary artery occlusion.

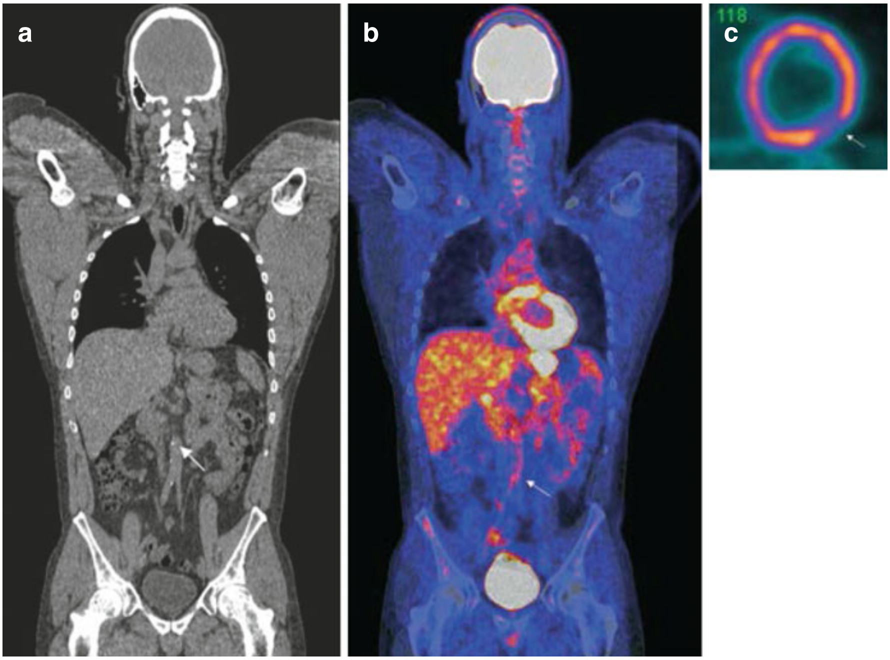

Fig. 44.3 ^{18}F-FDG PET/CT image of androgenic–anabolic steroid-associated atherosclerosis. Whole-body ^{18}F-FDG PET/CT of a 40-year-old ^{18}F-FDG male bodybuilder with mild abdominal aortic atherosclerosis on CT (**a**, *arrow*) and more extensive (^{18}F-FDG) uptake in soft plaques of the abdominal/iliacal arterial tract on PET (**b**, *arrow*) and (**c**) gated myocardial ^{18}F-FDG PET in the same patient indicating an inferolateral infarction (*arrow*) due to acute right coronary artery occlusion (Golestani et al. 2012)

In a previous study, ^{99m}Tc-interleukin-2 single-photon emission computed tomography (SPECT) was found to be able to depict T lymphocyte content within atherosclerotic plaques in humans (Annovazzi et al. 2006). This technique may enable clinicians to detect active inflammation within the atherosclerotic plaque. Foam cell formation has also been studied using various lipid-based radiotracers. Molecular targeting of oxidised LDL and macrophage uptake of radiolabelled LDL have verified promising targets for visualising vulnerable atherosclerotic plaques [31,32]. Moreover, a recent review reported the feasibility of ultra-small superparamagnetic particles of iron oxide (USPIO) in detecting inflammation in endothelial cells during atherogenesis with CMR (Briley-Saebo et al. 2011). However, none of the abovementioned probes and modalities has been applied to monitor AAS-associated vascular inflammation and leucocyte accumulation.

44.3.2 Adhesion Molecules Expression and Platelets Aggregation

Although therapeutic and physiological dosages of AAS seem to have beneficial effects on platelet aggregation (Bjarnason et al. 1997), deleterious effects of supra-physiological AAS dosages in promoting expression of adhesion molecules in vessel walls and facilitating platelet–endothelium binding have been reported as a mechanism that contributes to AAS-induced atherosclerosis (Wu and von Eckardstein 2003). Additionally, the role of AAS abuse in thrombogenicity has been reported in some studies. In a study on healthy male volunteers, high-dose AAS treatment (200 mg/week) resulted in increased platelet aggregability as a result of increased thromboxane A2 (TxA2) receptor density (Ajayi et al. 1995). In this study TxA2 density peaked at 4 weeks after single-dose AAS treatment and returned to baseline density at 8 weeks. The same trend was reported for platelet aggregability, with 5.2 and 7.3 % increase after 2 and 4 weeks, respectively. The contrary effects of castration on TxA2 receptor and platelet aggregation was also reported in a cross-sectional case–control study (Ajayi and Halushka 2005). The effects of AAS on TxA2 receptor density can in part be explained by AAS-associated hyperhomocysteinaemia (Alessio et al. 2011; Graham et al. 2006).

44.3.3 Vascular Imaging: Imaging Adhesion Molecules Expression

Detection of adhesion molecules expression as an upstream process leading to binding of platelets to the arterial wall can depict atherosclerotic plaque formation at early stages (Gawaz et al. 2005). Vascular cell adhesion molecule-1 (VCAM-1) and integrins provide suitable targets for molecular imaging of adhesion molecules expression. VCAM-1 is expressed by endothelial cells, macrophages and smooth muscle cells (Fisker Hag et al. 2008). VCAM-1-targeting nanoparticles have been used for signal enhancement in atheromatous arteries of apoE −/− mice, and CMR showed promising results (Nahrendorf et al. 2006). Recently, the same group labelled the same tetrameric peptide with positron emitter ^{18}fluoride for PET imaging and was able to demonstrate early atherosclerotic changes in apoE −/− mice (Nahrendorf et al. 2009).

Integrins, e.g. αvβ3 integrin, are adhesion molecules that are expressed following endothelial cell injury, as well as at more progressed stages of atherosclerotic plaque formation during neo-angiogenesis (Gawaz et al. 2005). αvβ3 integrin has high binding affinity to arginine–glycine–aspartate (RGD) amino acid sequence facilitating cell–extracellular matrix interactions. It has been shown in many oncological and myocardial remodelling studies that radiotracers based on RGD can be applied targeting αvβ3 integrin (van den Borne et al. 2008; Zhang et al. 2006). One recent report showed that ^{18}F-RGD PET can show atherosclerotic changes in apoE −/− mice (Laitinen et al. 2009). In that report, quantified measures of ^{18}F-RGD uptake were correlated with ^{18}F-FDG PET measures. However, none of the tracers on adhesion molecules has currently been applied to investigate AAS-associated vascular injury.

44.3.4 Impaired Vasodilation

Although endogenous testosterone has been shown to exert vasodilatory effects (Ong et al. 2000), AAS use in hypogonadal men has been shown to result in paradoxical pro-atherogenic vasoconstrictive effects (Sader et al. 2003). It was shown that testosterone therapy in hypogonadal men is correlated with impaired vasodilation, independently from lipid profile measures (Sader et al. 2003). Supraphysiological doses of AAS have also shown to exert similar effects on vasoreactivity in human and animal studies (Ferrer et al. 1994; Lane et al. 2006). In a study on male bodybuilders who abused AAS for 3–4 years, vasodilation was significantly lower than that of ex-abusers and controls (Lane et al. 2006). AAS abuse in bodybuilders independently of the other factors impaired endothelium-independent vasodilator pathways. It was also shown that a 3-month period of abstinence results in a degree of improvement in vascular function.

The mechanisms through which AAS induces deleterious effects on vasodilation are not sufficiently investigated. However, endothelial injury as a result of lipid profile alterations and establishment of atherosclerosis could explain impairment in endothelium-dependent pathway through decreased NO production. Also the increase in TxA2 receptor density in vessel walls as a result of AAS treatment results in impaired endothelial-independent vasodilator pathways (Matsuda et al. 1994). Further studies should be performed to reveal more information on cellular and molecular processes related to the role of AAS on vasoreactivity.

44.3.5 Imaging Impaired Vasodilation

The cold pressure test (CPT) is known to be a useful tool to demonstrate endothelial dysfunction (de Vries et al. 2006; Schindler et al. 2006). Cold exposure induces

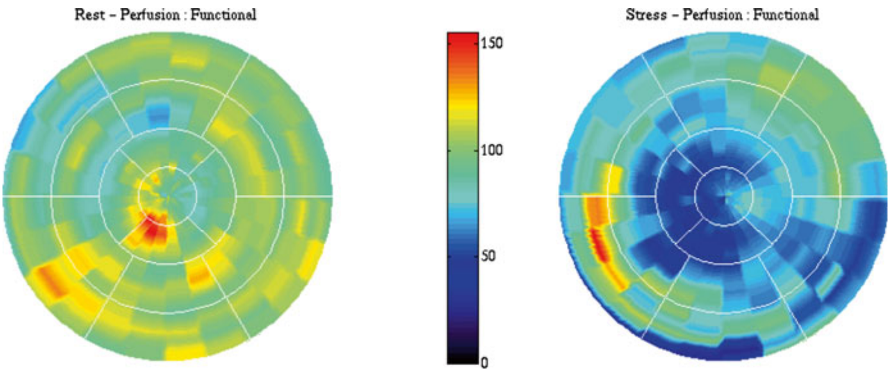

Fig. 44.4 Polarmap of rest ^{13}N-ammonia (*left*) and stress ^{13}N-ammonia (*right*) PET of the left ventricle in a patient with chest pain. The colour bar indicates the perfusion level (mL/min/100 g myocardial tissue). During stress myocardial perfusion is reduced at the apical, anteroseptal and infero-lateral region compared with the rest situation. The calculated absolute stress/rest perfusion ratio was 1.28 (normal > 2). Coronary angiography showed normal coronaries. In this patient microvascular disease was diagnosed (Golestani et al. 2012)

vasodilation in coronary arteries but paradoxically results in vasoconstriction in dysfunctional arteries. This paradoxical effect can be measured by myocardial perfusion imaging agents such as the PET tracers ^{15}O-water and ^{13}N-ammonia (Fig. 44.4). Performing CPT could reveal early vascular effects of AAS abuse in humans.

44.4 Myocardial Effects

44.4.1 Myocardial Hypertrophy

The role of AAS abuse in myocardial hypertrophy has been shown in animal and human studies. In a recent investigation on rats treated with high-dose nandrolone for 8 weeks, electrical remodelling and increasing myocyte nuclei diameter in the AAS group suggested early stages of myocardial hypertrophy (Medei et al. 2010). Significant increase in left ventricular mass index, ranging from 7 to 24 %, has been shown in studies on rats treated with low-dose and high-dose AAS for 8 to 10 weeks (Beutel et al. 2005; Rocha et al. 2007). Adverse effects of AAS administration in this study were counteracted by aerobic exercise, suggesting more risk for AAS abuse in non-athlete abusers.

Also many case reports of sudden cardiac death in athletes who abused AAS have shown clinically important left ventricular hypertrophy (Fineschi et al. 2007; Stergiopoulos et al. 2008). Association between AAS abuse and echocardiographically detected myocardial hypertrophy has been shown in a study on athletes who chronically abused AAS (median = 24 months) (Urhausen et al. 2004). In this study hypertrophic index (interventricular septum plus posterior wall thickness divided by the internal diameter) was significantly higher in AAS (ex-)abusers compared with non-user athletes. Moreover, the extent of AAS abuse was linearly correlated with mean left ventricular wall thickness.

Although the mechanisms responsible for left ventricular hypertrophy in AAS abusers are not well understood, it has been shown that long-term AAS abuse increases peripheral vascular resistance (Beutel et al. 2005), blood pressure (Bissoli et al. 2009) and myocardial sympathetic nerve activity (Alves et al. 2010) which can explain mechanical stress-induced myocardial hypertrophy in AAS abusers. Moreover, androgen receptors which are responsible for AAS-induced hypertrophic effects on skeletal muscles are also present in myocytes and result in increased protein anabolism within myocardial cells and interstitium (Fontana et al. 2008; Rocha et al. 2007). In a study in rats treated with high-dose AAS for 10 weeks, increased left ventricular mass was shown to be a result of both myocardial cell hypertrophy and interstitial fibrosis. Both effects were further effectively inhibited by losartan, which suggest the role of renin–angiotensin system (RAS) in increase of left ventricular mass (Rocha et al. 2007). It has been shown that in AAS-treated rats, angiotensin-1 (AT1) receptor expression increases 60–120 % comparing with non-treated groups. However, it is not yet investigated whether AAS treatment directly enhances RAS activity or the process of the mechanical stress-induced hypertrophy is the trigger.

44.4.2 Imaging Pathophysiology of Myocardial Hypertrophy

Due to the role of RAS in AAS-associated cardiac mass change, detection of RAS activity in early stages of myocardial injury would predict future myocardial adverse outcomes in AAS (ab)users. Recently, Verjans et al. (2008), in a study on post-MI mice, have shown that ^{99m}Tc-losartan uptake increases 2.4-fold after MI compared to control animals. This promising result, in targeting AT1 receptor, could provide a valuable tool to investigate early stages of AAS-associated cardiac pathogenesis in abusers and animal models in vivo.

44.4.3 Cardiac Function

AAS abuse has been shown to affect the cardiomyocyte survival and heart function in cell cultures, animal models and humans (Baggish et al. 2010; Beutel et al. 2005). Beutel et al. were the first to investigate the effects of AAS administration on cardiac output in animal models (Beutel et al. 2005). In their study three groups of rats were treated with vehicle, low-dose AAS or high-dose AAS, for 8 weeks, and groups were compared with regard to cardiac output. The results showed that AAS treatment in high doses results in significant decrease in cardiac output comparing with low-dose AAS and control group (107, 154, and 121 ml/min, respectively). A more recent study reported that both diastolic and systolic functional parameters are impaired in AAS abuser athletes comparing with non-abuser athletes (Baggish et al.

2010). In this study echocardiography in AAS abusers showed a significantly lower ejection fraction (50 % vs. 59 %), longitudinal strain (16.9 % vs. 21 %) and radial strain (38.3 % vs. 51 %) compared to AAS non-abusers. A similar trend was observed in diastolic functional parameters. In a study of Luijkx et al. (2013), strength athletes who use AAS showed significantly different cardiac dimensions and biventricular systolic dysfunction and impaired ventricular inflow as compared to non-athletes and non-AAS-using strength athletes. Increased ventricular volume and mass did not exceed that of strength-endurance athletes. These findings again may help raise awareness of the consequences of AAS use.

The mechanisms of high-dose AAS-associated heart dysfunction are still not thoroughly investigated. However, some studies showed deleterious molecular and cellular effects of high-dose AAS administration on the myocardium, which overlap early injury pathways of heart failure. It is known that in hypertrophic myocardium, hypertrophy can be linked with any of the heart failure signalling pathways, resulting in heart failure (Mudd and Kass 2008). It has also been shown that AAS indirectly mediates the processes, which precede mitochondrial damage, apoptosis and sarcomere disruption. In a study on rats treated with AAS, it was shown that lesions compatible with early stages of heart failure, such as swollen mitochondria and disintegrated contractile units, were present in the myocardium as early as 3 weeks after treatment (Behrendt and Boffin 1977). Association of AAS abuse and apoptosis has been studied in rat ventricular myocytes exposed with different doses of AAS and showed that AAS exposure results in dose-dependent myocardial apoptotic cell death (Zaugg et al. 2001). In another animal study with rabbits that were treated with daily supraphysiological doses of AAS for 60 days, apoptotic lesions and higher caspase-3 activity were noticed in treated animals (Fanton et al. 2009). Fibrosis is known as a process leading to heart failure. It has also been reported that high-dose AAS treatment in small animal models is associated with interstitial collagen deposition and fibrosis (Belhani et al. 2009; Rocha et al. 2007). Fibrosis is assumed to occur initially as an adaptation in myocardial hypertrophy to preserve the function of the ventricles and, thereafter, as a repair mechanism to compensate apoptotic myocardial cell loss (Rocha et al. 2007). In one study on rabbits treated with daily oral high doses of AAS for 3 months, the AAS-treated group showed myocardial interstitial fibrosis associated with higher caspase-3 activity (Belhani et al. 2009). Local RAS activity which has been shown to be activated in high-dose AAS treatment in rats (Rocha et al. 2007) induces interstitial fibrosis and has been shown to be a key signalling pathway for heart failure (Towbin and Bowles 2002).

44.4.4 Imaging Pathophysiology of Impaired Heart Function

Pro-apoptotic effects of AAS (ab)use can be further investigated in vivo by apoptosis-targeting tracers such as ^{99m}Tc-annexin-A5 (Vriens et al. 1998). Annexin-A5 has high affinity to phosphatidylserine, a protein which is expressed during apoptosis on cell membrane. Feasibility of ^{99m}Tc-annexin-A5 has been shown in detecting myocardial apoptosis in patients with acute allograft rejection (Vriens et al. 1998).

Significance of RAS system activation in AAS-associated heart failure can be explored by further in vivo investigations on human and animals using ^{99m}Tc-losartan SPECT. Future studies are warranted to better explain the mechanisms and feasibility of nuclear medicine techniques for pathophysiological understanding of AAS-induced myocardial injury.

44.4.5 Cardiac Arrhythmia

Cardiac arrhythmias are associated with AAS abuse. Most commonly, atrial fibrillation but also ventricular tachycardia and ventricular fibrillation have been described secondary to AAS abuse in human case reports (Pereira-Junior et al. 2006). In a rat study treated with high-dose nandrolone for 10 weeks, heart rate variability measurements revealed a reduction in parasympathetic activity compared with the vehicle-treated group (Medei et al. 2010). Sympathetic indices were also higher in the AAS-treated group. It was also shown that AAS-treated animals show prolonged action potentials as a result of reduced density of transient potassium outward current in the left ventricle. This change can be explained by left ventricular hypertrophy as well as downregulation of expression of Ito membrane channels.

44.5 Summary and Future Perspectives

The diversity of underlying aetiologies that can account for cardiovascular diseases and sudden athlete cardiac death necessitates a clear imaging approach in investigating these patients:

1. Symptoms, signs, ESC and family history suggestive of underlying disease
2. The athlete who has a cardiac arrest with successful resuscitation

Screening: The principles of screening are well defined by Corrado and colleagues in the WHO guidelines of 1968 (Corrado et al. 2005). These principles lay out several criteria that must be considered in order to successfully screen for and treat early disease (Table 44.2).

Table 44.2 WHO principles of early disease detection

1. The condition should be an important health problem
2. There should be a treatment for the condition
3. Facilities for diagnosis and treatment should be available
4. There should be a latent stage of the disease
5. There should be a test or examination for the condition
6. The test should be acceptable to the population
7. The natural history of the disease should be adequately understood
8. There should be an agreed policy on who to treat
9. The total cost of finding a case should be economically balanced in relation to medical expenditure as a whole

Table 44.3 Overview of cardiovascular pathology associated with athletes including androgenic–anabolic steroid (AAS) (ab)use and appropriate detecting techniques

Vascular	AAS effect		Imaging technique (modality)
	Endothelial dysfunction		CPT (PET)
	Adhesion molecules exposure	VCAM-1	VINP-4 (MRI)
			^{18}F-4V (PET)
		$\alpha_v\beta_3$integrin	^{18}F-FDG (PET)
	Leucocyte recruitment and foam cell formation		^{18}F-FDG (PET)
			^{99m}Tc-Il2 (SPECT)
			USPIO (CMR)
Myocardial	Apoptosis		^{99m}Tc-annexin-V(SPECT)
	RAS activity		^{99m}Tc-losartan (SPECT)
	Hypertrophy		Echocardiography
	Dysfunction		Echocardiography
	Perfusion		^{13}N-ammonia/^{82}Rb/ ^{15}O-water (PET) ^{99m}Tc-sestamibi/tetrofosmin (SPECT)
	Innervation		^{11}C-mHED (PET), ^{11}C-CGP (PET), ^{18}F-FDG, ^{123}I-MIBG (SPECT)
	Viability and inflammation		(^{18}F-FDG) (PET)

Screening in relation to sudden athlete cardiac death is complicated by the fact that it is not screening for a single condition but rather multiple potential underlying aetiologies. A number of further issues have been highlighted regarding the implementation of population-based screening programmes that may lead to difficulty. These issues include the large number of athletes, the low prevalence of underlying heart disease (0.2 ~ 0.3 %), the cost of implementation and the effects of false-positive results (Corrado et al. 2006; Maron 1998; Maron et al. 1980, 2007).

Sophisticated imaging techniques and specific radiopharmaceuticals and probes against specific biomarkers (Table 44.3) need PET/MRI to be developed for the early detection of cardiovascular abnormalities in athletes. PET/MRI is a novel camera system and on its way to be implemented in the clinic. PET/MRI would have the following advantages: improved soft tissue contrast, the possibility of performing truly simultaneous instead of sequential acquisitions and the availability of sophisticated MRI sequences, such as diffusion and perfusion imaging, functional MRI and MR spectroscopy, which can add important information. Moreover, the use of PET/MRI would result in a significant decrease in radiation exposure, which is of foremost importance for serial follow-up in athletes and especially of imaging in the young. Strong tools in PET imaging are the absolute quantification of myocardial blood flow, including myocardial perfusion reserve, sympathetic innervation and β-adrenoceptor imaging in the era of arrhythmias and molecular imaging. MRI can be used for functional imaging and combined with targeting molecular imaging with PET.

Detection of anabolic abuse (Golestani et al. 2012): There are only few studies focusing on the mechanisms responsible for AAS abuse-associated cardiovascular pathology. Nonetheless, some case reports, cross-sectional human studies and animal reports have demonstrated an adverse role of AAS abuse on the vascular wall and the myocardium. The wave of now middle-aged ex-AAS abusers and the increasing group of the elderly AAS users necessitates more detailed documentation of the underlying pathophysiology to enhance insight into the delicate balance between benefit and harm. Owing to the obvious ethical reasons, prospective double-blinded human studies are not easily justified. Accordingly, retrospective case–control studies of cohorts and prospectively follow-up of such cohorts seem to be the most feasible strategy for human studies to obtain more conclusive epidemiologic data. In addition, imaging techniques as summarised in Table 44.3, future studies on AAS-specific pathophysiological processes and molecular imaging techniques of AAS-associated cardiovascular disease would provide clinicians diverse diagnostic tools for early detection, evaluation and monitoring of adverse cardiovascular consequences of AAS abuse (Golestani et al. 2012). For instance, dehydroepiandrosterone (DHEA) mediates its action via multiple signalling pathways involving specific membrane receptors and via transformation into androgen and oestrogen derivatives (e.g., androgens, oestrogens, 7a and 7b DHEA and 7a and 7b epiandrosterone derivatives) acting through their specific receptors and is associated with ischaemic heart disease, endothelial dysfunction and atherosclerosis. These pathways include also sigma receptors (sigma-1) expression. The specific sigma receptor PET ligand ^{11}C-SA4503 may be a method to quantify the androgen receptor expression of the vascular system to evaluate the atherosclerotic status in relation with AAS abuse (Rybczynska et al. 2009). This may lead to selective non-invasive diagnostic imaging in relatively young population of AAS abusers as promising tools for AAS-related atherosclerosis development which can be complemented with blood sampling.

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Diagnostic Imaging of Equine Sport Injuries

45

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Contents

Abstract

The horse is the most prominent veterinary athlete, competing in many different disciplines. Musculoskeletal injuries account for the majority of injuries encountered in athletic horses and are the main cause of wastage in the equine industry. Most musculoskeletal lesions in horses resemble those occurring in human athletes. Diagnostic imaging encompasses the same modalities as used in human

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medicine with the exception that due to the size of the animal, the tomographic modalities are mainly limited to the head and the lower limb area. Similar to man, radiography and ultrasonography are the first choice for imaging of orthopedic problems. Currently, computed tomography (CT) is mainly used for examination of head injuries and magnetic resonance imaging (MRI) for lower limb problems. Generally, veterinary imaging techniques make use of techniques also used in human imaging. Nuclear medicine modalities are used to pinpoint undefined orthopedic problems and to evaluate the clinical importance of radiographic findings. The advantage of scintigraphy is that all areas of the body can be screened.

In this chapter, pathogenesis and diagnostic procedures of common sport injuries in the horse will be presented.

45.1 Introduction

In veterinary medicine, two species can be considered "athletes," the horse (e.g., racing Thoroughbreds, Standardbreds, show jumpers, etc.) and the dog (e.g., racing Greyhounds, working dogs, etc.). Both provide interesting material as natural models from a human medicine point of view. They are also patients and as such have to receive optimized care. Especially in the case of the horse, the economical factor plays an important role. The value of these horses varies between several thousands to several millions of Euros. However, the best horses may also be great moneymakers. The Thoroughbred is the most exquisite example of this economical impact, with a whole industry built on racing. Musculoskeletal injuries are very common and are the main reason for wastage in athletic horses. Hence, they present a considerable economical and welfare issue. The type of pathology encountered in the equine athlete is basically comparable with that seen in the human athlete, only the anatomical location may differ between species. Some injuries are very similar, e.g., tibial stress fractures in horses and humans. Others have different predilection sites mainly due to the difference in locomotion (four-legged versus two-legged, rendering different directions and magnitude of loading to the musculoskeletal structures) and anatomy.

Historically horses were primarily used for transportation and war. Nowadays, they are mainly used for various sport disciplines, such as dressage, jumping, eventing, endurance, polo, racing, western riding disciplines, and others. Unlike humans, horses walk on the tip of their "fingers" and "toes" with 60 % of the body weight leaning on the front limbs. Training and competition cause tendon/ligament, joint, or less commonly bone and muscle injuries, due to chronic repetitive overload/microtrauma, exhaustion, abrupt stops and turns, or traumatic incidents. More than 75 % of equine disease results from orthopedic disorders. The rest are mostly disorders of the digestive tract (e.g., gastrointestinal disorders resulting in colics) or the respiratory tract. The type and frequency of orthopedic sport injuries depend on the sport activity, tract/training surface, and training regime. Three levels of activities are recognized, depending on the type of sport, with high-speed activities as racing, moderate-speed activities as endurance and eventing, and low-speed activities

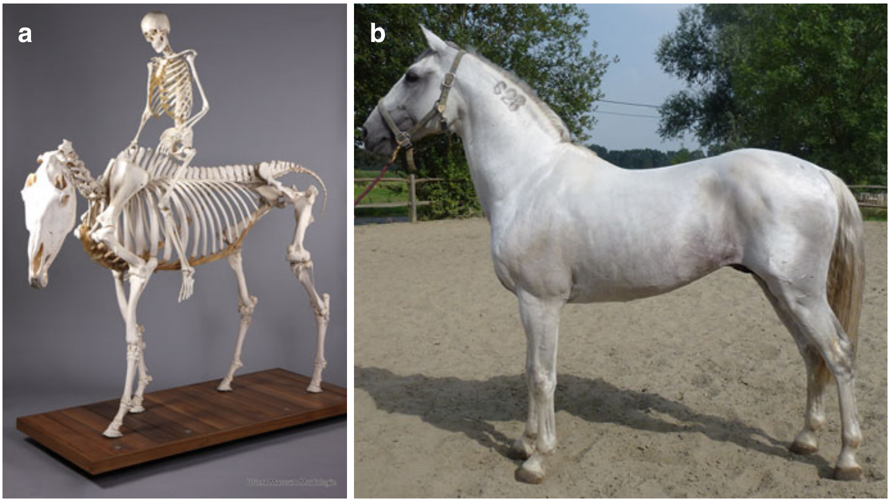

Fig. 45.1 (**a**) The equine and human skeleton. The equine distal limb (fingers and toes) is a reduced version of the human skeleton, e.g., consisting of one fully developed metacarpal/metatarsal bone and one proximal, middle, and distal phalanx. Note that the carpus and the tarsus are located halfway the fore- and hind limb. (**b**) The horse in real life

including dressage and jumping. High-speed athletic horses start their careers early in life, for example, Thoroughbred racehorses have their first start when they are 2 years, while moderate- to low-speed performance horses start at a later age (competitive work at a basic level starts at the age of 4 years).

45.2 Anatomy

The basic components of the musculoskeletal system are the same as in humans; however, several modifications enhance the horses' ability to run fast if needs be but also maintain a slow- to moderate-speed over long distances. To reduce the cost of locomotion, the horse legs have elongated by adopting a digitigrade stance, effectively walking "on its toes," thus increasing its stride length (Fig. 45.1a, b). The distal limb of the horse is as light as possible while still strong enough to withstand the forces of locomotion (up to 2.5 times its body weight during gallop). Reduction of the bones to a single digit and limiting of the muscle mass to the proximal limb achieve this. Fibula and distal ulna are underdeveloped compared to man, and distal to carpus and tarsus, only one weight-bearing metacarpal/metatarsal bone with only one digit consisting of proximal, middle, and distal phalanx exists. Metacarpals 2 and 4 and metatarsals 2 and 4 are rudimental. The third phalanx is protected by a horn capsule, which encompasses the third phalanx and corresponds to the human nail.

The equine musculoskeletal system incorporates several energy-saving mechanisms based on the elastic properties of tendons, which allow them to store elastic energy when being stretched and released upon recoil (Fig. 45.2). There are two of these elastic tendons arranged on the flexor side of the equine leg (i.e., the superficial and deep digital flexor tendons) traveling all the way from the distal end of the humerus/femur to the digit, crossing several joints, protected by tendon sheaths (type II tendons) and supported by their respective accessory ligaments (commonly known as the superior and inferior check ligament) and the ligamentous third interosseous muscle (commonly known as the suspensory ligament). The relatively straight horse leg changes direction dramatically in the metacarpo(tarso)phalangeal joint, which is hyperextended in the standing horse. During locomotion this joint becomes even more extended and causes the flexor tendons to stretch when the leg is on the ground; when the leg leaves the ground, the tendons relax and release their energy. Sesamoid bones at the level of the metacarpo(tarso)phalangeal and the distal interphalangeal joint (navicular bone) increase the distance between the joints and the flexor structures, thus increasing their lever arm. While these evolutionary modifications are advantageous for lowering the costs of locomotion, they come at a price. Light distal limbs and elastic tendons have small cross-sectional areas thus undergoing high stresses and hence being prone to injuries. The third metacarpus

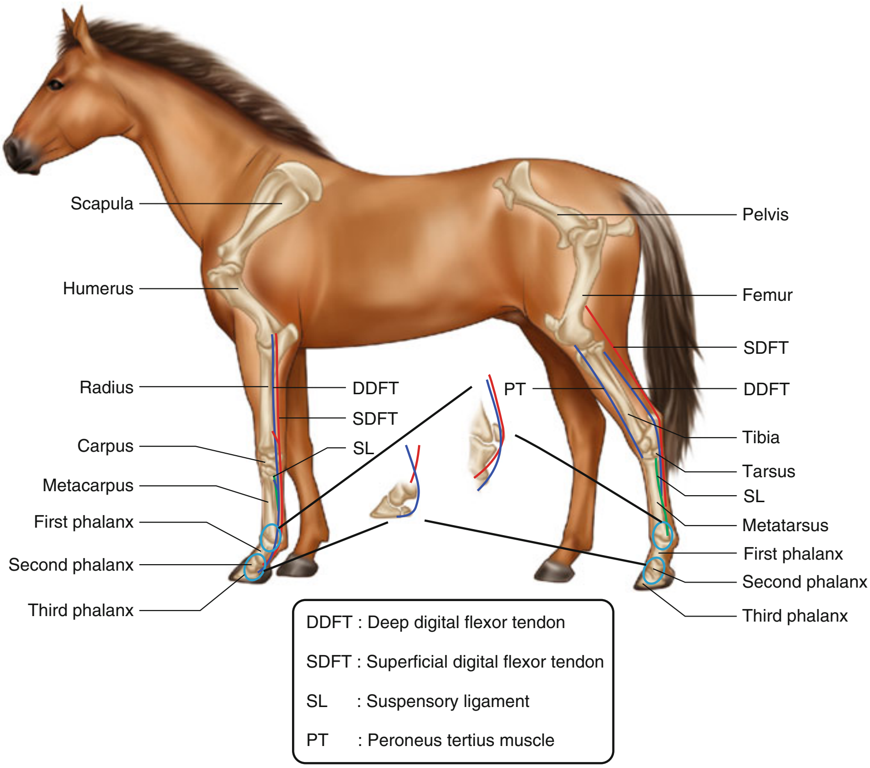

Fig. 45.2 Schematic representation of the equine flexor tendons. *DDFT* deep digital flexor tendon, *SDFT* superficial digital flexor tendon, *SL* suspensory ligament, *PT* peroneus tertius muscle, *1* scapula, *2* humerus, *3* radius, *4* carpus, *5* metacarpus, *6* first phalanx, *7* second phalanx, *8* third phalanx, *9* pelvis, *10* femur, *11* tibia, *12* tarsus, *13* metatarsus, *14* first phalanx, *15* second phalanx, *16* third phalanx

and proximal phalanges are the most common sites of fractures in racehorses, and the superficial digital flexor tendon is the most commonly affected soft tissue structure. Sesamoid bones come under high pressure by the flexor tendons wrapping around them, and this can lead to pathology. Disorders associated with the navicular bone and the deep digital flexor tendon are extremely common.

The anatomy of the neck, back, pelvis, and upper limb is basically comparable with human anatomy. Comparable to man, conformational limb defaults may predispose the individual to maladaptive musculoskeletal alterations or injuries. Despite the fact that most abnormalities can be considered as negatively influencing factors for all sport activities, some play a more dominant role depending on the type of activity (e.g., hyperextension of the hind limb fetlock predisposes dressage horses, already vulnerable to suspensory ligament (SL) injuries in the hind limb, to this type of lesion. Racehorses, prone to maladaptive remodeling of the carpal bones, with concave formation of the carpus are at increased risk to develop fractures in this area).

45.3 Diagnostic Imaging

The imaging modalities available for horses are the same as used in humans, including radiography (Fig. 45.3), ultrasonography (Fig. 45.4), computed tomography (CT) (Fig. 45.5), magnetic resonance imaging (MRI) (Fig. 45.6), and scintigraphy (Fig. 45.7). However, the application of these modalities differs considerably

Fig. 45.3 Setup of a radiographic examination of the equine foot

Fig. 45.4 Ultrasonographic tendon examination (the area under investigation is shaved)

Fig. 45.5 Computed tomography of the equine stifle under general anesthesia

Fig. 45.6 Magnetic resonance imaging (open magnet system) of the equine distal right front limb under general anesthesia

Fig. 45.7 Scintigraphic examination of the equine pelvic area

between man and horse due to the sheer size of the animal. Radiographic assessment is increasingly performed in the field using portable digital radiography systems. *Digital radiography* systems are now small and affordable and have become a standard piece of equipment for ambulatory vets. Hospital-based systems for horses use the same generators and registration systems (film screen/CR or DR systems) as human hospitals but are mounted differently to allow the use of horizontal and angled x-ray beams. *Ultrasonography* is considered a quite cheap modality, and nearly all veterinary practices have an ultrasound machine. This modality is strongly "operator dependent," but each practitioner can decide for himself/herself for which indication he/she will use it depending on training and knowledge. Ultrasonography is used a lot in the practice mainly for orthopedic injuries but also for any body part giving an appropriate acoustic window. For orthopedic disorders, linear 7.5–15 MHz (tendons, small joints, e.g., fetlock, tarsus), microconvex 6–9 MHz (feet, back, pelvis), or convex 5–8 MHz (large joints, e.g., stifle, hip) transducers are used. In adult horses, *tomographic modalities* (MRI, CT) are limited to the head, cranial part of the neck (till C5), and (distal) limbs due to the limited gantry opening (60–70 cm). For the rest of the neck, back, pelvis, and the majority of the upper limb, only radiography, ultrasonography, and scintigraphy are used because they can technically be performed in these areas, not because they are the best choice for the suspected disease. *Computed tomography* is used at some specialist centers to allow accurate assessment of fracture configuration before surgical repair. The same systems are used in equine than in humans but with a custom-built horse table that allows loads of up to 2 t to accommodate horses. The head and neck can be scanned with the horse standing, while for the limbs, general anesthesia/recumbent positioning is required, which is not undertaken lightly due to the associated high risk of potentially fatal complications (especially at recovery). The most frequently used *MRI* system in horses is an open low-field magnet 0.27 T MRI system developed by Hallmarq (Hallmarq Veterinary Imaging Ltd). This system is operating with the horse standing and it allows imaging of the foot and lower limb. Other open or closed magnets for equine MRI are the scanners used in human medicine, with field strengths from 0.2 to 3.0 T, and they require general anesthesia and recumbent positioning. Due to the noncooperative nature of many equine patients, *scintigraphy* is usually performed in the standing, heavily sedated horse, often resulting in "swaying," necessitating the application of motion correction software. For this same reason, dynamic images are acquired. The mounting of the gamma camera requires special modification to allow movement of the camera around the whole patient. This is usually achieved by suspending the camera from a railing system or the use of a forklift. The examination is time consuming, especially in cases where lameness cannot be attributed to a specific limb, because this requires total body imaging. Contrary to human patients, the classical total body acquisition is not possible, due to the size of the animal, and planar images of all the to-be-evaluated regions have to be obtained. Single-photon emission tomography (SPET) is not performed up till now because this necessitates general anesthesia and the limited gantry opening of conventionally used systems allow only investigation of selective parts of the equine body.

Fig. 45.8 Urine contamination prevention by bandaging the lower limbs and taping the feet

Preparation of the patient regarding urine contamination is a necessity. The lower limbs are bandaged and the hoofs are taped (Fig. 45.8). During the subsequent waiting period, the horses are stabled on shavings to increase the absorbing potential of the beddings and decrease contamination of the limbs. Some institutions use diuretics to induce voiding during this waiting period; however, this is considered a controversial procedure. During acquisition urinating may also occur as a result of the sedative, and containers to collect contaminated urine have to be in the immediate vicinity. After a scintigraphic examination, the horse remains hospitalized in an isolated stable for 24–48 h, and neither the horse nor its bedding is touched during this period (unless there is a medical emergency). The bone scan is extremely sensitive for imaging of bone (re) modeling. Increased bone metabolism may be the result of both adaptive and maladaptive bone modeling. Similar to humans, uptake can be seen in different strain-exposed areas that are not necessarily associated with pain (Drubach et al. 2001), and the findings on the bone scan have to be interpreted in the light of clinical findings and regional analgesia results. Scintigraphic examination is most valuable in the acutely lame animal and less in cases of chronic mild lameness or in horses with vague complaints such as decreased or suboptimal performance. The so-called false-positive scans may occur as a result of adaptive bone remodeling in sport-related predilection sites. Studies have been conducted in horses with different athletic activities to define the regions that show "physiologic" or sport-related stress-induced bone remodeling. These regions are however also potential sources for maladaptive bone alterations. Negative studies may be encountered when the lesion is primarily tendinous or ligamentous. False-negative scans may be due to suboptimal scan quality (camera distance to the region under investigation, insufficient counts, limited views) or due to vascular compromise. The “cold leg” phenomenon is well recognized in the equine patient. It is the result of the relatively poor perfusion to the lower limb, and preventative measures include bandaging of the lower limb or exercising the horse prior to the investigation (which is not without risk when a fracture is suspected). False-negative scans may also occur following traumatic injuries, especially in the pelvic area, a region additionally affected by image degrading factors such as motion, attenuation due to the heavy muscles overlying this area, and background radiation from the urinary bladder. It may take days before osteoblastic activity results in increased uptake (maximal tracer uptake occurs 8–12 days after bone injury in general but has not yet been studied in the horse) (Ross 2005). Severe disruption of the vascular supply may additionally hamper the regional delivery of the tracer. Scintigraphy is an expensive procedure; however, athletic horses are expensive to buy and even more expensive to train, which makes scintigraphic monitoring of these athletes worthwhile. The use of radioactive substances and the necessary legal radioprotective issues (which show variation among states and countries) limit its use to licensed institutions.

45.4 Diagnosis of Musculoskeletal Disorders

The diagnosis of orthopedic disorders can be challenging. Horses do not communicate orally and are less cooperative than humans. Therefore, the first mandatory step in the diagnostic process is to localize the site of pain. This process is quite different compared to adult human medicine and is comparable to small children medicine and starts with a clinical examination including observation of the standing and moving horse; palpation of the musculoskeletal structures; manipulation to elicit a pain response, e.g., flexion of joints; and systematic analgesia of specific nerves and/or joints from distal to proximal. The clinical examination can be compromised by the noncooperative nature of the patient and by nonspecific findings or may be limited by the nature of the suspected disease, e.g., systematic analgesia, and trotting a horse is contraindicated if fissures/fractures are suspected. The clinical findings guide the choice of the imaging modality subsequently used to characterize the cause of pain further, inform prognosis, and allow the appropriate choice of treatment.

45.4.1 Injuries of the Appendicular Skeleton

45.4.1.1 Bone Injuries

Bone injuries may result from traumatic events, such as a fall or collision, but are much more commonly the consequence of chronic repetitive overload causing “stress” remodeling and ultimately fractures. Risk factors for falls and related injuries during races have been distillated particularly in racehorses, and length of race, age, and race experience of the horse play an important role. Risk for fractures increases when

Fig. 45.9 A typical example of an incomplete proximal phalanx fracture

horses do not perform fast exercise during training or when they are in their 1st year of racing, with increasing race distance and firm/hard race ground conditions. Increasing distance at canter and gallop in short time periods in previously untrained animals increases the risk for tibia and pelvic fractures (review: Clegg 2011).

Traumatic fractures can occur in any bone but are more commonly seen in the lower part of the limbs. These fractures can usually be visualized with radiography (Fig. 45.9a, b). Computed tomography is sometimes performed presurgically in complex fractures allowing multiplanar two-dimensional and 3D reconstruction of the fracture. Both CT and MRI are useful in the assessment of acute distal phalanx fractures that are not always easy to spot on radiographs.

Stress-induced bone changes are the result of a mismatch between training-induced load and bone metabolism causing microfractures and changes in bone material properties. Stress-induced (re)modeling can be found in cortical bone as well as in cancellous bone, leading to alterations in bone microstructure, microfractures, and finally overt fractures. In horses with subchondral stress-related bone injuries, osteoarthritis is also a possible sequel. These stress-induced bone changes are most commonly, but not exclusively, observed in athletic horses performing at high speed such as gallop, trotting, and pacing racehorses. Remodeling changes have been found in horses suffering fractures of the humerus, pelvis, carpus, and distal metacarpus/metatarsus, indicating underlying pathology (review: Davidson and Ross 2003). The changes observed form a continuum, and it is not always easy to determine where the transition between

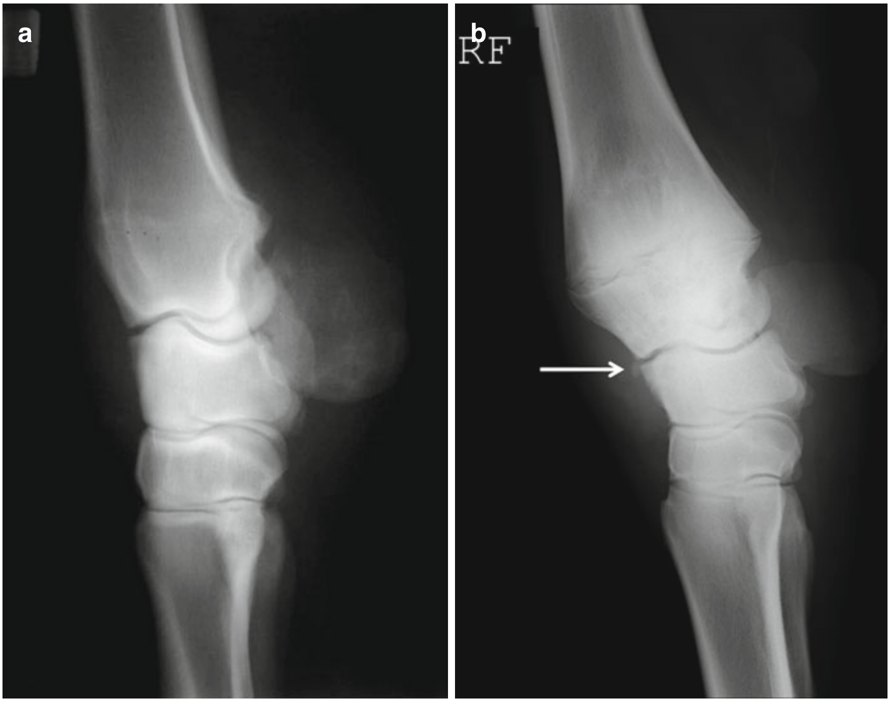

Fig 45.10 (**a**) Lateral (lateral to medial) radiograph of the normal carpal conformation. (**b**) Lateral radiograph of a carpus showing the typical "back at the knee" conformation with a chip fragment dorsal to the radiocarpal joint (*arrow*)

adaptive and maladaptive bone changes lays. In early stages of disease, the horses may only show a loss of performance, while in more advanced cases, the horse will be overtly lame, ranging from mild (often bilateral) to severe lameness, once the changes have progressed to a proper fracture. The most common sites for stress remodeling are the third and radial carpal bone, the dorsal cortex of the metacarpus/metatarsus, and the distal metacarpal/metatarsal epicondylar region (Ross 1998). Concave conformation of the carpus ("back at the knee") predisposes to carpal bone injury (Fig. 45.10a, b). Maladaptive changes result in typical slab or chip fractures in the radial carpal bone and the third carpal bone. Stress remodeling of the dorsal cortex of the metacarpus (dorsal metacarpal disease, DMD, or "bucked/sore shins") is often seen in young Thoroughbreds at the start of their training. To avoid the risk to develop DMD, gradual introduction of high-speed exercise has been recommended in order to induce an adaptive bone response (Clegg 2011). In most cases, DMD subsides with less intensive training. Stress fractures in the distal metacarpal/metatarsal regions may be accompanied by first phalanx fractures, a combination that usually finalizes the horse's sporting career. Stress remodeling and overt fractures are, similar to human running athletes, also seen in the tibia and femur.

Clinical signs of cortical bone remodeling are periosteal thickening and local pain. However, some regions can be difficult to palpate due to overlying muscles (e.g., lateral tibia). Regional analgesia carries a risk for development of a complete fracture and has

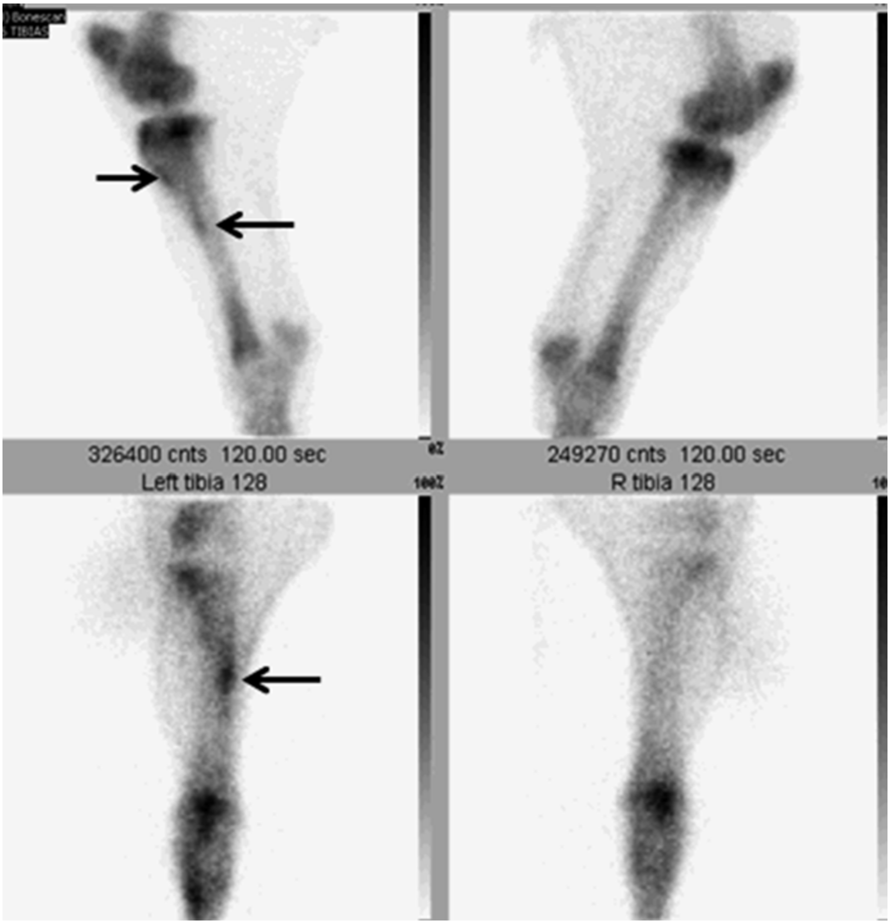

Fig. 45.11 Bone scan of both upper hind limbs, demonstrating a fissure of the left proximal tibia (*arrows*)

to be performed with caution. Regional analgesia of the upper limb regions (above carpus and tarsus) is insufficient or impossible. Clinical features of subchondral remodeling are variable. In horses with early disease, overlying joint cartilage will not be affected and clinical symptoms related to joint disease may be lacking. Focal sensitivity may not be present and intra-articular analgesia may be negative.

The value of radiography in stress-related bone remodeling is limited in the early stages due to its low sensitivity in depicting changes in bone density, while in more advanced stages, radiography is very useful to demonstrate periostitis, sclerosis, and fissure or fracture lines. In general, the use of radiography is limited by the size of the animal in the more proximal regions such as the pelvis. Also, radiography is not able to discern clinical silent disease from active bone remodeling. Scintigraphy has an excellent sensitivity in depicting changes in bone metabolism and is the imaging modality of choice to assess horses with stress-induced bone changes (Fig. 45.11). Planar images are acquired 2.5–3 h after injection of Tc99m-methylendiphosphonate

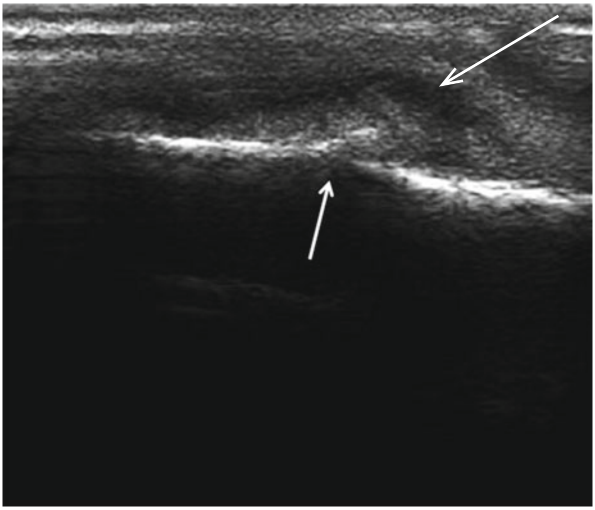

Fig. 45.12 Longitudinal sonogram revealing an acute fracture with cortical disruption of the second metacarpal bone (*large arrow*) with accompanying hematoma formation (*small arrow*)

at a dose of 1GBq/100 kg (a standard racehorse would require about 5GBq). Scintigraphy allows identifying changes at a very early stage and consequently can be used to alter the training regime in order to prevent progression of disease. Scintigraphy may also be of help to recognize subtle radiographic changes and to determine clinical significance of findings. The use of scintigraphic patterns of uptake in the tibia, as is used in humans, to define the severity of pathology and predict the duration of decreased training regimes, has been reported to be of no use in the equine athlete (Ramzan et al. 2003). It is of paramount importance that an adequate number of high-quality views are taken. Scintigraphic findings are often a helpful guide for subsequent use of other imaging modalities, mainly ultrasonography. The bone scan has also been used to determine specific areas subject to stress-related bone remodeling depending on the type of sport activity (Davidson and Ross 2003; Ehrlich et al. 1998). Magnetic resonance imaging is useful in the detection of bone pathology such as bone edema, and it seems promising to show early stages of stress-induced bone remodeling. However, unlike scintigraphy, it is mainly limited to the lower part of the limbs. Ultrasonography, as a very accessible modality, can be a helpful tool. Cortical disruption, irregular bone contours, and hematoma formation are the common occurring signs (Fig. 45.12).

45.4.1.2 Tendon and Ligament Injuries

Tendon and ligament injuries are encountered in all sport disciplines but are mostly investigated in racing Thoroughbreds (see for nice reviews: Firth 2006 and Thorpe et al. 2010). The incidence of tendon injuries in Thoroughbreds is slightly higher in those that race over fences. Tendon loading and stretching is associated with speed, being minimal at walk, twice as high during trotting, and approaching or exceeding its physiological limits during a fast gallop. However, tendon injuries are also common in eventers, show jumpers, and dressage horses. All tendons can be affected by tendinopathy, and all ligaments can show a desmopathy, but the majority of tendon injuries occur in the forelimb (97–99 %), and the most commonly injured flexor structures are the superficial digital flexor tendon (SDFT) and the suspensory ligament (SL). Suspensory ligament desmopathy may also occur in the hind limb, particularly in the dressage horse, which is related to the strain on the hind limbs during collected movements such as piaffe, passage, and pirouettes. The SDFT and the SL in the forelimb act as springs to store and release energy during locomotion and as such decrease the energetic cost of locomotion. They are subjected to higher strains compared to the DDFT, a tendon not primarily involved in energy storage and release. Many of these tendon injuries result from preceding degenerative alterations that are centrally located (called core lesions) and initially not accompanied by inflammatory signs (swelling and lameness), similar to what is seen in humans (Riley 2008). The risk for tendon injury increases with age, starting at the moment of training and racing (at the age of 2–3 years). Degeneration and effect of training on the SDFT structure has been extensively studied. Tenocytes have limited ability to adapt their matrix to strains, with adaptation possible under normal conditions but not under "superphysiological" strains. During training and racing, inflammatory mediators and degenerative enzymes are released (similar events occur in human tendons), accelerating physiological aging phenomena. An additive potentiating factor is the considerable heat produced in the tendon during galloping activities inducing also production of proinflammatory cytokines. In addition, heat is only slowly dissipated due to the poor blood supply to the equine tendon.

Superficial digital flexor tendon lesions are common in the metacarpal region but also found elsewhere, including the accessory ligament of the superficial digital flexor tendon; the palmar carpal region; the palmar fetlock, with distension of the corresponding tendon sheaths; or the pastern region, including the insertion on the second phalanx. Proximal lesions are the most painful. Suspensory ligament injury may involve one or both distal branches, the main/midbody, or the proximal metacarpal/metatarsal origin (Fig. 45.13). The metatarsal origin injuries have the poorest prognosis for functional recovery.

One abnormal loading cycle, i.e., abrupt overstretching, can also provoke tendon injury. Muscle fatigue and uneven surfaces are risk factors. Occasionally tendon injury results from blunt trauma causing a local superficial tendon bruise (Fig. 45.14a, b), perforating trauma with subsequent infection, or inclusion of foreign material. Prior to athletic career, flexor tendons of new born foals may be too short, requiring orthopedic or surgical correction. In old mares progressive weakening of the SL of the hind limbs and hyperextension of the fetlocks may occur, which probably has a hormonal origin.

Injury of extensor tendons predominantly results from trauma/wounds, and the prognosis for complete and fast functional recovery is excellent.

Dislocation of the superficial flexor tendon of the tip of the calcaneus is not uncommon and has also a traumatic origin. Compared to human athletes, injury of the Achilles tendon is a rare phenomenon and is contrary to man, mostly caused by an acute traumatic event. The molecular characteristics of Achilles tendon lesions in humans show more similarities with the equine flexor tendon lesions.

Healing of tendon injuries is a very slow process. It may take 6–12 months, or even more, thus seriously delaying or even ending athletic performance. Additionally, relapse is not uncommon. Research focused on improvement of tendon repair is

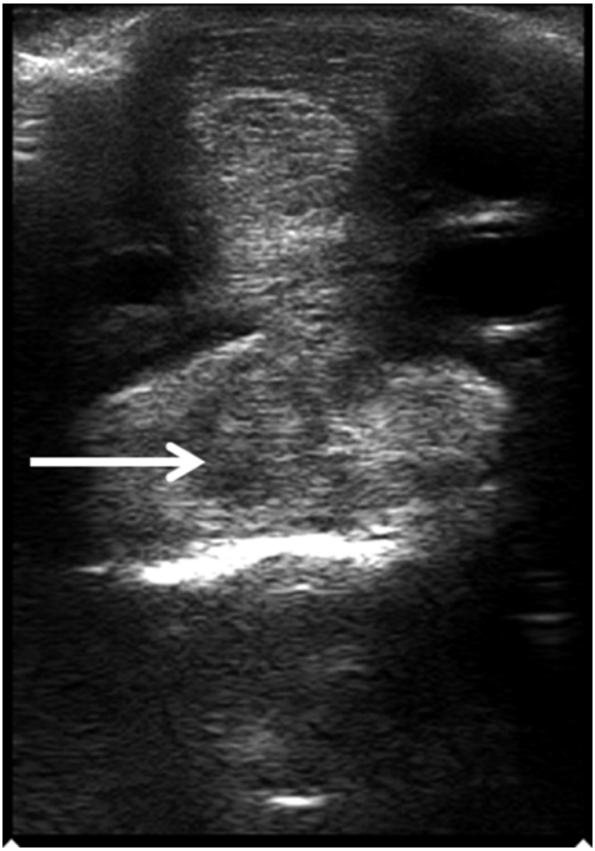

Fig. 45.13 Transverse sonogram of the suspensory ligament demonstrating a core lesion (*arrow*) combined with swelling of the ligament

very complex. Standardized double-blind field studies are almost impossible, and the behavior and therapy response of experimentally induced injuries may be different to spontaneous occurring lesions. More, the loading and composition of different tendons and tendon regions varies. Ultrasound-guided intralesional injected material may mask the structural damage/loss of echogenicity, thus creating a false impression of repair. Therefore, promising results of new therapies, like stem cells, are questionable, and (ultrasound-guided) controlled accelerating exercise remains still the fundamental therapeutic approach at the moment.

The clinical examination is a poor indicator for assessment of tendon injury. Pain may subside rather soon, swelling may be minimal or peritendinous, pain alleviated by nerve analgesia may actually arise from adjacent structures, and accurate assessment of the location, extent, and structural damage is impossible. Ultrasonography is, in the hands of skilled operators, an excellent modality for detailed imaging of the location, extent, and structural damage/loss of echogenicity of tendon lesions and follow-up of tendon repair. Recent technical advances such as harmonic imaging, spatial compound, elastography, or specific software for quantification may improve the diagnostic capabilities of ultrasonography. An ultrasonographic examination is relatively cheap and performed in the horse standing. Magnetic resonance imaging is considerably more

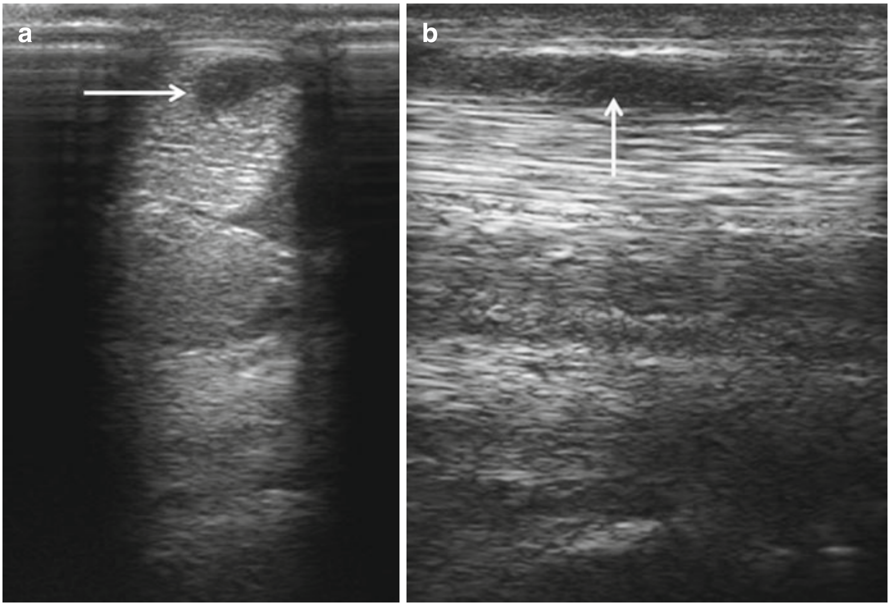

Fig. 45.14 (**a**, **b**) Transverse (**a**) and longitudinal (**b**) sonogram demonstrating a tendon acute bruise (*arrow*)

expensive, but it is the imaging modality of choice for assessing soft tissues that are located within the hoof capsule, including the deep digital flexor tendon and ligaments associated with the navicular bone and the distal interphalangeal joint. Contrary to ultrasonography, MRI allows recognition of signal changes reflecting changes of biochemical composition, prior to gross structural changes. This could explain the better functional recovery prognosis of equine tendon lesions reported in MRI versus ultrasonographic studies. Regretfully standardized MRI examination protocols are not yet available. Intra-arterial contrast CT, visualizing the blood supply of tendon lesions, is also an option but by far less commonly used than MRI, and it requires general anesthesia. The bone scan can be valuable in cases of proximal metacarpal/metatarsal SL insertion problems, a pathology that is often a diagnostic challenge.

Another frequently occurring problem is termed "navicular syndrome," which is a commonly used term for all the disorders associated with the navicular area in the (front)foot. Because of the progresses made with MRI and ultrasonography in the last decade, we know that this umbrella term covers a whole range of disorders affecting the navicular bone, its anchoring ligaments, and/or the deep digital flexor tendon and the distal interphalangeal joint. This "navicular syndrome" is a common occurring problem in the warm-blood horse, especially when engaged in jumping activities. However, other types of horses can suffer from this syndrome as well. Low heel and long toe conformation are predisposing conformational factors. Diagnosis begins with clinical examination and regional analgesia usually followed by radiography. However, especially in cases with equivocal radiographic findings, ultrasonography, MRI (Fig. 45.15), or scintigraphy (Fig. 45.16) is indicated to exclude other causes for foot pain and to come to a precise diagnosis.

Fig. 45.15 A transverse T1 MRI sequence of the foot revealing deep digital flexor injury (*arrows*)

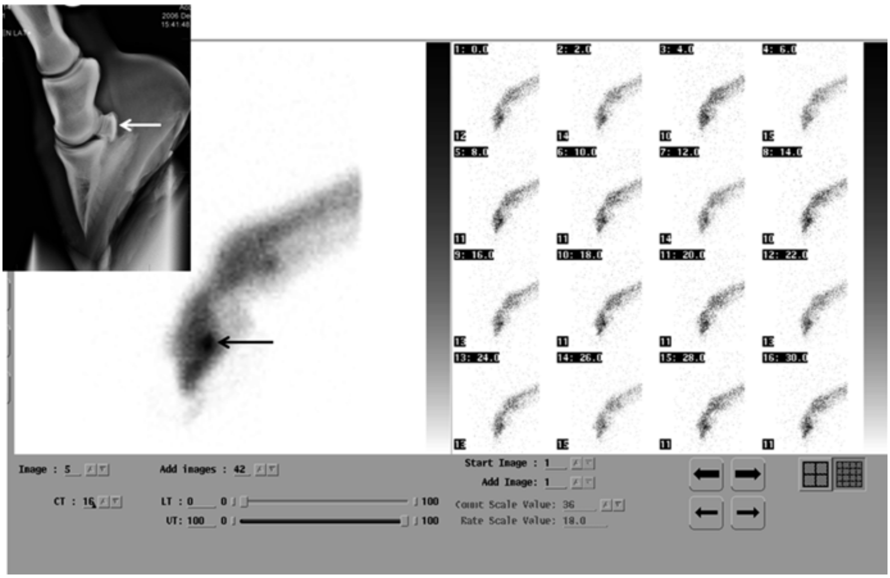

Fig. 45.16 A lateral view bone scan with lateral tomography of the lower limb shows increased uptake in the navicular bone (*arrow*). Typically dynamic acquisitions are obtained to allow motion correction. The left image represents a summation of the dynamic acquisitions. The radiograph (inset) shows the location of the navicular bone in the foot (*arrow*)

Fig. 45.17 Lateral radiograph of the stifle. A contour defect of the lateral femoral trochlear ridge, with corresponding fragments, characteristic for osteochondrosis (*arrow*)

45.4.1.3 Joint Injuries

Joint lameness may be a direct consequence of athletic activity, e.g., distortion or (sub)luxation, but it is frequently induced by underlying joint disorders. The most common joint disorders are osteochondrosis (Fig. 45.17), subchondral bone cysts (Fig. 45.18a, b), work-related cartilage wear and tear, osteoarthritis triggered by age, and bone fragments (from osteochondral or traumatic origin). Equine osteochondrosis is defined as a developmental disorder with a genetic, nutritional, and traumatic origin as opposed to humans where it is more a collection of multiple disorders involving the osteochondral junction in general. In horses this disorder is specifically characterized by focal delay of ossification of articular cartilage and results in contour defects of the articular surface, with or without fragmentation, if not recovered spontaneously prior to 1 year of age. The main predilected sites are the stifle, tarsal, and fetlock joints. Not all osteochondrotic fragments cause joint problems; nevertheless, the removal of these bone fragments for economical reasons (in connection with prepurchase examinations) is a big business in horses! Lameness originating from the fetlock, carpal, tarsal, stifle joints, and the foot region is frequent. The predominantly involved joints depend on the use of the

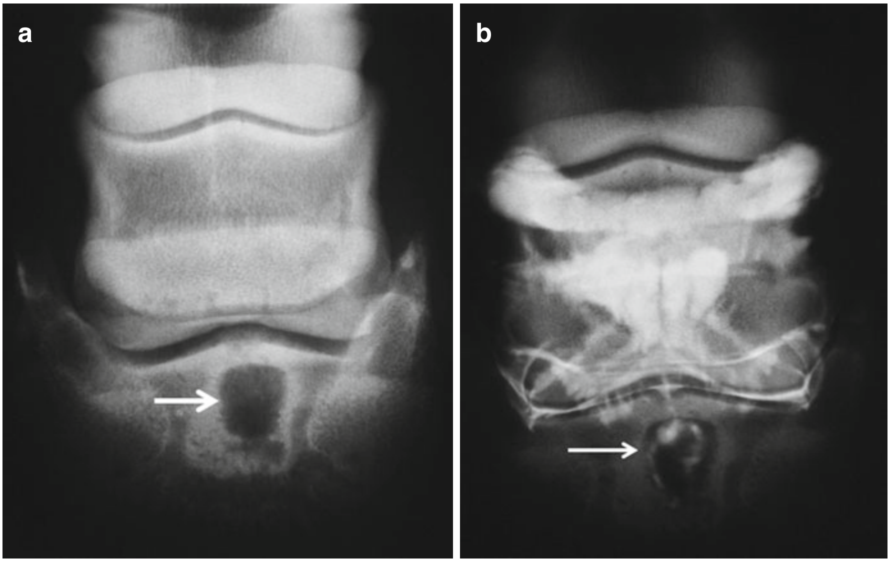

Fig. 45.18 (**a**, **b**) PA (posteroanterior or dorsopalmar) view of the foot. (**a**) A large cystic lucency is visible in the distal phalanx (*arrow*). (**b**) Clinical significance (e.g., connection with the distal interphalangeal joint) is demonstrated by intra-articular injection of contrast (arthrography) medium entering the cystic cavity (*arrow*)

horse. The front fetlock is the most commonly affected joint regardless of athletic use, followed by the carpi in horses performing at speed. Remodeling changes in the subchondral bone often precede cartilage changes in young racehorses. Increased uptake on the bone scan in these predilection areas or subchondral sclerosis on radiographs is frequently found without joint effusion or radiographic periarticular osteophytes (Ross 2005). In these animals, this bone remodeling may lead to either overt fractures (see previous section) or to osteoarthritic joint alterations. In other performance horses, the phalangeal joints, hocks (tarsus), and stifles are most commonly affected. Although riders and trainers think otherwise, shoulder and hip lameness are relatively rare.

Radiography is still the basic tool for imaging of the equine joints. Considering the frequent occurrence of underlying joint disorders, radiography is also the favorite modality for equine prepurchase examinations, which corresponds to prospectively estimating the lameness risk. This estimation is obtained by combining the results of history, clinical examination, and radiography. Prepurchase examinations are a core business of equine practitioners! Ultrasonography is also used to visualize joint capsules, cavities, ligaments, and articular cartilage when accessible. In most joints, ultrasonography allows satisfactory evaluation of the soft tissue structures. In the stifle joint, ultrasonography will demonstrate meniscal and collateral ligamentous injury but the evaluation of the cruciate ligaments is very challenging. In the foot, visualization of the frequently affected structures is mainly limited to the axial section. However, the usual lesions reported in MRI studies are also found with

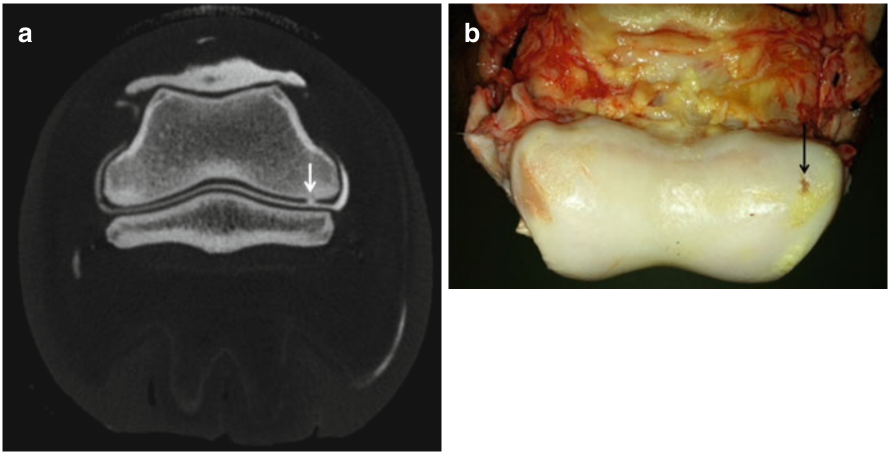

Fig. 45.19 (**a**) Computed tomographic arthrogram of the distal interphalangeal joint showing a full-thickness cartilage defect (*arrow*) and (**b**) corresponding specimen

ultrasound. The combination of radiography and ultrasonography is an attractive alternative for joint imaging when MRI cannot be performed because it is not available or it is too expensive. Magnetic resonance imaging is the most appropriate modality to visualize the articular soft tissues, i.e., joint capsule and cavity, ligaments, as well as subchondral bone bruise and cysts. When selecting MRI for imaging a joint, a choice has to be made between low-field units with the horse standing that are less suitable for the imaging of articular cartilage lesions due to a limited resolution and high-field units that have a higher resolution but require general anesthesia. While medical insurance of horses is common in some countries (e.g., the UK), it is still uncommon in others, and hence the financial aspect often plays a role in the decision-making process. Computed tomography of joint disorders is inferior to MRI and therefore used less frequently. CT allows clear visualization of small bone lesions in 3D, like very small bone cysts, or subtle bony features of navicular disease due to the lack of superimposition and the ability to "window." In most examination of joints, CT arthrography (Fig. 45.19a, b) has to be performed after native CT. This is mandatory for the stifle joint. The shoulder, elbow, and hip joints are not accessible with both CT and MRI. Scintigraphy reveals functional adaptive remodeling of the adult and developing bone, within specific joint loading regions. Diagnostically it is considered useful to pinpoint to the site of pain, if not localized by the clinical examination. Increase in bone turnover does not equate to pain, contrary to the biased opinion of many clinicians, and the relevance of hot spots has to be seen in the clinical context (when possible substantiated by targeted diagnostic nerve or joint analgesia) and confirmed with other imaging modalities. However, it has to be borne in mind that when structural imaging does not confirm the hot spot, follow-up investigations are needed as functional alterations precede structural lesions.

45.4.1.4 Muscle Injuries

Traumatic muscle disorders are fairly uncommon. Traumatic incidences occasionally result in hematoma in direct muscle trauma; rupture of the muscle itself, at its tendinous insertion on the bone; or abscesses. In Quarter horses, fibrosis and calcification of the flexor muscles of the proximal hind limb, resulting in abrupt limitation of limb protraction ("goose step" gait), are well known. Peroneus tertius rupture, due to abrupt hyperextension of the hind limb, is also a familiar entity. This entirely fibrous muscle originates from the distolateral femur and inserts to the dorsoproximal metatarsus, thus coordinating stifle and tarsal flexion. Rupture results in a typical clinical appearance with flexion of the stifle, extension of the hock, and simultaneous loss of tension of the Achilles tendon. Functional recovery may result from repair or compensatory hypertrophy of the overlying long digital extensor and underlying tibialis cranialis muscles. Myopathy of the triceps muscle of the upper front limb, mimicking radial nerve paralysis, may be a complication of lateral recumbent positioning of the anesthetized horse. All these disorders are easily diagnosed using ultrasonography. Myopathies of the back and upper hind limb muscles, induced by exhaustion and nutrition or idiopathic, are preferably seen in endurance horses and sometimes in Standardbreds. The diagnosis is mainly based on the amount of muscle enzymes in blood samples, before and after exercise. In acute cases, a bone scan may reveal an uptake in the muscles involved.

Neurogenic atrophy of the lateral shoulder muscles, i.e., supra- and infraspinatus muscles and the associated lateral instability of the shoulder ("Sweeny"), may be a consequence of injury of the nerve branches arising from the brachial plexus. Imaging of the equine brachial nerve plexus is impossible, but the clinical appearance of Sweeny is characteristic.

45.4.2 Injuries of the Axial Skeleton

Sport injuries and disorders hindering athletic performance are also encountered in other musculoskeletal body regions, like the back, neck, and head, but are far less common than limb disorders.

45.4.2.1 Back Pain

Mutual "kissing" of spinous processes in the thoracolumbar region (T10–L4) is considered the most common cause of primary back pain. Due to the poor correlation between back pain, radiographic appearance, and scintigraphic hot spots, an accurate diagnosis requires local analgesia of the suspected back region. Regretfully, this is not a common practice; thus, the validity of the "diagnosis" is frequently questionable. Back pain may also be secondary, i.e., resulting from (hind limb) lameness. Such "back pain" will be relieved by analgesic nerve blocks of the diseased limb. Low back pain may be lumbosacral or a consequence of iliosacral instability. Scintigraphy will demonstrate the activity of kissing spines (a condition similar to Baastrup disease in humans) (Fig. 45.20) and lumbosacral or iliosacral

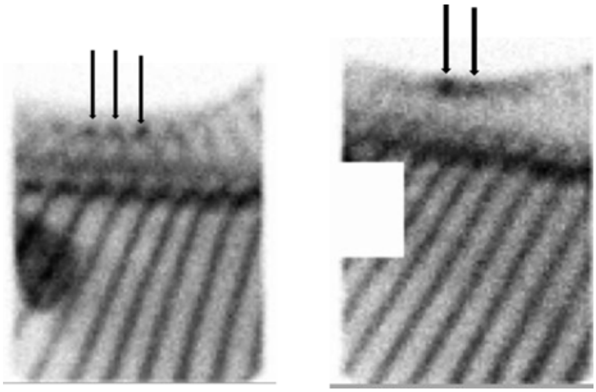

Fig. 45.20 Bone scan of the thoracic spine. Increased activity is seen at the level of several spinous processes, reflecting "kissing spines" (*arrows*)

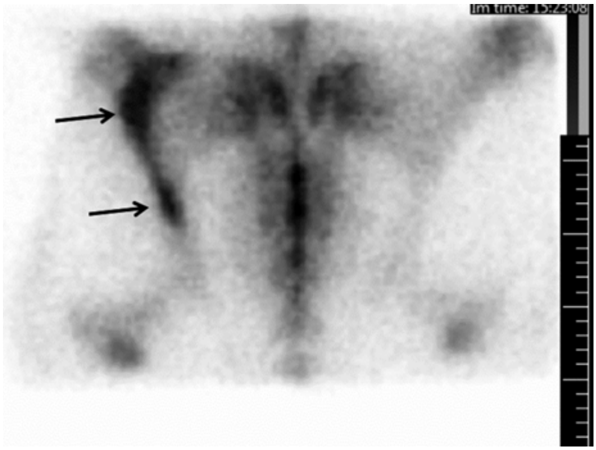

Fig. 45.21 Bone scan of the pelvic area showing increased tracer accumulation in the left iliac wing and body due to a fracture (*arrows*)

disease. It has to be correlated with radiography and/or ultrasonography for morphological demonstration of the suspected lesion. However, visualizing the lesion is not always successful as radiography is usually limited to lateral imaging of the thoracolumbar region on the standing horse and the interpretation of the ultrasonographic findings of the supra- and infraspinous ligaments, dorsal muscles, and the ventral aspect of the lumbosacral region and iliosacral joints (using a rectal approach) is difficult.

45.4.2.2 Pelvic Injuries

In racehorses pelvic fractures are typical stress-related fractures (Fig. 45.21). Acute severe pain is present. Iliac wing fractures can be diagnosed with ultrasonography, using a transcutaneous or transrectal approach. Scintigraphy can be used but can be falsely negative especially when the fracture is not stress related and the region does not show previous remodeling changes. The reasons for this are related to motion,

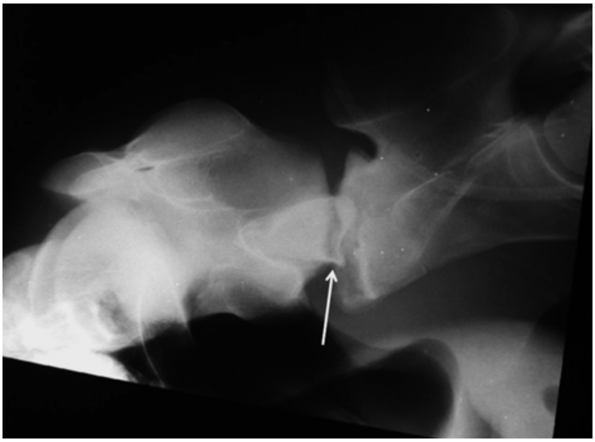

Fig. 45.22 Lateral radiograph of the cranial neck demonstrating a fracture/dislocation of the dens of the second vertebra (*arrow*)

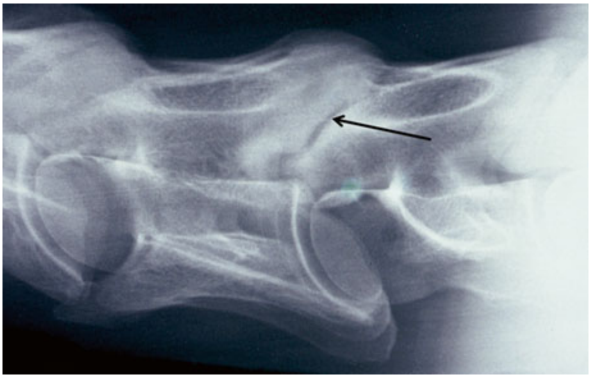

Fig. 45.23 Lateral radiograph of the caudal neck region demonstrating facet joint osteoarthritis between C6 and C7 (*arrow*)

thickness of the soft tissue overlying the pelvic area, and nearby presence of the urinary bladder resulting in less optimal images. Also a lag time before osteoblastic activity has reached its peak, and vascular compromise related to the injury has to be taken into account. Repeated scans after at least 1 week are indicated in these cases (Ross 2005).

45.4.2.3 Neck Injuries

In the cervical region, fractures/luxations (Fig. 45.22) of the vertebrae usually result from a fall and frequently are fatal. Such fractures are preferably encountered in eventing horses. A common cervical disorder is osteoarthritis of the articular facets between the caudal cervical vertebrae (C5–T1) (Fig. 45.23). Osteoarthritis may hinder neck flexion, which is a serious problem, particularly in high-level dressage horses. It may also encroach the descending nerves causing a uni- or bilateral front limb lameness. Obviously such lameness is not alleviated by analgesic nerve blocks. It should be noted that facet joint osteoarthritis may also be an accidental finding during a prepurchase examination and not hindering athletic performance. Another common entity is (hind limb) ataxia arising from compression of the cervical spinal cord. A very subtle degree of ataxia may be advantageous, particularly for jumping horses (personal observations), possibly due to "overcompensation." However, with a more serious degree, riding becomes too dangerous.

The basic imaging tool for the cervical region is radiography performed on the horse standing. Contrast radiography, i.e., myelography, is used to visualize compression of the spinal cord. This procedure is expensive and risky, as it requires general anesthesia and lateral recumbent positioning, with the neck in neutral, flexed, and extended position. Ultrasonography enables imaging of the facet joints and is used for left-right differentiation and guided therapeutic injections of the facet joints. Computed tomography and MRI in adult horses are limited to the cranial neck region and therefore seldom used. Scintigraphy is performable on the horse standing and will reveal the activity of facet joint osteoarthritis. Recently, preliminary reports presented endoscopic evaluation of the equine spinal cord and adnexa.

45.4.2.4 Head Injuries

Facial, orbital, or mandibular fractures of the equine head usually result from blunt trauma. A skull base fracture usually is a consequence of rearing and falling backwards. A common tumorlike disorder is a progressive ethmoidal hematoma. This causes a hemorrhagic nasal discharge, which excludes the horse from competition. Dental disorders, frequently associated with secondary sinusitis, are common in horses and prevent normal riding. Surprisingly temporomandibular joint disease, usually resulting from trauma or infection, does not hinder chewing and eating. However, such horses become reluctant if the rider pulls the rein attached to the corresponding side of the moor/bit.

Computed tomography is the modality of choice for head disorders, diagnostically as well as for surgical planning, if radiography is inconclusive. Computed tomography in the standing horse on a moving platform and a stationary gantry or the reverse is becoming more and more widely used for the assessment of head problems, especially dental problems. Magnetic resonance imaging is also an option but not the favorite tool for head disorders, other than brain diseases. Ultrasonography can also be helpful in the equine head, e.g., in the assessment of the temporomandibular joint (Fig. 45.24), maxillary sinus, and dental problems. Scintigraphy may be used to localize bony changes; however, disease characterization is not possible (Weller et al. 1999).

A very serious problem hindering athletic activity is "headshaking." It may result from "sunlight allergy," but various other causes are possible. Regretfully most of them are untraceable by diagnostic imaging.

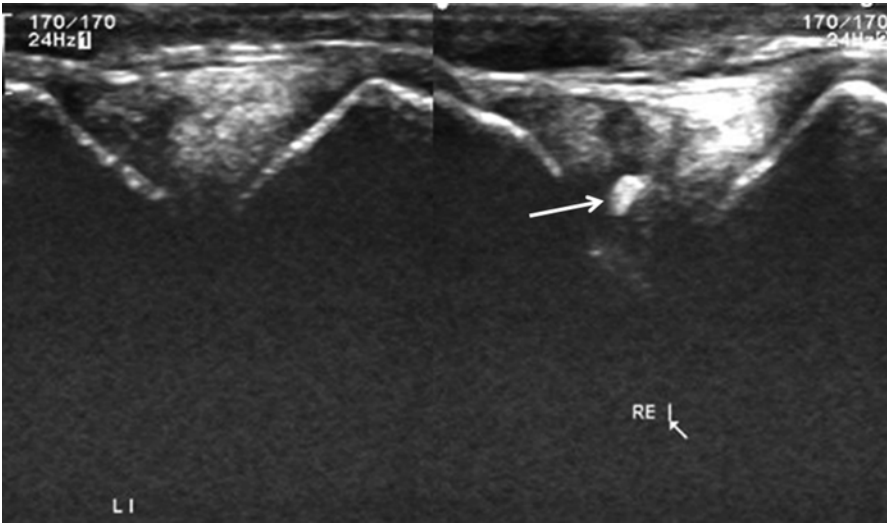

Fig. 45.24 Sonograms of the left (normal) and right (diseased) temporomandibular joint showing an intra-articular loose bone fragment (*arrow*)

Conclusion

Thorough clinical examination is the first line of approach in the equine orthopedic patient. Several imaging modalities may be used to offer diagnostic clues depending on the type and location of the specific pathology. The size and conformation hamper the thorough imaging of certain areas with conventional structural imaging modalities. Computed tomography and MRI cannot be used for upper foreleg, lower neck, back, pelvis, and hip. Larger CT bore gantries and large open MRI magnets permit the investigation of the stifle area. Ultrasonography is a helpful tool also for inaccessible regions such as back and pelvic area. The main problem, besides its operator dependency, is that the region of injury has to be already defined. Scintigraphy is a highly sensitive modality, allowing a total overview of the equine patient, in cases with bone involvement. The combination of structural and functional imaging, e.g., SPECT/CT image fusion as in humans, would be ideal. However, when available, again, the size of the gantry will limit its use to the lower extremities, head, and cranial neck.

The major issue, related with sport activity, is the occurrence of maladaptive changes especially in sports involving high-speed activity at a young age, e.g., races. Until now, little information is present on which training regime is optimal to minimize maladaptive bone, cartilage, and tendon remodeling (Firth 2005). Too little or, in case of racing Thoroughbreds, deprivation of high-speed exercise seems to be a risk factor as well as too intensive exercise (Thorpe et al. 2010). Future studies preferably should include scintigraphic follow-up of youngsters in training to evaluate the effect of certain training schemes on bone metabolism. Follow-up investigation of tendon remodeling is a more difficult issue, as a recent study showed that developing core lesions could not be depicted by ultrasonography in the early phase (Avella et al. 2009), and when visible, an acute tendon injury was likely to occur. Standing MRI is a potential alternative but at the moment limited due to availability and costs.

Prevalence and risk factors for musculoskeletal injuries are best documented in the racing Thoroughbred (Stover et al. 1992; Parkin et al. 2006; Verheyen et al. 2006; Clegg 2011; Reed et al. 2012). The reason is the structured nature of the race industry with information on the individual animal (age at first race, number of starts, winning sum) readily available. These horses are trained collectively in relatively large stables. Therefore, comparison between training regimes and track conditions is possible for large groups of animals. Furthermore, their activity is "limited" to run at high speed over different distances with or without fences. Information on other sport disciplines is scarce (Singer et al. 2008; Murray et al. 2010). Most of these horses are managed in a more individual way, dispersed over numerous (often small) stables, making the comparison between management and training conditions a difficult task. Levels of competence of both rider and horse and training regimes/arena surfaces show much more variability compared to racing activities. Training may vary and may overlap, e.g., dressage horses jump and jumping horses perform dressage during training. Many of them are sold during their career (often abroad, to owners with more or less competence or to owners using them for other activities) and as such are difficult to follow-up. Therefore, particularly in these horses, research on risk factors and injury prevention remains a complex but challenging domain.

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The Expert View on Tennis Injuries

46

Floor Groot and Babette Pluim

Contents

Abstract

Tennis is one of the major global sports, played by people of all ages and at all levels of society. Playing tennis, at no matter what level, places the participant at risk of injury. This chapter provides extensive information regarding tennis injuries and the role of imaging in the diagnostic process.

First, physiological and biomechanical aspects of tennis are briefly illustrated, as well as the epidemiology of tennis injuries. Hereafter, a wide range of tennis injuries is thoroughly discussed, including underlying pathophysiology, the role of imaging, and potential treatment. This part of the chapter is divided into three sections according to anatomical area, distinguishing injuries from the upper extremity, trunk, and lower extremity.

The chapter forms a comprehensive overview of tennis injuries and the role of diagnostic imaging.

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Abbreviations

ACL	Anterior cruciate ligament
CT	Computed tomography
ECRB	Extensor carpi radialis brevis
ITF	International Tennis Federation
MRI	Magnetic resonance imaging
RICE	Rest, ice, compression, and elevation

46.1 Introduction

With over 75 million participants worldwide (Pluim et al. 2007), tennis is one of the major global sports. In addition to the active recreational participants, the game is an enormously popular spectator sport, especially the four so-called Grand Slams (Australian Open, French Open, Wimbledon, and US Open). In 1988 tennis officially returned to the Summer Olympics, after being absent since 1924. The International Tennis Federation (ITF) is the governing body of the game of tennis, and its headquarters are located in the southwest of London (http://www.itftennis.com).

Tennis is a noncontact sport played between two players (singles) or between two teams of two players (doubles). A racket is used by each player, enabling the player to hit the hollow rubber ball over a net and into the opponent's court. The object of the game is to score points by hitting the ball in such a way that the opponent is not able to return it. A player can win the match by gaining "games" and "sets." Tennis is played by people of all ages and at all levels of society. Wheelchair tennis follows the same rules as able-bodied tennis, except the ball is allowed to bounce twice instead of once in able-bodied tennis.

46.1.1 Physiological Demands of the Game and Biomechanics of Tennis

While there is a set structure to the service, after that unpredictability plays a major role in tennis. It is what makes tennis interesting from a physiological point of view. Due to this variation of shot selection, point and match duration, strategy, weather, and – last but not least – the opponent, there is great variance in physiological demands. During a match, some 300–500 bursts of anaerobic effort may be required, with rest periods between points and games. The mean duration of rallies varies substantially, depending on numerous factors, and is on average between 5 and 15 s. As tennis does not have time limits, matches may last from less than 1 h to over 5 h; this requires athletes to have both high anaerobic and aerobic fitness levels (to aid in recovery during and after play). In summary, tennis might be classified as a predominantly anaerobic activity requiring high levels of aerobic conditioning to aid in recovery between points and to avoid fatigue (Kovacs 2006; Pluim and Safran 2004).

In addition to the abovementioned cardiorespiratory characteristics, tennis demands great speed and agility (when moving over the court), as well as strength (ball velocity) and flexibility (joint range of motion).

Biomechanics also play an important role in tennis. As all strokes (forehand, backhand, service, and volley) are repeated with high frequency, developing proper biomechanics and stroke technique helps to improve efficiency and reduce injury risk. A faulty technique is a major risk factor for injuries. It is a common misconception that muscular strength determines how hard one can hit the ball; "power tennis" is actually the result of the effective biomechanics (e.g., racket speed) and not just muscular strength (Elliott 2006; Pluim and Safran 2004).

46.2 Epidemiology of Tennis Injuries

Playing tennis, at no matter what level, places the participant at risk of injury. A review of the literature reveals a substantial variance in injury incidence, ranging from 0.04 to 3.0 injuries per 1,000 h played (Pluim et al. 2006). Some of this variation may arise from the fact that different definitions of injury have been used in the various studies. A consensus statement was made in 2009 in order to record injuries and illnesses in a more consistent and comparable way (Pluim et al 2009).

Most injuries in tennis occur in the lower extremity (31–67 %), followed by the upper extremity (20–49 %) and the trunk (3–21 %). Acute injuries tend to occur most often in the lower extremity (e.g., ankle sprain, muscle rupture), whereas gradual-onset injuries commonly affect the upper extremity or trunk (e.g., low back pain, rotator cuff tendinopathy, tennis elbow).

Some factors have been shown to increase the risk of injury in tennis. Both volume of play and playing competitive tennis increase the risk. There is no evidence that age, sex, and skill level are associated with a higher risk of injury (Abrams et al. 2012).

46.3 Injuries

46.3.1 Upper Extremity Injuries

Due to the repetitive motion of the serve and ground strokes, overuse injuries of the upper extremity occur frequently in tennis. Acute traumatic injuries may result from a fall onto the arm or hand but are much less common.

46.3.1.1 Shoulder

The fragile equilibrium between mobility and stability in the shoulder is the most important underlying principle in shoulder injuries in tennis. The large range of motion in all directions allows overhead action (e.g., during service), but the repetitive abduction-external rotation movement carries a risk of overloading the various anatomical structures around the shoulder. The kinetic chain, scapular (in) stability, capsulolabral complex, and glenohumeral internal rotation are all considered to play an important role in shoulder injuries (Hoeven and Kibler 2006). Disturbances in one of these factors may lead to internal impingement or labral pathology. In older players, the rotator cuff is more commonly involved, whereas in the young tennis player, shoulder pain is more often due to subtle instability. In the young tennis player, growth plate-related shoulder pain (e.g., epiphysitis humeri) should be taken into account as well. Modifying the training load and strengthening exercises of the scapula and shoulder is the cornerstone of treatment.

46.3.1.2 Elbow

Tennis elbow is a tendinopathy involving the extensor carpi radialis brevis (ECRB) causing lateral elbow pain. It is one of the most common overuse injuries in tennis, especially in recreational players. The overall career incidence has been reported to be between 35 and 51 %. Interestingly, only 5 % of the people with tennis elbow actually play tennis. Within 1 year, 90 % of patients recover, regardless of which treatment is used. Corticosteroid injections offer good short-term results (6–10 weeks) but lead to more recurrences after 1 year compared to wait-and-see policy (Smidt et al 2006; Smidt and Van der Windt 2006). This means that they should be avoided in most cases. As the diagnosis "tennis elbow" is made clinically, diagnostic imaging is rarely required.

Osteochondritis dissecans usually affects adolescents and young adults and may occur in the elbow as well. It can lead to swelling, pain, and locking of the elbow. The success of treatment is best after early detection. When the overlying cartilage is intact, nonoperative treatment is advocated. In case of intra-articular loose fragments in the joint, surgery might be the next step.

In case of elbow pain in the young tennis player, one should be aware of the possibility of Panner's disease (avascular necrosis of the capitellum). Medial elbow pain in the young player can be caused by overload of the medial humeral apophysis, resulting from repetitive traction forces of the medial collateral ligament and wrist flexor muscles on the inner epiphysis of the humerus. Radiography and MRI are important diagnostic tools in establishing the diagnosis. In the older player, medial elbow pain can be caused by tendinopathy of the flexor muscles of the forearm or by a partial tear or failure of the medial (ulnar) collateral ligament.

46.3.1.3 Wrist

Ganglions in the hand or wrist are common. They arise from an adjacent joint or tendon and may vary in size, usually becoming bigger on activity. Larger ganglions may cause mild pain, especially when they interfere with joint motion. The diagnosis is usually made on clinical examination. Radiographs are of no use, as they will not visualize ganglion cysts. Ultrasound or MRI can confirm the diagnosis.

Tendinopathies around the wrist may involve the flexor carpi ulnaris, the flexor carpi radialis, and the extensor carpi ulnaris. The rapid racket deceleration, with the associated huge eccentric force, is thought to be the underlying cause. Frequency of play might be a risk factor, as well as playing with a new racket, higher string tension, or suboptimal stroke mechanics (including grip). Normally the diagnosis can be made clinically, but MRI or ultrasound can be used.

A subluxating extensor carpi ulnaris tendon is characterized by a painful snapping over the back of the ulnar side of the wrist, particularly on forearm rotation. It results from a tear or stretching of the retinaculum of the tunnel, allowing the tendon to slide back and forth, in and out of its normal position in the groove of the tunnel. This is usually caused by one single, sudden movement of the wrist, with the palm of the hand turning upward and sideward, such as when hitting a slice forehand, low volley, or topspin serves. If the injury is acute, treatment may consist of immobilization in a long cast for 6 weeks. If nonoperative treatment fails, or if the symptoms are chronic, surgery may be necessary to repair the retinaculum. If the tendon is also torn, repair is necessary to restore its function.

In the growing tennis player with wrist pain, the possibility of Kienbock's disease (osteomalacia of the lunate bone) should be considered. X-ray and MRI can support in confirming or excluding the diagnosis. Overuse of the growth plates of the radius or ulna (epiphysitis) might occur as well and is treated conservatively by adjusting the training load. X-ray may confirm the diagnosis.

46.3.1.4 Stress Fractures of the Upper Extremity

Stress fractures of the upper extremity in tennis players can be found in the metacarpals, ulna, and distal radius, along with the hook of the hamate (Maquirriain and Ghisi 2006). Additional imaging, consisting of MRI or CT can be helpful in confirming the diagnosis.

46.3.2 Trunk, Spine, and (Low) Back

The trunk muscles play a vital role in the body's kinetic chain. Every stroke involves important activity of the trunk muscles and the spine; a lack of adequate trunk rotation, flexion, and extension leads to decreased power and less control of strokes. The serve places large stress on the lumbar spine, and especially the large lateral flexion forces that coincide with sizeable vertical force and coupled extension/lateral flexion movements during the drive phase are a likely mechanism for low back pain in tennis players (Campbell et al. 2013).

Injuries of the trunk and spine are common problems in athletes, with a reported prevalence of up to 85 % (Kujala et al. 1996). Tennis players are no exception to this phenomenon (Sward et al. 1990), although tennis players are not at increased risk of back pain compared to non-tennis players. Nonspecific low back pain is most likely to be the cause. However, the possibility of spondylolysis or listhesis must not be overlooked.

In the great majority of patients with low back pain, no specific anatomical abnormalities that may explain the pain are found by additional imaging. This is called nonspecific low back pain, including lumbar strain. Additional imaging plays a minor role in these cases. If performed, they must be interpreted with great caution, as over 80 % of asymptomatic adolescent elite-level tennis players have some imaging abnormalities on MRI (Alvas et al. 2007).

46.3.2.1 Stress Fractures in the Trunk

The cumulative hyperextension stress of the lumbar spine during the service puts adolescent tennis players at a higher risk to develop a stress fracture of the arches of the vertebrae, a so-called spondylolysis. If the involved vertebra slips anteriorly in relation to the one below it, spondylolisthesis has occurred. This spondylolisthesis takes place in approximately one third of the athletes with spondylolysis. The risk of slippage is very small in individuals over 25 years of age. Plain radiographs are the first choice of imaging in patients with suspected spondylolysis; whenever this is negative or inconclusive, MRI or CT might be helpful. Spondylolisthesis can be diagnosed with plain lumbar X-rays.

In elite tennis players, stress fractures of the rib have been reported (Maquirriain and Ghisi 2006). MRI or CT can be used to confirm the diagnosis.

46.3.3 Lower Extremity Injuries

The game of tennis demands great speed and agility in order to move over the court in multiple directions and to return the opponent's ball. It is no surprise that because of these sudden accelerations, decelerations, pivoting maneuvers, jumps, and lunges, injuries to the lower extremity are very common. Acute injuries tend to predominate over chronic injuries, and the ankle (lateral ligament injury) and thigh (muscle strain) are the most frequent.

46.3.3.1 Thigh

Muscle strains are a common acute injury to the upper leg. The biarticular muscles (hamstrings, quadriceps) are particularly susceptible to muscle strains, especially at the musculotendinous junction. The adductor muscles may be involved as well, sometimes as a result of slipping when playing on grass or clay. Ultrasound and MRI are helpful in classifying the strain, ranging from grade 1 (microscopic tearing) to grade 3 (total rupture). Rest, ice, compression, and elevation (RICE) are the initial treatment. As the pain and swelling decrease, the rehabilitation process can start (gentle stretching, range of motion exercises, progressive muscle strengthening), guided by pain.

46.3.3.2 Knee

A large epidemiologic study investigating knee injuries in more than 17,000 tennis players over a 10-year period reported that 11 % of all knee injuries involve a ruptured anterior cruciate ligament (ACL) (Majewski et al. 2006). Lateral collateral ligament injuries and medial meniscus pathology were more frequent in tennis players, when compared to other sports. In most cases, the X-ray will be normal, except when there is a chip fracture associated with an ACL rupture, called the Segond fracture. MRI is useful to confirm or rule out the clinically suspected diagnosis and to identify associated pathology (e.g., articular cartilage damage).

The most common chronic knee injuries are patellar tendinopathy (jumper's knee) and patellofemoral pain syndrome. Patellar tendinopathy is an overuse injury with degeneration of the patellar tendon at the inferior pole of the patella. It is usually a persistent injury, impairing the player's on-court performance and subsequently leading to inability to train or play matches. Ultrasound and MRI can be used to evaluate this injury, demonstrating degenerative tendon changes. Decreasing the training load in combination with eccentric exercises is the cornerstone of treatment. Corticosteroid injections should be avoided.

In patellofemoral pain syndrome, the pain is diffusely localized around the patella and is aggravated by running, squatting, prolonged sitting, or climbing and descending stairs. The underlying pathophysiology remains unclear and additional imaging is in most cases normal and thus of no added value. The diagnosis is mainly based on clinical symptoms and by excluding other causes of anterior knee pain (e.g., Osgood-Schlatter disease, patellar tendinopathy, and osteoarthritis).

In the growing tennis player, Osgood-Schlatter disease and Sinding-Larsen-Johansson syndrome must not be overlooked as a possible cause of chronic anterior knee pain. They are both self-limiting overuse injuries of the growth plates on which the patellar tendon is attached. In Osgood-Schlatter disease, the distal insertion on the tibial tuberosity is painfully involved, and in Sinding-Larsen-Johansson, the proximal insertion on the inferior pole of the patella is affected. Additional imaging is generally unnecessary, as the diagnosis is made clinically. Activity modification is most important; reducing intensity and frequency of training is usually all that is necessary.

46.3.3.3 Calf/Ankle

A "tennis leg" is a muscle strain at the musculotendinous junction of the medial head of the gastrocnemius muscle and occurs most often when forcefully pushing off the foot (e.g., in sprinting or jumping). General treatment principles are the same as in other muscle strains. Physician's awareness is required in acute calf pain, as it is important that a rupture of the Achilles tendon is not overlooked, because of the treatment consequences. Operative reconstruction of a ruptured Achilles tendon may be advocated, whereas the muscle strain can be managed conservatively. Both ultrasound and MRI can be used in distinguishing these two different causes of acute calf pain in the tennis player.

Achilles tendinopathy shows some similarities with patellar tendinopathy and tennis elbow: it is an overuse injury, the underlying pathology is degenerative rather than inflammatory, and the cornerstone of treatment is activity modification in combination with eccentric exercises. The pain and swelling can be located in the midportion of the tendon or at the insertion on the calcaneus. The diagnosis is made clinically; the added value of imaging (ultrasound or MRI) is mainly to rule out a partial tear.

An ankle sprain, in which a sudden uncontrolled inversion of the ankle leads to stretching or tearing of the lateral ligaments, is the most common acute injury in tennis players. The medial ligaments are involved only in a minority of cases (5–10 %). Stopping abruptly, changing directions quickly, and landing on an unstable foot can cause ankle sprains. Previous ankle sprains increase the risk of future ankle sprains. Immediate lateral ankle pain occurs at the time of injury, combined with subsequent lateral swelling within minutes to hours. X-rays can be used to rule out or confirm a fracture, whenever this is suspected. The initial treatment consists of RICE, followed by range of motion exercises and strength and balance or proprioception training. For assessing concomitant pathology (chondral defects of the talar dome), MRI or CT can be performed when complaints persist after appropriate initial treatment. Repeated ankle sprains may lead to chronic instability, a frequent giving way sensation combined with recurrent ankle sprains. Taping or bracing should be considered, as well as functional rehabilitation. When instability remains despite appropriate treatment, surgical reconstruction may be considered.

46.3.3.4 Foot

Heel pain in the young tennis player is most often caused by an overuse injury of the calcaneal growth plate (Sever's disease). This is the area where the Achilles tendon attaches to the calcaneus; running and jumping put significant traction stress on the calcaneal insertion. The diagnosis is made clinically; additional imaging is seldom required. The prognosis is favorable, as Sever's disease is self-limiting, with 95 % of young players respond to conservative treatment measures (activity modification and reducing training intensity and frequency).

In plantar fasciitis or heel spur, the pain is located under the heel in the adult tennis player and is an overuse injury of the insertion of the plantar fascia on the calcaneus. Despite its name (plantar fasciitis), the underlying pathology is degenerative. Risk factors for developing this injury are being overweight and a flattened longitudinal arch. Plain X-rays sometimes reveal a heel spur, but this is of no clinical consequence. Asymptomatic players sometimes have a spur as well, whereas patients with plantar fasciitis may have a normal X-ray. As with the other degenerative tendon injuries, the diagnosis is made clinically. Additional imaging (ultrasound, MRI) might play a role in ruling out other pathologies and a partial rupture but is generally not required.

46.3.3.5 Stress Fractures of the Lower Extremity

Stress fractures in elite tennis players have been reported in the tarsal navicular bone, metatarsals, and tibia (Maquirriain and Ghisi 2006). In stress fractures, imaging can be useful to confirm the diagnosis; MRI or CT can be considered. X-rays tend to be negative in the early stages but may show callus or a hairline fracture after 2 weeks. Bone scintigraphy is only rarely used nowadays after the introduction of MRI, except when multiple lesions are suspected. Treatment generally consists of load reduction, and surgery is rarely required.

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Soccer Injuries

47

Robbart van Linschoten

Contents

Abstract

As one of the most popular contact sports played, soccer certainly leads to high injury profiles among competitive and professional players. While being a typical 'lower extremity sport', injuries to the groin, knee, thigh, ankle and foot are regularly seen in soccer. Because of its popularity and high injury rates, soccer has been studied structurally the last 20 years, and recommendations have been made to prevent muscle injuries and knee and ankle ligament injuries. Furthermore, the recognition of injury patterns and the increasing clinical and radiological knowledge has led to an increased care of the injured soccer player.

This chapter deals with the most common soccer injuries, from head to toe, and their clinical, diagnostical as well as treatment considerations and is supported by recent literature and expert opinion. As sports medicine and its supportive medical investigations progress, the interaction between clinicians and soccer players and their coaches is highly valued to deliver the best clinical care to the soccer player.

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Abbreviations

AC	Acromio-clavicular
ACL	Anterior cruciate ligament
ATFL	Anterior talo-fibular ligament
CFL	Calcaneo-fibular ligament
FAI	Femoro-acetabular impingement
FIFA	Federation Internationale de Football Association
LCL	Lateral collateral ligament
MCL	Medial collateral ligament
ORIF	Open reduction and internal fixation
PCL	Posterior cruciate ligament
PRP	Platelet-rich plasma
PTFL	Posterior talo-fibular ligament
ROM	Range of motion
UEFA	Union Européenne de Football Association
US	Ultrasound

47.1 Introduction

Soccer (football) is the most popular team sport played worldwide. Current data indicate that over 265 million people play official matches and are involved in soccer training (http://www.fifa.com/worldfootball/bigcount/index.html). It is thought that an equal number of people are engaged in non-registered soccer playing. The world governing organization of soccer is the Federation Internationale de Football Association (FIFA) which has its seat in Zurich.

Soccer is played by two teams consisting of 11 players including one goalkeeper. Official matches take two times 45 min with a half-time break of 15 min. The purpose of the game is to score one goal more than the opponent and so winning the game. The ball may touch any body part except for the arms and hands. The game is regulated by a referee, two linesmen and a fourth official. Foul play may be sanctioned by free kicks given to the opponent, including penalty shots. Bookings of foul play are made by the referee who may give players an official warning (yellow card) or send players off from the field by giving a red card.

47.2 Epidemiology of Soccer Injuries

Since the 1990s, there is a growing interest by various research organizations and universities on soccer research. From medical perspective, the incidence and at a later stage the prevention of soccer injuries have gained much attention. Treatment of soccer injuries has been described in detail in the literature both in case reports and case series. With the introduction of clinical research in the world of soccer, there is a trend towards better scientific approach to study designs, the introduction of randomized clinical trials as well as the introduction of more soccer-specific outcome criteria in research.

The major challenge in soccer research from the 1980s and 1990s arose from the definitions of 'injury', the 'injury severity' and 'classification of injury type'. Besides issues concerning rehabilitation, reinjury, return to play and exposure time had to be solved (Hägglund et al. 2005). New studies are encouraged to incorporate the recommendations made by the authors on this UEFA model.

Research on the epidemiology of soccer injuries focuses on three major groups: professional soccer players, youth soccer players and female soccer players. The injury patterns for these groups differ both for type of injury and for severity. It is however still difficult to draw major conclusions and compare different studies due to the difference in study design and reporting.

Studies indicate that in professional soccer the incidence of an injury may vary between 4 and 8 injuries per 1,000 h of exposure (Ekstrand et al. 2011; Dauty and Collon 2011). Across the studies, it can be concluded that the lower extremities are mostly affected during an injury; muscle strains, contusions, ankle sprains and knee sprains constitute the majority of soccer injuries. Furthermore, match playing will increase the injury risk significantly and may be six to seven times higher compared with training. It is of interest to note that hamstring muscle strains are more frequent than any other muscle strain injury (quadriceps, calf muscles and adductor muscles). They also carry the risk of reinjury which may lead to reinjury rates of 20–30 % in some studies.

47.3 Injuries

47.3.1 Injuries to Head and Face

Concussions constitute a small number of however potentially severe injuries. Much effort is nowadays given to the awareness of players and staff concerning concussions and the possible negative outcome of re-trauma to the brain. Various consensus meetings over the last years have come up with practical guidelines concerning return to play after a concussion and the practical approach to a concussion (McCrory et al. 2013).

In general a concussion is diagnosed by its clinical symptoms. Players should be instructed about symptoms and will have 'wake-up calls' during the first night. Based on clinical signs, additional investigations (CT scan/MRI scan, cfr Chap. 7, 8, 9 and 50) might be needed to rule out structural/anatomical injury to the brain and/or surrounding vessels.

Besides, leading to a concussion, direct trauma to the head may lead to skull trauma as well. Well-known skull traumas in soccer are the laceration of the eyebrow, the nasal fracture, the zygomatic arch fracture and the orbital fracture.

Eyebrow lacerations are easily managed on the field by various stitching or glueing techniques. FIFA regulations demand that players cannot continue the game with an open and/or bleeding wound. So proper wound management has to be performed by the medical staff on-field or off-field before the player can re-enter the game.

Nasal fractures demand the stopping of the epistaxis during the game and require medical follow-up after the match. Special concern is given to septal haematoma and malalignment of the nasal bone. In general 4 weeks of noncontact exercise is recommended though special face masks can be used during matches to prevent reinjury. The same considerations are applicable for zygomatic arch fractures or orbital fractures. These need proper radiological and surgical follow-up. In individual cases, a face mask may be applied which will give the player the opportunity for an earlier return to play.

47.3.2 Upper Extremity Injuries

Among soccer players, upper extremity injuries are significantly less common than lower extremity injuries. Furthermore, these injuries seem to lead to less time loss for practice and match playing. However, goalkeepers sustain more upper extremity injuries than field players.

47.3.2.1 Shoulder, Forearm, Wrist and Hand

Unlike in American football, Australian rule football or rugby, upper body tackling is not allowed in soccer. This is probably the main reason for the low numbers of shoulder and forearm/wrist injuries. Soccer is however a contact sport in which players may fall on the outstretched hand leading to traumatic shoulder dislocations, clavicle fractures, AC joint dislocations and various injuries to the hand or wrist. Primary shoulder dislocations are treated as soon as possible – if possible, relocation should be performed on the field or locker room with appropriate medical follow-up. Return to play will be based on clinical evolution and the effects of a rehabilitation programme but is not to be expected before 6 weeks after a first dislocation. Recurrent dislocations are managed on an episode-to-episode basis and may allow the player to return more quickly. Counselling for surgical shoulder stabilization is recommended which however can be delayed until the end of the season. The choice for an open or arthroscopic repair can be based on the player's demand and the surgeon's preference although many surgeons prefer an open procedure in contact sports due to the lower risk of recurrence. Clavicle fractures are mostly treated conservatively unless there is gross deformation. Also AC joint dislocations are primarily treated conservatively. Both conditions will in general lead to 6–8 weeks of absence in match playing although conditioning and noncontact drills can start after 1 week depending on pain. Distal radius fractures are not frequently seen in soccer. Treatment will be based on the type of fracture and according to international classification systems. Surgical treatment may be indicated. Players are generally allowed to an early return to play in protective cast. This may be feasible in 2–3 weeks. Since a solid cast may be harmful to the opponent, the medical staff should use soft cast material to protect the fracture and discuss the application of the cast with the referee to obtain allowance to play. Scaphoid fractures do not regularly show up in injury epidemiology and from personal observation are easily under-diagnosed in soccer. These fractures should however be included in the differential diagnosis of residual wrist pain after a direct trauma. High clinical suspicion must be raised when the pain is a result of a wrist trauma in goalkeepers. There is a common mechanism in which the ball is insufficiently blocked by the hand leading to a hyper-dorsal flexion motion of the wrist. Scaphoid fractures are known for poor visibility on a plain radiograph which underlines the need for CT scanning or MRI in these cases. Treatment is based on the fracture type and subsequent prognosis. There is nowadays a trend towards primary surgical treatment in soccer players which will speed up their recovery process and ability to play (Rizzo and Chin 2006).

Metacarpal and finger fractures are the result of direct trauma. A frequent mechanism for the metacarpal fracture is when the opponent's foot is on the player's hand when falling down. Finger fractures, finger dislocations or tendon ruptures occur mainly by falling with the finger in the grass or when the finger is caught in the opponent's jersey ('jersey finger'). Dislocations should be relocated when possible by the medical staff on or aside the field. Fractures and tendon injuries should be managed after additional examination (radiography, US) and may lead to absence to play from one to several weeks. Metacarpal fractures might be treated surgically depending on rotational deformity and axis deviation.

47.3.3 Injuries to the Groin, Abdomen and Spine

Although in soccer the ball can reach a speed of 100 km/h and players are frequently hit by the ball, major abdominal injuries seldom occur. Players may 'pass out' for several seconds when hit in the abdomen but are seldom substituted for medical reasons.

Also acute lower back injuries do not occur frequently. They may result from a poor landing or direct trauma to the lower back. These injuries usually recover quickly with relative rest and other strategies for pain relief.

Groin injuries however are an important injury component in modern soccer playing. The acute adductor strain and to a lesser extent the acute abdominal muscle strain are major contributors to muscle strain injuries (Ekstrand et al. 2011). Adductor strains occur as a result from sliding, passing, kicking and pivoting alone or in a combination of actions. Predominantly the adductor longus muscle is affected at its musculotendinous junction. Combined injuries do occur, especially the combination of adductor longus and rectus abdominis strains, which are seen more frequently when MRI imaging techniques are used. The injury then extends through the adductor aponeurosis at the symphysis up to the lower part of the rectus abdominis muscle. With proper imaging, also psoas muscle strains, gracilis strains and acute labral tears of the hip joint can be revealed. The clinical relevance of these injuries has to be studied in prospective series though in general a prognosis can be based on clinical and radiological grading systems. Rehabilitation of the muscle strains constitutes a major component of the recovery programme. Return to play may vary from 2 to 8 weeks based on the extent of the injury.

It is believed that minor adductor strains, incomplete rehabilitation and strength imbalances around the hip joint are risk factors for chronic groin injuries. In the end players may suffer for months from chronic exercise-related pain in the groin region. A current clinical-diagnostic approach to these injuries suggests to separate these injuries into 'adductor-related groin pain', 'abdominal wall-related groin pain', 'psoas muscle-related groin pain' and 'hip joint-related groin pain' (Hölmich 2007). Chronic groin injuries may require an extensive diagnostic workup including hip and pelvis radiographs, MRI scan, dynamic ultrasound of the abdominal wall, laparoscopic inspection of the abdominal wall and sometimes urological investigation. Treatment is based on the most likely diagnosis, and in most cases an extensive rehabilitation and muscle re-education programme is needed which may last 3–4 months. Weakness of the abdominal wall, interchangeably called 'sportsmen's hernia', may require surgical treatment. Abnormalities of the hip joint – especially femoro-acetabular impingement (FAI) – are a specific component of groin pain in soccer players (Keogh and Batt 2008). Whether this condition evolves during soccer playing or that some players are prone for this condition is currently not clear. Good outcomes have been reported for surgical interventions in which the mechanical impingement is addressed (Ryan 1969). As a note it needs to be addressed that radiological examinations in chronic groin pain may reveal multiple abnormalities (bone oedema in the pubic bone, sclerosis around the symphysis, calcifications at the adductor insertions, synovial fluid in the hip joint, micro-tearing of the adductor and rectus abdominis muscles) which may be regarded as the cause of the pain or as the functional outcome of chronic shearing and pulling forces around the symphysis.

47.3.4 Lower Extremity Injuries

47.3.4.1 Thigh

Hamstring muscle strains, quadriceps muscle strains and upper leg muscle contusions make almost half of all soccer injuries (Ekstrand et al. 2011). Hamstring muscle strains themselves are the most common muscle strains in soccer. Research into the injury mechanism shows that during running the hamstring muscles are eccentrically contracted just before landing. They act as a counter-agonist of the quadriceps muscles which are the major propellers in sprinting. The hamstring muscle is then elongated and contracts at the final stage of the sway phase of the leg. Atypically, soccer players may also suffer a hamstring strain by a backward pass when kicking the ball with heel. The biceps muscle – long head – is in about 80 % of the injuries involved. Strains are clinically graded from 1 to 3 in which a grade 3 strain leads to full disruption of the muscle and a grade 1 leads to elongation of muscle only (Peetrons 2002). Grade 2 strains are partial muscle tears. For ultrasound and MRI techniques, similar grading systems are used (Frobell et al. 2010). In clinical practice, grading of the strain is important while it is thought to be closely related to prognosis. There are however only a limited number of studies available on this subject. Hamstring strains are treated conservatively with rest, physical treatment and muscle re-education. Single cases with full muscle–tendon ruptures or bone–tendon avulsions might be considered surgically.

Quadriceps strains do usually involve the rectus femoris muscle at the musculotendinous junction or at the deep part (indirect head) of the rectus femoris. The mechanism of injury in soccer is classical: the player shoots the ball and is aware of a sudden pain in the upper thigh. Straining of the quadriceps muscle in a sprinting action – like in athletics – is a less common mechanism in soccer. Ultrasound scanning or MRI will confirm the diagnosis. From a clinical point of view, the deep part of the rectus femoris muscle strain can be easily overlooked since on palpation no muscle defect exists. Moreover, this strain seems to recover quickly, while in a later stage a painful mass in the rectus femoris may appear. Rehabilitation of the quadriceps strains takes 3–12 weeks depending on the grade of the injury and the clinical evolution.

47.3.4.2 Knee

Acute knee injuries in soccer may arise from various injury mechanisms; the most common mechanism is the valgus–external rotation movement in which the medial collateral ligament, the anterior cruciate ligament and the lateral menisco-capsular structures are being stressed. Around 70 % of the ACL injuries occur without player-to-player contact. ACL injuries usually have a typical appearance: during the injury mechanism, the player feels or hears a popping sound at the knee with sudden onset of pain. Most ACL ruptures lead to swelling of the knee in several hours. Physical examination can be difficult during the acute stage due to painful spasm at the knee. The Lachman test has proven to be the most accurate physical test for an ACL rupture. MRI scan is usually performed to document the ACL tear and to assess combined trauma to the meniscus, cartilage and other ligaments. Nowadays in high-level soccer players, ACL reconstruction is advised after 3–6 weeks after the incident. However, a recent study questions the urgency for ACL repair since in this study a reasonable amount of players had good clinical outcome with rehabilitation alone. Late reconstruction of the ACL was feasible as well from a practical point of view (Frobell et al. 2010). After ACL surgery a rehabilitation period of minimal 6 months is mandatory. Re-ruptures of the graft however do occur and can put the player's career at risk.

Low grade ruptures (grade 1) and moderate ruptures (grade 2) of the medial collateral ligament (MCL) are common in soccer. They occur due to a genuine valgus trauma to the knee like in blocking the ball and tackling or sliding sideward. They do not require surgical treatment and are best treated with progressive mobilization after a short period of a hinged brace. Most of these sprains recover within 4–6 weeks. Some players may experience residual pain that can last for many weeks at the insertion of the MCL on shooting and blocking. In such cases a local infiltration of a low dose of corticosteroids is likely to beneficial.

Ruptures of the posterior cruciate ligament (PCL) are a minority in soccer and can be overlooked clinically. They are best assessed using MRI techniques. Minor

PCL sprains recover within 4–6 weeks. Surgery is seldom indicated. An isolated injury to the lateral collateral ligament of the knee is rarely seen in soccer. When a varus trauma to the knee leads to the clinical suspicion of an LCL rupture, an extensive documentation of the knee stability is warranted. Combined ACL and LCL rupture and rupture of the posterolateral corner of the knee is an indication for acute surgery. An MRI scan can depict the involved structures.

Meniscal tears are still common in soccer although in literature they appear to be overpowered by ACL ruptures. Especially in younger players, isolated meniscal ruptures do occur, and if possible repair of the meniscus should be advocated. Rehabilitation will take in general 6 months, and counselling of the young soccer player and parents is crucial to underline the importance of saving the meniscus. Many older players suffer from degenerative meniscal injuries and are best treated conservatively. Full meniscal tears leading to a mechanical conflict in the knee joint are a surgical indication however.

Overload injuries to the knee constitute around 25 % of loss of playing time in soccer. They are related to high amount of training and match playing and are usually seen during pre-competition conditioning and at the end of the season. Patellar tendinopathy and quadriceps tendinopathy are the most common overuse injuries at the knee. Ultrasound and MRI techniques can depict the injuries. The treatment approach however is based on the clinical symptoms (pain) rather than the severity on US or MRI scan. Off-loading, eccentric training and stretching techniques are the mainstay in the strategy. Before opting in surgery, alterative treatment through PRP of polidocanol injections might be considered although there is lack of scientific proof for their efficacy.

47.3.5 Lower Leg, Ankle and Foot

In order to prevent lower leg fractures, it is mandatory for soccer players to wear shin guards during matches. Tibia fractures are less common in soccer as 30 years ago. Nowadays most tibia fractures are treated by open reduction and internal fixation (ORIF). Recovery time from a tibia fractures usually takes 6–8 months. Due to the various movement patterns in soccer, the incidence of stress fractures of the lower leg is low. An occasional antero-medial stress fracture of the tibia can be found as well as a stress fracture of the medial ankle. These stress fractures are easily overlooked on a day-to-day basis in soccer but require medical attention and additional radiological follow-up with MRI scan and CT scan. Anterior tibia stress fractures have a tendency for poor union and can lead to acute fracturing during sprinting or jumping. Individual cases should be followed carefully, and early intramedullary fixation should be discussed with the player.

Injuries to the ankle are a strong contributor to the overall amount of soccer injuries. Lateral ankle sprains, syndesmosis sprains and medial ankle sprains are common in soccer. Several injury mechanisms are reported: inversion trauma to ankle leads to lateral ankle complex injury including distal fibula fracture. Eversion combined with plantar flexion (kick in the ground) may lead to a trauma of the anterior tibia-fibular ligament (anterior syndesmosis). Pure eversion trauma (blocked ball) can lead to a (partial) rupture of the deltoid ligament of the ankle. Initial assessment of the acute ankle trauma may puzzle even the most experienced clinician. Most ankle traumas lead to swelling, pain and restricted ROM for which a clinical diagnosis is not that accurate. X-rays should exclude significant fractures to the ankle joint and distal fibula and tibia. Young players may suffer from epiphyseal fractures and need careful follow-up. Lateral complex ruptures are graded into three stages based on tested instability and ruptured ligaments (anterior talo-fibular ligament (ATFL), calcaneo-fibular ligament (CFL) and posterior talo-fibular ligament (PTFL)). Combined lateral injuries with syndesmosis injury may alter the treatment and prognosis. In general grade 1 and 2 lateral complex injuries will lead to 2–6 weeks absence of playing. Secondary prevention of ankle sprains is important and supported by scientific evidence (Verhagen and Bay 2010). Proprioception training and muscle strength straining is the mainstay during physical rehabilitation. High grade 3 and combined syndesmosis ruptures may require surgery to obtain anatomical repositioning. Injuries to the medial complex are known for longer recovery time but do in fact well on conservative treatment.

Muscle strains at the lower leg mainly involve the calf muscles – both the gastrocnemius and the soleus muscle can be involved. The majority of the calf muscles strains are seen at the junction of the distal soleus/gastrocnemius at the medial side. Isolated gastrocnemius and soleus strains also do occur at various levels of the muscle. Older – recreational – players are at risk for grade 3 gastrocnemius muscle tears which will take 8–12 weeks before return to play can be considered. Lower grade calf muscle strains recover in 4–6 weeks on rehabilitation. In daily practice, recurrence of calf muscle strains is seen and also chronic non-healing cases are common. This is however not clearly supported by the literature.

Achilles tendon ruptures do occur in soccer and are seen mainly in players around the age of 30 or in recreational players above the age of 40. Achilles tendon ruptures usually require surgical treatment in soccer players. Return to play after an Achilles tendon rupture is not to be expected before six months.

Chronic Achilles tendinopathy is not very common in the young and professional soccer age group. However, these tendinopathies may pose a serious risk on the player's ability to train and play. Like in the patellar tendinopathy, treatment is based on partial off-loading, eccentric training and local modalities. Ultrasound and MRI scan are helpful in understanding and staging the pathology but do not dictate the treatment strategy.

Fractures at the subtalar joint may result from an ankle distortion or direct trauma to the foot. Plain X-rays do not always reveal the extent or the location of the fracture, whereas CT scan is very useful to give proper insight. Contusions of the foot are very common and may resolve slowly due to bone oedema and residual synovitis of the subtalar joints. An MRI scan can reveal the extent of the bony oedema, but sometimes an additional CT scan is needed to rule out discrete fractures.

Fractures of the metatarsal bones usually occur at the fifth metatarsal as a result of an acute inversion-related avulsion trauma or may present as stress fractures. Stress fractures and Jones fractures have a tendency for slow healing. Current treatment in soccer indicates that most surgeons advocate screw fixation of the fracture to avoid malunion or nonunion and to support earlier return to play (Polzer et al. 2012).

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Retracted Chapter: The Expert View on Bicycling Injuries

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Contents

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48.1 Introduction

Bicycle riding is a popular form of recreation among persons of all ages, and related injuries cause significant morbidity and mortality. Cycling injuries can be classified into bicycle traumatic, contact, and overuse injuries. Few studies, all retrospective, have been conducted on professional cyclists. Incidence of traumatic injuries range from 38 to 48.5 %, and overuse injuries occur in 51.5–62 % of top-level professionals. More than two-thirds of traumatic injuries occur in the upper extremity, and two-thirds of overuse injuries occur in the lower extremity (De Bernardo et al. 2012). There are no known studies grouping bicycle contact injury separately from overuse injuries. Muscle tears, common in runners from eccentric load, are rare in cyclists with high quadriceps concentric load. Cyclists are exposed to high traumatic risk racing in a peloton, at high speeds, on various road and weather conditions. In a 4-year study of 51 top-level professionals, 43 cyclists experienced 103 injuries, with 50 (48.5 %) traumatic injuries and 53 (51.5 %) overuse injuries (De Bernardo et al. 2012). Only eight cyclists (15.6 %) were injury-free. Twenty-two (43 %) athletes experienced both overuse and traumatic injuries, while 13 (25.5 %) experienced only traumatic lesions and 10 (19.5 %) only overuse injuries. Twenty-nine cyclists (67.4 %) experienced more than one injury. Twenty-eight fractures occurred, with the clavicle having the most common fracture (11 cases). The majority (68.5 %) of overuse injuries was located in the lower limbs, most occurring during preseason. Severe injuries requiring more than 1 month off occurred in four cases, and all of them are trauma (8 % of traumatic injuries) requiring surgery.

48.2 Traumatic Injuries

Baker (2003) reported on traumatic injuries on 85 cyclists in a racing Masters club. Seventy-nine percent were seen emergently for trauma, 33 % were admitted to the hospital, and 15 % were admitted to an intensive care unit. Fifty-four percent sustained fractures and 45 % a head injury, 34 % reported a concussion, and 9 % sustained multiple concussions. Ninety percent experienced road rash. Sixty-nine percent of injuries occurred riding alone and 31 % occurred riding in groups. Thirty-seven percent of solo road injuries were from crashes with motor vehicles, 9 % from potholes, rocks, or dogs, 12 % from operator errors (cornering too fast or adjusting parts while riding), and 10 % by mechanical reasons (broken fork or flat tire). Of the injuries during group riding, 17 % occurred riding in a pace line, most trying to avoid crashing into other crashed riders, with 12 % in races, mostly criteriums. Statistics on deaths from motor vehicle collisions specifically in athletes do not exist.

There is less risk bicycling on good road surfaces, with streetlights, and on multiuse paths versus sidewalks. About 50 % of traumatic cycling injuries result in fractures (De Bernardo et al. 2012). The most common is the clavicle followed by the wrist, ribs, and elbow. Lower extremity fractures are rarer and often involve the pelvis, hip, or femur. Femur fractures are displaced usually, requiring surgery, while pelvis fractures are nondisplaced often, non-life-threatening, and detected often with computed tomography (CT) or MRI after negative x-rays. Off-road cyclists in events appear to sustain more fractures, dislocations, and concussions than road cyclists in events (Pfeiffer and Kronisch 1995).

48.2.1 Clavicle Fractures/Shoulder Injuries

It is joked commonly, "If you race long enough, you will eventually break your collarbone." Clavicle fractures are caused by a direct blow to the shoulder from falls, often going over the front end. They are associated often with concussions and rib fractures. Cyclists with clavicle fractures treated nonoperatively usually can ride a stationary trainer within 1 week, ride outdoors within 2–3 weeks, and race in 4–6 weeks. Most clavicle fractures are treated nonoperatively, except when communition, shortening, or severe displacement is present. Initial shortening of displaced middle third fractures greater than or equal to 20 mm was found to have a highly significant association with nonunion and unsatisfactory result (difficulty lifting heavy objects, pain, paresthesia, or cosmetic complaint) with closed treatment (Hill et al. 1997). Displacement of more than one bone width on initial x-ray (0° and 45° tilted view) in another study was found to be the strongest radiographic risk factor for persistent symptoms at 6 months with nonoperative treatment (Nowak et al. 2005). Late repairs of painful nonunion or malunion displaced midshaft fractures also have been found to have similar results to immediate fixation (Potter et al. 2007). Fractures treated operatively may allow a cyclist to return to training sooner. If there is suspicion of sternoclavicular (SC) joint injury, obtain a CT. Posterior dislocations should be reduced operatively. Delayed erosion into vessels and stroke has occurred in chronic SC posterior dislocations. AC separations are equally common, and all but the most severe grade 3 separations are treated nonoperatively. Brief use of sling may be used with return to stationary workouts almost immediately and road riding in 1–2 weeks.

48.2.2 Radial Head Fractures

Radial head fractures are common from falls on an outstretched hand. Aspiration of hemarthrosis with infiltration of anesthesia helps with pain relief and evaluation for mechanical block. Early range of motion exercises should be encouraged to achieve full extension. Most athletes with nondisplaced fractures can return usually to riding in 1–2 weeks.

48.2.3 Rib Fractures

Rib fractures are common from falls. Single or multiple rib fractures can cause a pneumothorax or an intra-abdominal trauma. Evaluation by chest x-ray and CT scan to evaluate damage can be very useful. Return to racing may take 6–8 weeks (in case of no complications).

48.2.4 Concussions

Concussions in cycling historically have been managed differently from other contact/collision sports like boxing and rugby. In stage races like the Tour de France, a rider must finish the stage within a percentage of the stage winner's time to continue racing. There are no time-outs or substitutions, and the peloton waits for no one. A rider who crashes has to get back on his bike and "chase back on" drafting off team cars. On stage 1 of the 1996 Tour, Luc Leblanc crashed and lay on the side of the road motionless. He was put back on his bike when he regained consciousness. He went on to win stage 7. A stage win in the Tour de France is a career-defining win for a cyclist, bigger than an Olympic medal. It is common to this day to put a rider back in a race after a closed head injury as long as the rider is willing and able to ride. There is no Sideline Concussion Assessment Tool in cycling. Assessment on the side of the road is done rapidly as the race goes on, often by a mechanic or team director. If a rider can get up and mount his bike, he soldiers on. Slower reaction times and impaired speed of processing information are seen commonly in concussed athletes, and return of a cyclist who might be experiencing a concussion may place the athlete and the peloton at risk from further accidents. Helmets were made mandatory in professional cycling in 2003 after the death of professional road cyclist Andrei Kivilev, who sustained a skull fracture from a crash in Paris-Nice. Helmets have been shown to prevent skull fractures and intracranial hemorrhage (Bergenstal et al. 2012). There is no scientific evidence that they reduce the incidence of concussions. Bicycle helmets are designed to protect the head by reducing the rate at which the skull and brain are decelerated by an impact. The expanded polystyrene liner upon impact is designed to compress, dissipating the energy over a rapidly increasing area like a cone. After a blow to the head, a helmet should be discarded whether or not it appears broken. Concussions in cycling should be handled as in other sports with recommendations from the Fourth International Consensus Conference on Concussion in Sport held in Zurich in 2012 (McCrory et al. 2013). Any cyclist who is suspected of sustaining a concussion should be evaluated on-site, and if no health care provider is available, the athlete should be removed from the sport, with urgent referral to a physician trained and experienced in management of concussions. Any cyclist diagnosed with a concussion should not be allowed to return to play on the day of the injury. The cornerstone of concussion symptom management is complete physical and cognitive rest until the acute symptoms resolve, although, to date, there is no published scientific evidence evaluating the effect or duration of rest. Once asymptomatic, a stepwise graded return to play may be initiated, beginning with easy rides on a stationary trainer. Management and return to play should be guided ultimately by clinical judgment on an individual case basis.

48.2.5 Abrasions

The wound should be thoroughly cleaned and scrubbed soon after the injury has occurred.

Road rash is the most common crash injury and should be treated with thorough cleaning and scrubbing. Embedded dirt particles and stones can serve as a nidus for infection and thus must be removed. Topical anesthetic should be used. Wounds should not be left uncovered; large scabs inhibit wound healing and inhibit range of motion required to pedal or hold the bars. Open wounds will stick painfully to bedding at night. Wounds can be covered with semipermeable films, hydrocolloid dressings, or occlusive bandages. Alternatively wounds may be covered with nonadherent dressings and antibiotic ointment with daily dressing changes and cleansing of exudates until pink healthy granulation tissue forms. Dressings are padded with gauze, wrapped in stretch gauze, and then covered in tube stretch gauze.

48.2.6 Contusions

Contusions are equally common as road rash. The most common site is the quadriceps, from contact with pavement or collision with cars. Immediate placement of the knee in 120° of flexion for 24 h may allow an athlete to return to sports sooner (Aronen et al. 2006). Scientific studies on the use of ice or nonsteroidal anti-inflammatory drugs in contusions are lacking. Localized hematomas or seromas, common from cycling contusions, can be visualized easily by ultrasound and are treated most effectively with aspiration and may require repeat treatments. Prepatellar and olecranon bursitis may be caused by direct blow from a crash or from repetition. If from a crash with road rash, have a high index of suspicion of infection. Most cyclists with bursitis can continue to train at modified intensity. Cortisone is for recalcitrant cases.

48.2.7 Intra-abdominal Cavity Contusions

Intra-abdominal traumas occur more often in children performing BMX stunts and in mountain biking. The cause is often blunt trauma from horizontal bar ends. In a retrospective review of children involved in cycling crashes admitted to a tertiary center over 5 years, 31 out of 196 (16 %) sustained abdominal injuries with 19 major visceral injuries, seven requiring surgery. Over the same period, no child with head trauma required surgery (Muthucumaru et al. 2012).

48.2.7.1 Spleen Rupture

Niels Albert, 2009 and 2012 cyclocross world champion, fractured his rib in 2008 after a solo crash on a descent, which punctured his lung and ruptured his spleen. Most intra-abdominal contusions are treated with serial observation and diagnostic imaging (Clarnette and Beasley 1997).

48.3 Bicycle Contact Injuries

Cyclists contact their bicycles at three areas: the pedals, the seat, and the handlebars. Each contact point is associated with particular cycling ailments.

48.3.1 Shoe Pedal Interface

48.3.1.1 Plantar Neuropathy

Burning feet, "hot foot," numbness, or pain is a common complaint as a result of compression of interdigital plantar nerves from a fixed cleat/pedal interface and narrow rigid cycling shoe. Diagnosis of Morton's neuroma, a perineural fibroma commonly occurring between the third and fourth metatarsals, should be made only when seen on ultrasound or magnetic resonance imaging (MRI). On ultrasound, it appears as a noncompressible hypoechoic mass greater than 5 mm.

Symptoms may be relieved with cleat adjustment (usually with the cleat positioned further back), by wearing a shoe with a wider toe box, by loosening the straps on the shoes, or by using a wider pedal. An insole with a metatarsal pad and manual therapy may be tried. For recalcitrant cases, cortisone injection or sclerosing injections may be considered.

Neurectomy, via plantar or dorsal approach, is the mainstay of surgical intervention. However limited evidence was found with which to assess the effectiveness of surgical and nonsurgical interventions for Morton's neuroma (Thomsom et al. 2004).

48.3.2 Saddle Interface

48.3.2.1 Saddle Sore

The second area of contact the cyclist has with the bicycle is the seat or saddle. Most riders experience some degree of saddle soreness. This is especially true for recreational riders at the start of the season and for tourists early in a long-distance trip.

The combination of moisture, friction, and pressure leads to skin disorders in the perineal region. Soreness is the most common problem, relieved with brief time off and an emollient cream. Cycling in wet clothing, such as in triathlons or the rain, is a frequent cause of chafing. Ulceration from severe friction requires wound treatment. Saddle sores, ranging from furuncles and folliculitis, may limit riding for a prolonged period. They often require incision and drainage. Perineal nodular induration (PNI) or "biker's nodule" is a fibroblastic pseudotumor that presents not only exclusively in male cyclists' "third testicle" (accessory testicle) but also in female population of cyclists. It develops in the soft tissues of the perineum immediately posterior to the scrotum or in the labial area in women, as a bilateral or single, central or lateralized mass (Gonzalez-Perez et al. 2009). Surgical excision is often required. As a means of prevention, time off the bike, warm soaks, cortisone, or antifungal or antibacterial ointment may be considered.

Prevention involves riding on a dry, clean chamois and changing clothing immediately after cycling.

48.3.2.2 Perineal Vasculopathy/Neuropathy

A significant percentage of body weight may be positioned on the bicycle saddle during seated bicycling depending on variables such as a rider's position on the bike and rider effort.

Regardless of the saddle design, it is the racing position of a cyclist, in an effort to get good aerodynamics by lowering the torso toward a horizontal flat back position and tilting the pelvis anteriorly that transfers pressure from the ischial tuberosities to the perineum, where vascular and neural structures reside. Transcutaneous penile oxygen pressure (tPO_2) monitoring, believed to correlate with penile blood flow, has been found to be a reliable method for measuring penile oxygen levels during cycling (Cohen and Gross 2005). A significant decrease in penile oxygen perfusion occurs during seated bicycling, with measurement as high as an 82 % drop in tPO_2 (Schwarzer et al. 2002). The implications of decreased tPO_2 over different time intervals when bicycling is unknown and needs to be further researched.

Hypoxemia in the corpus cavernosum is associated with penile fibrosis, which is known to lead to erectile dysfunction (ED). ED rates have been reported to occur as high as 24 % in amateurs with weekly mileage greater than 400 km (Sommer et al. 2001). Ischemic neuropathy may result also from compression of the neurovasculature in the perineum and in Alcock's canal. Rates of genital numbness have been reported as low as 10 % in amateurs on an 8-d ride of 500 miles to as high as 91 % in a small study of 17 cycling policemen (Schrader et al. 2002). "Cyclist's syndrome" is a specific form of pudendal nerve entrapment related to prolonged bicycling resulting in pain, burning, and numbness, sometimes accompanied by sexual dysfunction, impotence, or urinary incontinence. The pathogenesis of pudendal neuropathy is unknown. Compression, friction, and stretching of nerves are implicated. A rider's position, bike fit, and riding technique play the greatest roles in prevention and treatment of perineal compression.

Risk of compression is greatest during time trialing, in indoor riding on rollers or a trainer without frequent standing, in heavier cyclists, and in mountain biking. Preventive measures such as changing riding style, alternating standing, and sitting often are recommended. Riding on a recumbent bike causes no decrease in penile perfusion, as does standing while cycling. Three minutes of standing are required to produce stable increases in penile oxygen levels after seated compression. An excessively high saddle, narrow saddle, excessive saddle tilted up, or handlebars excessively forward or low can all increase compression. Ergonomic wider saddles, with a split saddle, chopped nose, or central cut out, have all been designed to decrease compression. Cohen and Gross (2005) studied tPO_2 in three racing saddle designs (a "standard" narrow saddle, a padded saddle with an elliptical hole in the center and a cutout seam in the nose, and a saddle with a split V in the rear and a central depression from the back to the tip of the nose) and found none of the saddles spared a drop in penile tPO_2 (decreases of 76, 73, and 62 %, respectively). Dettori et al. (2004) actually found an increased risk of ED with a cutout saddle among those who experienced numbness versus those who did not experience numbness, possibly due to compression on the cutout edge or decreased surface area. Time off the bike is warranted for prolonged compressive symptoms as irreversible neuropathy can occur (Leibovitch and Mor 2005). Physical therapy, manual therapy, and injection therapy are treatment options for relief of pain from neuralgia. The symptoms for most cyclists are transient, but the implications are unknown.

Prevention involves proper saddle height and tilt, handlebar reach and height, and saddle type and width. The general rule for a recreational or touring saddle is that it should be 2.5–5.0 cm wider than the interischial distance. This distance is greater in the female pelvis, and many bicycle-seat manufacturers offer saddles designed to accommodate the wider female pelvis. Another anatomical difference between the male and female pelvis is the steepness of the pubic arch in relation to the anterior saddle cant. In the male pelvis, the steeper arch of the pubic symphysis allows some clearance above the nose of the saddle. The shallower arch in the female means that the soft tissue of the perineum presses against the nose of the saddle. Many women attempt to correct this by riding in a more upright posture to take the weight off this area. While the seat should usually be level, some men prefer a slight upward tilt. However, too acute an angle can cause pressure on the n. pudendus, resulting in transient numbness of the penis, scrotum, or both.

48.3.3 Hands-Handlebar Interface

The third area of contact between the cyclist and the bike is the handlebars. Cyclist's palsy, or ulnar neuropathy, is a familiar affliction of the long-distance cyclist.

Stiefler, in 1927, was the first to report on bicycling causing prolonged compression of the ulnar nerve ("cyclists palsy"), and it is less common in the median nerve (Hankey and Gubbay 1988; Maimaris and Zadeh 1990). Thirty-two of 89 (36 %) cyclists on a tour of 80 d and 4,500 miles experienced hand numbness, 10 (11 %) in the median nerve distribution, with 1 unable to adduct his thumb, 1 unable to adduct his little finger, and 1 unable to abduct his little finger (Fairclough et al 2006).

Mononeuropathy of the deep palmar branch of the ulnar nerve in Guyon's canal may cause clawing. With a type I lesion, mixed sensory and motor, compression is proximal (outside of Guyon's canal) and clawing usually is not seen. Isolated lesions of the deep terminal motor branch, with distal sensory branches intact, result in the athlete unaware of any compression until the motor lesion develops. Increased compression occurs with prolonged riding without change in hand position, stationary biking, downhill cycling, rough terrain, handlebars too low or forward, poor padding in gloves or bars, or improper suspension or "death grip" (an overly tight grip on the handlebars caused by fear) in mountain biking. Most cases result in a transient neuropraxia, with full recovery with modification or cessation of activity. However rarely permanent damage may occur. Treatments for the cyclist include the following: reduction in training, changing hand position often, increasing padding in the bars or gloves, shortening the reach or raising the handlebars, or using aerobars.

48.4 Overuse Injuries

Overuse injuries are common in cycling but rarely require prolonged time off the bike. In a study of 108 professionals in 1 season, 58.3 % experienced an overuse injury (Clarsen et al. 2010). In a study of 51 professionals over 4 seasons, 62.7 %

reported an overuse injury (De Bernardo et al. 2012). In a study of 518 amateur cyclists, 85 % experienced an overuse injury (Wilber et al. 1995). Among overuse injuries in professionals, 64 % required less than 7 days off from competition, 32 % required 7–28 days off, and 4 % required more than 28 days off (1 case of osteitis pubis and 1 case of iliac artery endofibrosis) (Barrios et al. 1997).

48.4.1 Knee

The knee is the most common overuse injury site in the cyclist. Knee injuries account for 62 % of all overuse injuries in professionals (Barrios et al. 1997). Based on the location of pain, bicycle adjustments may be made (Asplund and St Pierre 2004). Ultrasound may help localize extra-articular pathology.

48.4.2 Lateral Knee Pain

Iliotibial band syndrome (ITBS) is the most common cause of lateral knee pain in cyclists. Historically regarded as a friction syndrome from a snapping iliotibial band (ITB) over the lateral femoral condyle. Kulund and Brubaker (1978) argue that ITBS is not from snapping but from compression of fat beneath the ITB. In cadavers, the ITB was found anchored to the femur by fibrous strands, associated with innervated and vascularized fat containing Pacinian corpuscles, suggesting that ITBS is more of an enthesopathy. Some report found no bursal sacs (Fairclough et al. 2006). Others have treated ITBS with bursectomy (Hariri et al. 2009). Some have removed surgically cyst-like structures, which are possible extensions of the lateral synovial capsule (Costa et al. 2004). Holmes et al. (1993) reported fibrosis and chronic inflammatory changes on microscopic examination of excised ITB, while others question if any pathological change takes place in the ITB (Fairclough et al. 2006). The syndrome is likely a spectrum of different entities. The causes of ITBS are rapid increase in intensity and mileage, pushing big gears, hills, windy conditions, time trialing, and positional causes such as toes pointing inward, excessive pedal float, or worn cleats. Weak hip abductors may be less of an issue in cyclists than in runners with ITBS since cyclists are seated in the saddle most of the time. Bike fit treatments involve adjusting cleats, checking bike fit, and leg length evaluation with shims as needed. Physical therapy, stretching, foam rolling, and massage therapy are treatment options. Professional cycling teams employ soigneurs for daily massage therapy. Manipulation of the pelvis should be performed for somatic dysfunctions, which commonly occur from crashes and are overlooked often. Cortisone injection may be considered. Under ultrasound guidance, injections may be directed at the tendon sheath, if tenosynovitis is present, or between the ITB and femoral condyle, if anechoic or hypoechoic echotexture is noted against the femoral condyle. Many cyclists with ITBS can recover while continuing to ride at a lesser intensity and duration. Surgery for recalcitrant cases has ranged from removal of an elliptical piece of the distal posterior band to the "mesh technique" to surgical lengthening or Z-plasty.

Biceps femoris tendinopathy presents with pain more posterior lateral than ITBS. Biceps femoris tendinopathy occurred equally as patella tendinopathy in professionals (De Bernardo et al. 2012). Massage therapy, eccentric strengthening, dynamic stretching, and a short time off the bike for severe cases are all treatment options.

48.4.3 Anterior Knee Pain

Anterior knee pain is the most common reason cyclists seek medical care. Anterior knee pain should not be put into one diagnosis of patellofemoral pain syndrome (PFPS) or chondromalacia. Patella tendon pain may occur at the entheses of the tibia tubercle, midportion, or inferior pole of the patella and may be a strain, tear, or tendonosis (Rees et al. 2013). Pain can become chronic or recurrent. Common causes in cyclists are similar to ITBS and include pushing big gears, hills, windy conditions, rapidly increasing mileage or intensity, or a bicycle setup with a saddle too low or forward or with cranks too long. Time off the bike or limiting intensity and duration may be needed. Physical therapy, manual therapy, and massage are treatment options. Eccentric strength training on a 25° decline board is a popular home exercise program that may have a positive effect for patella tendinopathy (Visnes and Bahr 2007). Sclerosing neovessels outside the tendon for painful chronic tendinopathy is a novel treatment that may challenge the need for surgery (Alfredson and Ohberg 2005). Percutaneous tenotomy, platelet-rich plasma therapy, and stem cell injection therapies are other nonsurgical treatments warranting more scientific research.

PFPS is a diagnosis of exclusion. An effusion indicates intra-articular pathology and warrants an MRI or aspiration for fluid analysis. PFPS may be caused by a saddle too low or forward or from cranks too long. Cycling causes and treatments are similar to the patella tendon. A diagnosis of chondromalacia patella should be made only after arthroscopy, although it is not treated easily surgically. Barrios et al. (1997) found chondromalacia in 10 out of 10 cyclists who underwent arthroscopy for recurrent pain.

Anterior knee pain may also result from friction of the quadriceps tendon on the top end of the patella. Common causes include a bicycle setup with a saddle too low or forward, cold conditions, and a history of trauma of the knee (fall or a simple hit by the handlebars). Time off the bike and starting up training at limited intensity and duration may be needed. Cortisone injection may be considered. Surgery for recalcitrant cases may be needed.

48.4.4 Medial Knee Pain

The most common causes of medial knee pain in the cyclist are MCL bursitis, medial plica syndrome, pes anserine syndrome, and less commonly medial meniscus tear. Excessive float or no float in a pedal may contribute to medial knee pain.

Bike fit evaluation, modification of training, physical and manual therapy, or injections are treatment options.

Medial meniscus tears while not caused by pedaling can become symptomatic from twisting out of a pedal. Symptomatic meniscal tears may be treated with modification of activity, pedal tension adjustment, watchful waiting, injections, and even continued cycling prior to entertaining a meniscectomy. Caution should be noted if a cyclist has a tear on MRI; one should not assume it is the cause of pain. Medial plica syndrome presents with pain and a snapping or clicking sensation anterior medial over the femoral condyle. A symptomatic thickened plica may be palpated over the medial condyle while the patient flexes and extends the knee. Diagnosis of a symptomatic plica is made by exclusion, and presence of a plica does not imply pathology. A plica may be seen on MRI, although a negative MRI does not rule out a symptomatic plica either. Treatments include cortisone injection, physical therapy, and modification of training prior to surgery. Rapid return to cycling after surgical excision is usual.

48.4.5 Proximal ITBS or Greater Trochanteric Pain Syndrome

Proximal ITBS, lateral "hip" pain and tenderness over the greater trochanter, is not as common in cyclists as ITBS at the knee. The athlete is misdiagnosed often with trochanteric bursitis. With ultrasound and MRI, we now know that bursitis is rarely present (Ho and Howard 2012). Pathological specimens from patients diagnosed with bursitis contained mostly fibroadipose tissue (Silva et al. 2008). In an MRI study on women with "trochanteric bursitis," 45.8 % had a gluteus medius tear, 62.5 % had gluteus medius tendonitis, and 8 % had bursitis (Bird et al. 2001). Some authors contend that gluteal tendinopathy is similar to rotator cuff pathogenesis, with reactive secondary bursitis similar to subacromial bursitis (Kingzett-Taylor et al. 1999). Pathology may include a spectrum of entities such as tendonosis, partial tears, complete tears, undersurface tears, and tears with retraction, with the gluteus medius tendon most commonly involved. Dynamic ultrasound of "external hip snapping" has documented snapping of the ITB over the greater trochanter with a hypoechoic and thickened ITB (Choi et al. 2002). Whether the source of the pain is the tensor fascia lata or ITB is unclear. There are no specific studies involving cyclists (seated athletes), where the mechanism of injury appears different from those who are studied more often such as runners or older nonathletes. The etiology of lateral "hip" pain in the cyclist may be similar to the theory of ITBS at the knee with compression of underlying tissue against the greater trochanter. It can mimic pain from a lumbar disk or tumor, which often causes posterior thigh or buttock pain or osteoarthritis of the hip, which should cause groin pain. The cause usually is riding excessive mileage. Backing off and massage will quickly cure most of these cases. Improper bike fit may reveal "hip rocking" when pedaling with a high saddle. Recommended treatment includes bike fit adjustment, physical therapy, manipulation, or cortisone injection.

Historically injections are directed at the point of maximal tenderness. With ultrasound guidance, the injection may be directed at any tendonosis, tear, or bursitis. A long needle is often required to reach the gluteal entheses at the greater trochanter or deeper bursal structures. There are no known clinical studies comparing outcomes of ultrasound-guided injections versus blind technique for the treatment of greater trochanteric pain syndrome. In a randomized clinical control comparison of fluoroscopic-guided injection versus blind injection, there were no differences in outcomes favoring either group (Cohen et al. 2009).

48.4.6 Achilles Tendon

In a 4-year study of 51 professional cyclists, five cases of Achilles tendinopathy were reported compared with three cases of patella and eight cases of ITB tendinopathy (De Bernardo et al. 2012). Achilles tendinopathy may occur from riding “too much too soon,” improper pedaling technique, or improper bike fit. Excessive plantar flexion at bottom dead center (BDC) from too high a saddle may cause strain. Francis reported that the optimum plantar flexion in BDC pedal position should be approximately 13°, which corresponds to about 20° plantar flexion from the horizontal (De Vey Mestdagh 1998). Excessive dorsiflexion at BDC from a low saddle or pushing the heel down in an attempt to generate more power also may cause strain of the Achilles. Physical therapy, manual therapy, and eccentric strengthening are treatment options for Achilles tendinopathy. The pedal stroke may be broken down into the downward propulsive phase and upward relaxation phase. Simple observation of cyclists (whether or not they are using clipless pedal systems) reveals that a rider’s heel lowers during the downstroke (ankle dorsiflexes) and a rider’s heel raises during the upstroke (ankle plantar flexes), mostly due to lower limb movement and the biomechanics of cycling with a rotating pedal spindle on a moving crank. If the saddle height is set correctly, then the heel should not drop below horizontal on the downstroke. “Ankling,” purposely pressing the heel down at the start of the downward pedal stroke to a point below the horizontal and then lifting the heel up on the up stroke, recently has been found to be significantly less efficient than normal pedaling (Zommers 2000) and likely contributes to ankle tendon problems. The leg cannot be pulled actively up faster and harder in the upstroke than the leg pushing down in the downstroke. It is the maximal torque during the downstroke that separates the elite from recreational cyclists (Broker 2003).

48.4.7 Neck and Back Pain

Neck (19 %) pain and back pain (60 %) are common overuse injuries in cyclists (Callaghan and Jarvis 1996). Neck pain is caused by the tension developed in muscles of the shoulder, neck, and upper spine that are in a hyperextended position. Lengthy excessive extension of the neck results in trigger point development in the muscles of the neck and of the upper back. The vibrating movement that is caused from cycling can aggravate this problem (Simons et al. 1999). Isometric contractions of muscles decrease blood flow and may cause an ischemic response that may further cause a muscular spasm and consequently increase pain (Asplund and St Pierre 2004). Many activities in cycling involve sitting and leaning forward. The transversus abdominis and multifidus muscles are weakened in these postures (Simons et al. 1999). Additionally, failure of the hamstring muscles to lengthen normally increases the stress placed on the posterior elements of the lumbar spine, particularly if the spine is in a forward flexed position as in the cycling posture, because the extensor muscles of the low back are elongated and cannot disperse the applied stress (Schafer and Faye 1989). Bicycle fit position and improper equipment (changing the position of the handlebars/handlebar width and using a shorter stem), training errors (changing hand position more often and keeping elbows unlocked, core strengthening, and stretching programs), and individual anatomic factors (posterior pelvic tilt/hamstring flexibility, asymmetric upper and lower limbs) are important evaluation considerations. By learning how to recognize and treat contributing factors, as well as learning a few simple bike fitting techniques, physicians can treat and prevent many common problems (Asplund and St Pierre 2004).

48.5 Iliac Artery Endofibrosis and Kinking

Flow limitations in iliac arteries have been reported mostly in cyclists likely from riding position, although cases exist in speed skaters, runners, soccer players, and cross-country skiers. Flow limitations may be from kinking (functional iliac artery obstruction) or endofibrosis (external iliac artery endofibrosis) (Peach et al. 2012). Schep et al. (2002) estimate the prevalence to be 10–20 % among elite and professionals. A rider often sees multiple physicians with comprehensive orthopedic and neurological workups prior to diagnosis. The cyclist may report a sensation of dead leg, lack of power, cramp, or pain in the leg worse with steady exertion such as climbing or time trialing. A detailed questionnaire helps differentiate vascular from nonvascular causes. Physical examination is usually normal, although a bruit in the inguinal region may be heard, more often postexercise. A reliable, reproducible imaging modality does not exist. A flowchart guiding investigation and management exists. Initial test is a provocative ankle brachial index and duplex ultrasound, immediately postcycling with the hip and knee flexed. Magnetic resonance angiography may assess vessel length or kinking, and digital subtraction angiography may identify tethering of arterial branches. CT angiography also has been used. There are multiple treatment options. Arterial release is performed if stenosis is less than 15 %, and artery is not lengthened. Vessel shortening with endofibrosectomy is performed for a lengthened vessel. Endofibrosectomy and patch angioplasty, or interpositional grafting, are performed for intravascular lesions. Complete resection and replacement with a saphenous vein or synthetic graft have been performed also. Angioplasty or endoluminal stent placement is not recommended.

Professionals have returned to racing postsurgery, although no long-term outcomes exist.

Conservative treatment in recreational cyclists includes a change in position to one of less hip flexion or cessation of sport (Peach et al. 2012).

Conclusion

Injuries in cycling occur at a high rate from bicycle contact, traumatic events, and overuse. Overuse ailments occur primarily in the knee. Traumatic lesions occur primarily in the shoulder region. Many bicycle contact and overuse ailments are relieved with bike fit adjustments. Overuse injuries are treated successfully with massage, physical therapy, and modification of training. Most injured cyclists are able and willing to train and even race while injured. More evidence-based research on injuries in cycling is needed.

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The Expert View on Running Injuries

49

Ida Buist and Henk van der Worp

Contents

Abstract

Recreational running is a popular sport. As the numbers of participants increase, so does the number of running-related injuries. The incidence of injuries among runners is high and varies between 20 and 90 %. The diversity of incidence strongly depends on study population, definition and assessment of injury and period of follow-up. Although there is much literature concerning running-related injuries, there is little agreement when it comes

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to the aetiology of these injuries. Risk factors that are consistently associated with the occurrence of injuries in runners are higher running mileage and previous injury. There is a lack of proof for the link between gender, age, anatomical variation and biomechanical variables and psychological factors and running-related injuries. The clinical presentation, pathophysiology and supposed injury mechanism of the most common running-related injuries are described.

Abbreviations

BMI	Body mass index
MTSS	Medial tibial stress syndrome
PFPS	Patellofemoral pain syndrome
ROM	Range of motion
RRI	Running-related injury

49.1 Introduction

An increasing number of people realise that physical exercise is beneficial for their health. Running was already a popular form of exercise in the late 1970s. A newly found interest in recreational running can be observed nowadays (van Bottenburg et al. 2006). More people, especially women, include running as part of their healthy active lifestyle. Running has changed from being mainly a competitive sport to also being a popular leisure-time activity (Brill and Macera 1995). Worldwide the number of runners and the number of running events are growing. Almost every city has its own annual running event in which runners of all levels participate.

Although running is a form of recreational exercise that is beneficial for fitness and health, injuries are a significant side effect. Reported rates of running-related injuries (RRIs) are high and vary from 20 to 79 % (Bovens et al. 1989; Buist et al. 2010a, b; Lun et al. 2004; Lysholm and Wiklander 1987; Macera et al. 1989; Marti et al. 1988; Taunton et al. 2003; Walter et al. 1989).

To keep the running population active without injuries leading to periods of forced inactivity, there is a need for preventive interventions. Many different methods to prevent injuries are currently being recommended and practiced by runners. However, to date only a few preventive interventions have been tested in the population of recreational and novice runners for their preventive capabilities (Buist et al. 2008; Bredeweg et al. 2012b).

The literature on the epidemiology of RRIs in novice runners is scarce compared to the popularity of running. Only a limited number of prospective cohort studies on the topic of incidence and risk factors of RRIs in novice and recreational runners can be found (Bovens et al. 1989; Buist et al. 2008, 2010b; Lun et al. 2004; Taunton et al. 2003).

49.2 Type of Injury/Overuse Injuries

Although acute injuries in runners do occur (i.e. ankle sprain, muscle strain or traffic injury), most RRIs are overuse injuries (Hreljac 2005). Each kilometre an average runner's foot lands 800 times, with forces that are as high as two to three times the runner's body weight (Hargrave et al. 2003). Per definition, injuries occur when energy is transferred to the body in amounts or at rates that exceed the threshold for human tissue damage. In running, an overuse injury is the result of a large number of small-magnitude repetitive forces, each lower than the acute injury threshold of the structure. An injury means that the structure's capacity was insufficient in proportion to the applied stresses (Hreljac 2005). If the applied training load is sufficient and the time between two training sessions lasts long enough, there will be a positive adaptation of the musculoskeletal system. The muscles, bones and connective tissues that were stressed will become stronger. Since running mainly loads the lower extremities, most RRIs, that is, 69–91 %, are located at the knee and below (Bovens et al. 1989; Buist et al. 2010a, b; Taunton et al. 2003; Walter et al. 1989; Wen et al. 1998).

49.3 Incidence of Running-Related Injuries

There are different ways to specify the incidence of RRIs. The most common ways of reporting RRIs are absolute number of injuries, proportions of injuries and number of injuries per exposure. Van Mechelen (1992) showed in his review an incidence of 2.5 up to 12.1 injuries per 1,000 h of running. Lun et al. (2004) found in their study an incidence of 59 per 1,000 h of running exposure. The reported incidence numbers strongly diverge. The wide range of incidence rates that have been reported in the literature is caused by differences in study populations, follow-up periods and definitions of injury. In a prospective cohort study of 1,680 runners participating in two running events, 48 % experienced at least one RRI during a 12-month follow-up (Walter et al. 1989). Among participants of a popular 16-km race, 46 % of the male participants sustained RRIs during the 1-year study period (Marti et al. 1988). Macera et al. (1989) found in their prospective study of 538 habitual runners that 51 % experienced an RRI. In another prospective cohort study, 255 runners preparing for a marathon were followed. During the 32-week follow-up, 35 % sustained an RRI (Bovens et al. 1989). Lun et al. (2004) found that during a follow-up of 6 months, 79 % of 87 recreational runners experienced at least one injury of the lower extremity. The most recently published review of lower extremity RRIs in long-distance runners showed rates varying from 19.4 to 92 % (van Gent et al. 2007).

49.3.1 Definition of Injury

The definition of an RRI differs between studies. The definition of an injury in epidemiological studies on RRIs is frequently stated as (1) ailment or pain (Bennell et al. 1996; Bovens et al. 1989; Buist et al. 2010a, b; Lysholm and Wiklander 1987;

Macera et al. 1989; Taunton et al. 2003; Walter et al. 1989; Wen et al. 1998), (2) caused by running (Bennell et al. 1996; Bovens et al. 1989; Buist et al. 2010a, b; Macera et al. 1989), (3) resulting in a restriction of running (Bennell et al. 1996; Bovens et al. 1989; Buist et al. 2010a, b; Lun et al. 2004; Lysholm and Wiklander 1987; Macera et al. 1989; Walter et al. 1989; Wen et al. 1998) and (4) for at least 1 week (Bennell et al. 1996; Buist et al. 2010b; Lysholm and Wiklander 1987). In one single study, pain without a restriction of running was considered as an injury (Taunton et al. 2003). It is understandable that the incidence number will be higher as the definition of injury becomes broader. Participants' level and assessment of injury will also influence the incidence. Elite runners will have different training routines and will therefore be more exposed to running than novice runners.

49.4 Aetiology of Running-Related Injuries

Factors that may influence the aetiology of RRIs can be classified in several ways. They are frequently classified as intrinsic (personal-related) and extrinsic (training-related) risk factors. Personal-related risk factors can also be subdivided into anthropometric, anatomical, biomechanical and psychological variables and previous injury.

The training-related variable that is most frequently associated with the occurrence of an RRI is excessive running distances (Macera et al. 1989; Marti et al. 1988; Taunton et al. 2003; Walter et al. 1989). A higher weekly running distance leads to more time at risk and is therefore associated with more injuries. A sudden increase of running distance or running pace is also a risk factor for injuries in runners (Macera et al. 1989; Wen et al. 1998). An increase of no more than 10 % per week is regarded as safe in the literature in order to prevent injuries (Johnston et al. 2003). However, applying the 10 % rule did not prevent RRIs in novice runners enrolled in a systematic training programme (Buist et al. 2008). Other training-related variables linked to the occurrence of RRIs are running frequency (Macera et al. 1989; Taunton et al. 2003; Walter et al. 1989), implementation of stretching exercises (Macera 1992; Walter et al. 1989), footwear (Taunton et al. 2003; Wen et al. 1998) and running surface (James et al. 1978; Macera et al. 1989).

49.4.1 Running Surface and Footwear

Most people run on hard surfaces such as asphalt or concrete. The advantage is that this surface is often flat; therefore, the risk of sustaining an ankle sprain or another acute injury will be low. On the other hand, hard surfaces may place higher levels of stress upon the structures of the musculoskeletal system. In the non-scientific literature, the emphasis lies on wearing proper shoes to prevent injuries in runners. It is frequently written that novice runners are advised to visit a specialist in order to select proper running shoes. However, the terms 'specialist' and 'proper running shoes' are difficult to operationalise. Older shoes are said to lose their shock-absorbing functioning, probably leading to higher stresses on the musculoskeletal system. One study showed that three brands of low- and medium-priced running shoes tested provided the same (if not better) cushioning of plantar pressure as high-cost running shoes (Clinghan et al. 2007). Recently it has been argued that shock-absorbing running shoes, rather than being preventive for injuries, may be a cause of injuries because they facilitate rearfoot striking, which leads to greater collisions forces than mid- or forefoot striking (Lieberman et al. 2010).

49.4.2 Anthropometric Variables

Several characteristics of a runner, that is, gender, age and body mass index (BMI), are associated with injury. The results from a systematic review article on risk factors for RRI in long-distance runners showed a positive link with the female gender (van Gent et al. 2007). The link between age and the occurrence of RRIs seems controversial. In the 1980s study participants were primarily male runners, and in those studies no significant association was found with age (Macera et al. 1989; Walter et al. 1989). More recently, a prospective cohort study showed that females older than 50 were two times more at risk than younger female participants (Taunton et al. 2003). It is plausible that due to the ageing process, the structures of the musculoskeletal system become more prone to injury. On the other hand, as runners become older, they may also be more familiar with early signs of an RRI, and perhaps only the injury-free runners will continue to run. Marti et al. (1988) call this last phenomenon the 'healthy runner effect'.

The association between BMI and injury has been studied several times, but findings are not consistent. One study showed that male runners with a BMI higher than 26 had fewer injuries compared to male runners with a BMI of 26 or less (Taunton et al. 2003). In this study the potential risk factors were not corrected for running exposure. Therefore, running exposure could be a confounding factor, that is, heavier persons may have been less exposed to running. Another study showed that participants with a BMI lower than 19.5 or higher than 27 had an increased risk of sustaining an RRI (Marti et al. 1988).

49.4.3 Anatomical Variables and Variants

A number of anatomical variants are associated with RRIs. Of the various lower extremity 'misalignments', high longitudinal arch (pes cavus) and low longitudinal arch (pes planus) are probably the factors most commonly associated with running-related injuries (Hreljac 2005). A high longitudinal arc is frequently said to be associated with a stiff foot, resulting in a reduced capability of shock absorption. Although a pes cavus or a pes planus could be associated with a higher risk of injury, this is not consistently shown in research (Hreljac 2005). Wen et al. (1997) found in runners with both high and low longitudinal arches an increased risk for sustaining an injury. However, Lun et al. (2004) found no obvious predominance of subtalar valgus or pes planus/cavus in those who were injured. In another prospective study of the knee (valgus/varus), the longitudinal arch and the score of the rear foot (valgus/varus) were measured. None of these anatomical variables appeared to have an association with the occurrence of an RRI (Walter et al. 1989).

Other anatomical variants that may be linked to injuries in runners are the range of motion (ROM) of the hip and ankle (Hreljac 2004; Lun et al. 2004; Messier and Pittala 1988; Montgomery et al. 1989). Whether these variables are risk factors for the occurrence of RRIs has yet to be determined.

49.4.4 Biomechanical Variables

The majority of the biomechanical factors that are associated with injuries in runners can be classified as kinetic or rearfoot kinematic variables. Kinetic variables that have been associated with RRIs are the magnitude of impact forces, the rate of impact loading, the magnitude of active forces and the magnitude of joint moments (Bredeweg et al. 2012a; Hreljac 2005; Thijs et al. 2008). Pronation of the foot is the rearfoot kinematic variable that has been suggested to be most often related with an injury in runners (Hreljac 2005). Pronation is a protective mechanism during running which absorbs shocks by dividing forces over a longer period of time. In situations of abnormal pronation, that is, pronation beyond midstance, potentially large torques and instability are generated. On the basis of information provided by static tests, it is frequently stated that injured runners have excessive pronation. In the study of Messier and Pitalla (1988), it was shown that injured runners had more pronation and higher pronation velocity than noninjured runners. In another study it was suggested that runners who had developed stride patterns that incorporated a moderately rapid rate of pronation were at a reduced risk of incurring overuse RRIs (Hreljac et al. 2000). Navicular drop is used to clinically measure dynamic foot pronation (Menz 1998) and is defined as the change in height of the navicular bone when the foot moves from a subtalar neutral to a relaxed weightbearing stance (Brody 1982). Reinking and Hayes (2006) showed that athletes with an exercise-related lower leg pain history did not have a greater foot pronation as measured by navicular drop compared to those without previous injury.

49.4.5 Previous Injury

History of previous injury is the strongest intrinsic risk factor of injuries in runners. An injury twelve months prior to the study is frequently labelled as a previous injury (van Mechelen et al. 1992). Both among female and male runners, a previous injury is shown to be a risk factor for subsequent injury (Macera et al. 1989). Walter et al. (1989) showed that runners with a previous injury had approximately a 50 % higher risk for a new injury during the follow-up. Reasons for this phenomenon may be that the causal factor is still present or that the previous injury did not heal completely.

49.4.6 Psychological Variables

Whereas some runners hardly ever sustain injuries, others have recurrent RRIs. Ekenman et al. (2001) compared selected personality traits in a group of runners who had sustained a previous tibial stress fracture with a matched group of runners who had never experienced stress fractures. The results indicated that the injured runners, especially the women, scored higher than the noninjured runners on inventories measuring both type-A behavioural pattern and exercise dependency. People who run to compete instead of running to increase their level of fitness are said to be more prone to injury (van Mechelen et al. 1992). Runners with increased levels of motivation are more likely to be injured. Several authors allude to the existence of a certain 'readiness to take risks' among athletes who became injured (Junge 2000). The hypothesis is that strongly motivated runners will ignore the first signs of an injury and will hold on to their training programme.

49.5 Common Running-Related Injuries

RRIs can be divided into overuse and acute injuries. Most of the RRIs in recreational runners are overuse injuries, that is, injuries that occur without a single, specific, identifiable causative event. The ratio of acute to overuse injuries in distance runners is around 1–7 (Knobloch et al. 2008). In the next paragraphs, the characteristics of a number of common overuse and acute RRIs will be described. A short overview of clinical presentation and pathophysiology is given. Furthermore the mechanisms that may cause these injuries are described.

49.5.1 Overuse Injuries

Most of the running-related overuse injuries are situated at or below the knee (Table 49.1). The most common overuse RRIs are medial tibial stress syndrome, Achilles tendinopathy, patellofemoral pain syndrome, stress fractures, iliotibial band friction syndrome and plantar fasciitis (Table 49.2).

49.5.1.1 Medial Tibial Stress Syndrome (MTSS)

MTSS (also known as shin splints) is characterised by pain at the posteromedial border of the tibia. It is thought to be the result of a imbalance between bony resorption and bone formation of the tibial cortex. Bony resorption takes place at a higher rate than bone formation (Magnusson et al. 2001). This theory has replaced the original theory that MTSS is caused by traction-related periostitis. MTSS is more common in women than in men, and hyperpronation of the foot during running is thought to be one of the main running-related risk factors (Reshef and Guelich 2012).

49.5.1.2 Achilles Tendinopathy

Two types of Achilles tendinopathy can be distinguished: insertional tendinopathy and mid-portion tendinopathy. Tendinopathy consists of a short acute inflammatory

Table 49.1 Distribution of RRIs to location

	Taunton et al. (2002)	Van Middelkoop et al. (2008)	Buist et al. (2010b)	Bredeweg et al. (2012b)
	Patients with RRI visiting clinic	Marathon runners – injuries in previous year	Recreational runners during 8-week training	Novice runners during 2–3-month training programme
Injured runners (*N*)	*N*=2,002	*N*=397	*N*=163	*N*=58
Knee	42.1 %	30.7 %	38.0 %	39.7 %
Foot/ankle	16.9 %	22.9 %	11.7 %	12.1 %
Lower leg	12.8 %	–	–	–
Lower leg/Achilles/calf	–	39.4 %	41.1 %	29.3 %
Hip/pelvis	10.9 %	–	–	–
Hip/groin	–	17.9 %	8.6 %	–
Hip/back	–	–	–	15.5 %
Achilles/calf	6.4 %	–	–	–
Upper leg	5.2 %	12.3 %	3.7 %	3.4 %
Lower back	3.4 %	–	6.7 %	–
Others	2.2 %	–	13.5 %	–

Table 49.2 Distribution of the most common RRIs

	Taunton et al. (2002)	Nielsen et al. (2013)
	Patients with RRI visiting clinic (all injured)	Incidence of RRIs in inactive persons taking up running
	N=2,002	*N*=931
MTSS	4.9 %	4.2 %
Achilles tendinopathy	4.8 %	1.6 %
PFPS	16.5 %	2.9 %
Stress fractures	4.3 %	–
Iliotibial band friction syndrome	8.4 %	–
Plantar fasciitis	7.9 %	–
Hamstring injuries	2.3 %	0.8 %
Gastrocnemius injuries	1.3 %	1.1 %
Ankle sprains	0.8 %	–

stage, but after some time it gradually becomes a degenerative condition (Abate et al. 2009). Chronic tendinopathy is characterised by a disorganised tendon structure, thickening of the tendon with increased ground substance and formation of peri- and intratendinous vascular sprouts and nerve endings (neurovascularisation). These changes, however, do apply to mid-portion tendinopathy whereas often the insertion site (enthesis) where the tendon connects to the bone is involved. Reasons why the osteotendinous junction is often affected are the low flexibility, the arrangement of fibres in relation to the direction of muscle force and a small insertion zone compared to muscle size (Renstrom and Hach 2005). Risk factors for Achilles tendinopathy related to running are a lateral rollover following heel strike and diminished forward force transfer underneath the foot (Van Ginckel et al. 2009). The later rollover may cause Achilles tendinopathy because of diminished shock absorption and increased stress on the lateral side of the tendon, whereas the diminished forward force may result in a reduced moment of the plantar flexors, which may be compensated by increased Achilles tendon forces, and thereby increased strain.

49.5.1.3 Patellofemoral Pain Syndrome

Patellofemoral pain syndrome (PFPS) is characterised by anterior knee pain in or around the patella, related to activity. PFPS is one of the most common causes for knee pain seen in primary care (Bahr et al. 2012). PFPS may result from increased cartilage and subchondral bon stress (Fredericson and Yoon 2006) and should be distinguished from patellar tendinopathy which involves the attachment of the patellar tendon to the patella. The risk factor that is most often associated with PFPS is weaker knee extension strength (Lankhorst et al. 2012b) Others factors for which there is some evidence that they are related to PFPS are a larger patellar tilt angle, lower peak torque knee extension, larger Q angle, larger sulcus angle, lower hip abduction strength and lower hip external rotation strength (Lankhorst et al. 2012a). Risk factors related to running are an excessive impact shock during heel strike and propulsion phase (Thijs et al. 2008), which results in high loads on the patellofemoral joint, and a less pronated position of the foot at heel strike and a more lateral rollover (Thijs et al. 2007), resulting in a supinated position of the foot and a less internally rotated tibia, leading to an increased Q angle, which would influence the patellar tracking and increase contact pressures.

49.5.1.4 Stress Fractures

Stress fractures of the lower leg and foot are typical in runners and are characterised by localised bone tenderness and oedema. In the lower leg, they occur most often in the distal and proximal part of the tibia and in the distal part of the fibula. In the foot they occur in the navicular bone and the metatarsals. The most common location for stress fractures among runners is the tibia (Lopes et al. 2012).

Stress fractures typically occur a few weeks to a few months after training has started (Bahr et al. 2012). Two theories, that are not mutually exclusive, exist about the aetiology of stress fractures (Sanderlin and Raspa 2003). According to the first theory, osteoclastic activity precedes osteoblastic activity by a few weeks, making the bone susceptible to injury during this period. The second theory finds the explanation for stress fractures in high stress on the bone at the insertion point of the muscles, which leads to bending stresses. A foot arch that deviates from normal may be a risk for tibial stress injuries (Barnes et al. 2008). Also, high vertical loading rates during running seem to be a risk factor for stress fractures in the tibia and metatarsals (Zadpoor and Nikooyan 2011).

49.5.1.5 Iliotibial Band Friction Syndrome

This injury is also known as runner's knee and is characterised by lateral knee pain near the lateral femoral condyle (Bahr et al. 2012). Repetitive friction between the iliotibial band and the femoral epicondyle is thought to be the cause of this condition, which is therefore termed 'iliotibial band friction syndrome'. Some however have questioned this account and have argued that pain is caused by compression of the tissue between the tract and the epicondyle and have proposed ‘fascia lata compression syndrome’ as a more accurate name (Fairclough et al. 2007). Hip abductor weakness has been implicated in the onset of iliotibial band friction syndrome, although there is conflicting evidence regarding its role, and there is some evidence that early hip flexion and early knee flexion may be related to iliotibial band friction syndrome (van der Worp et al. 2012).

49.5.1.6 Plantar Fasciitis

Plantar fasciitis is an enthesopathy that occurs at the proximal attachment of the plantar fascia to the calcaneus and is associated with heel pain. As in tendinopathy it is a degenerative condition, although lacking an initial inflammatory stage, and is therefore sometimes called ‘plantar fasciopathy’. Sometimes a heel spur is formed (Bahr et al. 2012). Risk factors for plantar fasciitis are increasing age, being female, increased body weight and running/playing on hard surfaces (Orchard 2012), whereas biomechanical running-related risk factors are higher impact peaks and loading rates (Pohl et al. 2009).

49.5.2 Acute Injuries

Besides these overuse injuries, acute injuries do also occurs in runners, although less often. Acute injuries, especially muscle injuries, are more common in sprinters and middle-distance runners than in long-distance runners (Lysholm and Wiklander 1987). Common acute RRIs are hamstring muscle injuries, gastrocnemius muscle injuries and ankle sprains (Table 49.2).

49.5.2.1 Hamstring Muscle Injury

Hamstring muscle strain injury is a typical sprint injury. Most often the biceps femoris muscle is involved (Bahr et al. 2012), although depending on aetiology other anatomical locations can be affected (Askling et al. 2000). Risk for injury to the hamstring during sprinting is highest during the last part of the swing phase when the hamstrings are eccentrically contracting (Heiderscheit et al. 2005; Schache et al. 2010), and in line with this, it has been shown that eccentric weakness of the hamstrings increases the chances of reinjury (Lee et al. 2009).

49.5.2.2 Gastrocnemius Muscle Injuries

The injury at the gastrocnemius muscle tissue has also been termed “tennis leg” and is most common in middle-aged people (Froimson 1969). Subjects often describe sensation of the rupture as “having been struck on the back of the calf” and sometimes report “hearing a snapping sound” (Russell and Crowther 2011). The muscle-tendon junction of the medial gastrocnemius head is the most common location for ruptures of the gastrocnemius muscle (Delgado et al. 2002). Simultaneous forced dorsiflexion of the ankle and knee extension is thought to be the primary cause of this injury (Froimson 1969), a situation that can occur during the stance phase of running (Johnson and Buckley 2001).

49.5.2.3 Ankle Sprains

Inversion ankle sprains are more common than eversion ankle sprains. In inversion ankle sprains, the lateral ligaments of the ankle are involved, and there is tenderness and swelling around the lateral malleolus. Three grades of severity are distinguished, ranging from mild stretching of the ligament complex without joint instability (grade 1) to partial rupture (isolated rupture of one ligament) with mild instability (grade 2) and to complete rupture with instability (grade 3) (Struijs and Kerkhoffs 2010). The most common injury mechanism of inversion ankle sprains during running is a combination of excessive supination of the rear foot and external rotation of the lower leg soon after initial contact of the foot (Hertel 2002). A lateral situated centre of pressure during initial contact is a risk factor for inversion ankle sprain as well as a mobile-foot type (Willems et al. 2005).

Conclusion

The incidence of RRIs is substantially high, and although there is a large body of literature on the subject of risk factors for RRIs, there is little consistency on the reporting of incidence, the aetiology and the risk factors of these injuries. The two most important factors for the occurrence of injuries in runners are higher running mileage and previous injury. Further research into specific injuries is required to determine the exact aetiology.

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Nuclear Medicine Imaging in Concussive Head Injuries in Sports

50

David Vállez Garcia and Andreas Otte

Contents

Abstract

Concussions in sports and during recreational activities are a major source of traumatic brain injury in our society. This is mainly relevant in adolescence and young adulthood, where the annual rate of diagnosed concussions is increasing from year to year. Contact sports (e.g., ice hockey, American football, or boxing) are especially exposed to repeated concussions. While most of the athletes recover fully from the trauma, some experience a variety of symptoms including

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headache, fatigue, dizziness, anxiety, abnormal balance and postural instability, impaired memory, or other cognitive deficits. Moreover, there is growing evidence regarding clinical and neuropathological consequences of repetitive concussions, which are also linked to an increased risk for depression and Alzheimer's disease or the development of chronic traumatic encephalopathy. With little contribution of conventional structural imaging (computed tomography (CT) or magnetic resonance imaging (MRI)) to the evaluation of concussion, nuclear imaging techniques (i.e., positron emission tomography (PET) and single-photon emission computed tomography (SPECT)) are in a favorable position to provide reliable tools for a better understanding of the pathophysiology and the clinical evaluation of athletes suffering a concussion.

Abbreviations

^{11}C-PK11195	(R)-^{11}C-1-[2-chlorophenyl]-*N*-methyl-*N*-[1-methylpropyl]-3-isoquinoline carboxamide
^{99m}Tc-ECD	Technetium-99m-ethyl cysteinate dimer
^{99m}Tc-HMPAO	Technetium-99m-hexamethylpropyleneamine oxime
ATP	Adenosine triphosphate
CBF	Cerebral blood flow
CMRglc	Cerebral metabolic rate of glucose
CT	Computed tomography
CTE	Chronic traumatic encephalopathy
FDG	2-Deoxy-2(^{18}F)-fluoro-D-glucose
FMZ	^{11}C-flumazenil
GCS	Glasgow Coma Scale
MRI	Magnetic resonance imaging
mTBI	Mild traumatic brain injury
NFL	National Football League
PCS	Post-concussive syndrome
PET	Positron emission tomography
SPECT	Single-photon emission computed tomography
SPM	Statistical parametric mapping
TBI	Traumatic brain injury

50.1 Introduction

Traumatic brain injury (TBI) is one of the most important causes of brain injury in our society. Recent studies have estimated an annual incidence of 230 per 100,000 inhabitants in the European Union (Tagliaferri et al. 2006) and of about 500 per 100,000 inhabitants in the United States (Faul et al. 2010). Among the TBI cases, 70–80 % are considered mild injuries (Tagliaferri et al. 2006), and about 85 % of the patients report one or more symptoms the day after the accident (Lundin et al. 2006).

While main causes of TBI are falls and motor vehicle-related accidents, sports and recreational activities are also a major severely underestimated source. While previous data reported that approximately 300,000 of such sports-related TBIs occur each year (Thurman et al. 1998), recent studies suggest that a better and accurate value of 1.6–3.8 million per year represents more precisely the current situation (Langlois et al. 2006). It is important to remark that this estimation might still be low, because some mild injuries are not properly detected or are underestimated by the patients and thus uncounted.

Contact sports are especially prone to mild traumatic brain injuries (mTBI), commonly termed as concussion. From these sports, ice hockey shows the highest incidence of concussion among team sports (American football, ice hockey, rugby, and soccer). It seems that the overreliance on protective equipment in some of these sports, such as in ice hockey and American football, may induce the athletes to be even more aggressive and then indeed have a higher incidence of concussion. On the other hand, in individual sports it is boxing which shows the highest frequency of concussion at the recreational and competitive level (Koh et al. 2003).

Boxing and other forms of unarmed combats are probably as old as human species. Not surprisingly, the link between repetitive concussions and cognitive or behavioral impairments later in life was originally noted in boxers. These clinical characteristics were first described in 1928 by Martland as the "punch drunk syndrome" (Martland 1928). Martland hypothesized that the clinical spectrum of abnormalities that he observed in boxers was the result of repeated blows to the head. Later in 1937, Millspaugh introduced to the condition the more formal term of "dementia pugilistica," a term that has survived until today (Millspaugh 1937).

Concussed athletes can experience a variety of symptoms including headache, fatigue, dizziness, anxiety, abnormal balance and postural instability, and impaired memory or cognitive deficits, among others. These symptoms, when prolonged in time, are frequently referred as post-concussive syndrome (PCS) (World Health Organization 2010), which is manifested in 15 % of those suffering a concussion (Rutherford et al. 1979). The common experience is that recovery following a single sports-related concussion is rapid and complete, i.e., without residual deficits or long-lasting structural changes. However, there is growing evidence of the clinical and neuropathological consequences of *repetitive* concussions. Several brain changes are potentially associated with repetitive head impacts (Orrison et al. 2009):

1. Hippocampal atrophy
2. Cavum septum pellucidum
3. Dilated perivascular spaces
4. Diffuse axonal injury
5. Cerebral atrophy
6. Increase in lateral ventricular size
7. Pituitary gland atrophy
8. Contusions
9. Arachnoid cyst
10. Hemosiderin deposition (from prior hemorrhage)
11. Vascular injury

Moreover, repetitive concussions have been linked with an increased risk of depression (Holsinger et al. 2002), Alzheimer's disease (Plassman et al. 2000), chronic traumatic encephalopathy (CTE), or neurodegenerative diseases (McKee et al. 2009; Gavett et al. 2010, 2011a). CTE is a distinct form of the acute symptoms of concussion, and it is not only merely a prolonged PCS any more (Gavett et al. 2011b). Symptoms of CTE typically do not present until years after the trauma and include dementia, impaired mental function and coordination, tremors, impulsive behavior, and cognitive impairment (Mendez 1995; Rabadi and Jordan 2001).

With the high rates of sports-related brain injuries during the adolescence and young adulthood, it is important to make an effort to fully understand the short- and long-term consequences of repetitive concussions. Thereby, appropriate guidelines can be created for clinical evaluation and to address the return to exercise and athletic participation. Computed tomography (CT) and conventional magnetic resonance imaging (MRI) are the first techniques of choice for initial brain evaluation after concussion. However, the metabolic changes due to the trauma are undetected by these techniques, as they naturally only focus on morphologic alterations. Likewise, these techniques cannot be used to predict neurocognitive function at any stage of the concussion nor the functional outcome at 1 year after the injury (Lee et al. 2008). Even if abnormalities are shown by these conventional neuroimaging tools, they do not image the pathology that is important for the neurocognitive outcome (Scheid et al. 2003, 2006; Hughes et al. 2004). In this context nuclear neuroimaging has great potential as a noninvasive metabolic tool. Techniques, such as single-photon emission computed tomography (SPECT) and positron emission tomography (PET), can be used to provide insight into the underlying metabolic changes that arise from a concussion. Moreover, functional neuroimaging using nuclear medicine techniques also provides insight into secondary damage and may serve as instrument for evaluating different therapeutic approaches or the evolution of the disease.

As – to the best of our knowledge – there are no substantial studies using functional magnetic resonance imaging (fMRI) in concussive head injuries in sports, this chapter is on PET and SPECT. Due to the scarce number of PET and SPECT research focusing specifically on the sport context, an overview of key studies on traumatic brain injury is also included (for a detailed review about PET and SPECT in TBI, please refer to, e.g., Sánchez-Catasús et al. (2014); for a review about metabolic imaging in mTBI, see, e.g., Lin et al. (2012); and for a summary of fMRI in mTBI, see, e.g., McDonald et al. (2012)).

50.2 Neuropathology of Concussion

To understand the relevance of nuclear imaging in the context of concussion in sport, it is necessary to start with an overview on the metabolic cascade of reactions that take place after a mTBI (for a detailed review, please see the paper by Bigler and Maxwell about the neuropathology of mild traumatic brain injury (Bigler and Maxwell 2012)). It is generally accepted that a concussion results from rotational or angular accelerations in the brain. The maximal rotational forces, which are a consequence of the head impact, are exerted in the midbrain and diencephalic region, creating a disruption of the electrophysiological and subcellular activities of neurons and glial cells. Contrary to common belief, the initial transmitted tension does not result in shearing of the axons, which can be stretched and twisted without being sheared or torn (Iverson 2005). In fact, the neuropathology of concussion is the result of a complex process and not an instant, consequence of the "neurometabolic cascade" that follows the head trauma (Giza and Hovda 2001). This "neurometabolic cascade" is shown in Figs. 50.1 and 50.2:

- Immediately after the mechanical injury of the brain, there is a cellular response with a widespread release of excitatory neurotransmitters (i.e., glutamate) and an uncontrolled ion flux. The binding of glutamate to its receptors leads to further neuronal depolarization, with efflux of potassium (K^+) and influx of calcium (Ca^{2+}), sodium (Na^+), and chloride (Cl^-). This ionic shift causes a failure to generate and propagate action potentials, leading to acute and subacute changes at cellular level. This process will end in a secondary axotomy 4 h to 12 weeks after the mTBI (with a minimum of 2 h in animals and 12 h in human beings).

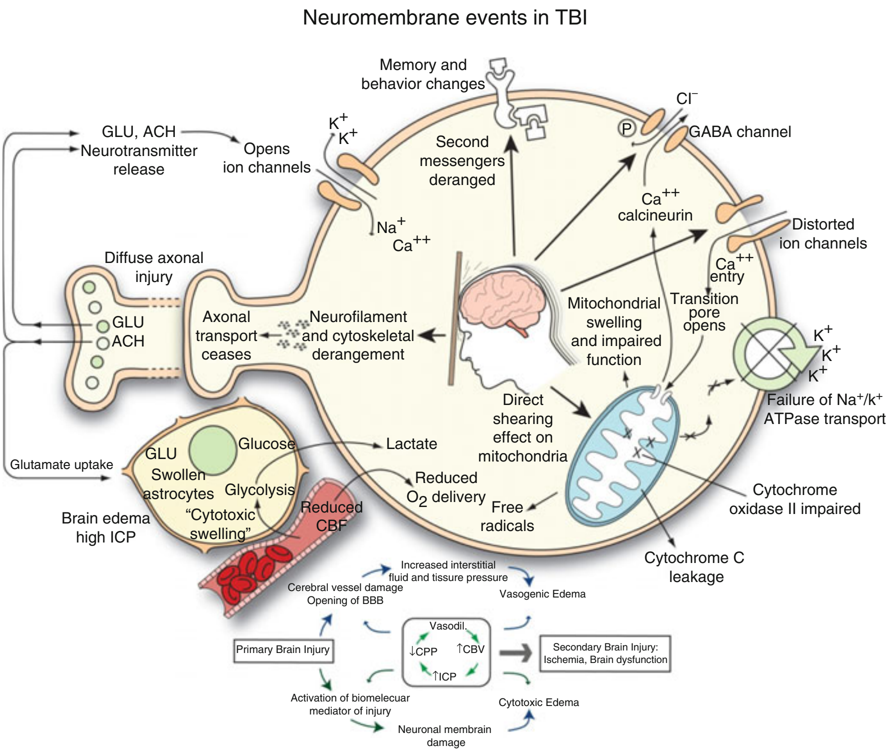

Fig. 50.1 Neuromembrane events in TBI. Scheme demonstrating the complex cellular and vascular pathophysiological interactions occurring following TBI and the central role of mitochondrial failure that relates to all neuromembrane events (Bigler and Maxwell 2012)

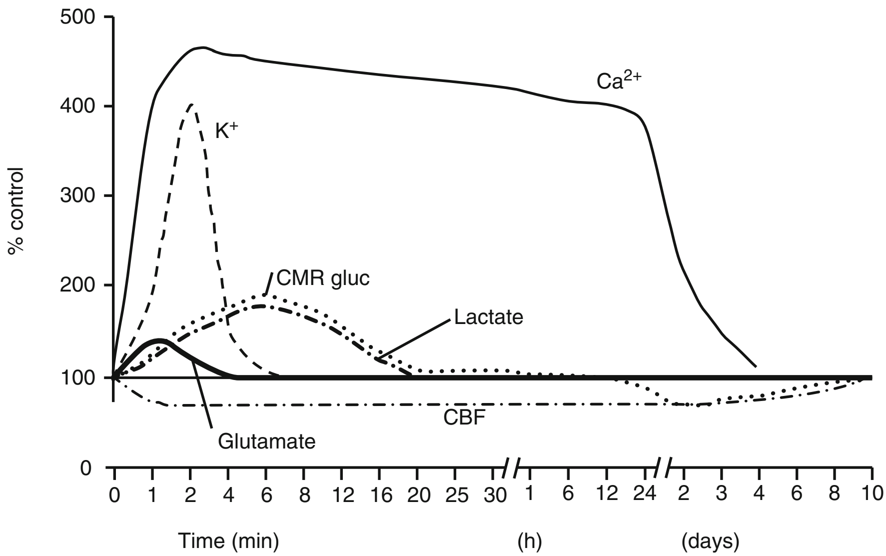

Fig. 50.2 Neurometabolic cascade following experimental concussion. *K+* potassium, *Ca2+* calcium, *CMRgluc* oxidative glucose metabolism, *CBF* cerebral blood flow (Giza and Hovda 2000)

- In the acute stage, the sodium-potassium (NA^+-K^+) pumps increase their function by trying to restore the neuronal membrane potential, with the corresponding increment in production of adenosine triphosphate (ATP). Triggering of the glucose metabolism into a diminished cerebral flow state creates a mismatch between glucose supply and the demand of energy that ends in a cellular energy crisis and failure of the ATP-dependent membrane pumps.
- In the subacute phase, after the initial period of increased glucose consumption, the brain undergoes a period of depressed metabolism. The reduction in ATP production creates a failure in ATP-dependent membrane pumps, with a reverse pumping of Na^+/Ca^{2+} exchangers. This leads to a marked increase of Ca^{2+} concentration in the cytoplasm, which is sequestrated by the mitochondria, causing damage to it and worsening the energy crisis. This process starts a cascade of reactions including oxygen radical production, disruption of protein phosphorylation, formation of proteases and free fatty acids (e.g., arachidonic acid), depolymerization of microtubules, collapse and loss of neurofilaments, and, in later stages, separation of myelin lamellae.

It is important to understand that this complex pathophysiologic sequence of events and metabolic changes occurs prior to what can be visualized using conventional CT and MRI, while it can be the target of the more specific nuclear imaging techniques aiming to visualize particular metabolic processes.

50.3 SPECT

50.3.1 SPECT in TBI

SPECT is a functional imaging technique extensively used in mTBI, essentially to determine the cerebral blood flow (CBF) based on technetium-99m-hexamethylpropyleneamine oxime (^{99m}Tc-HMPAO) or technetium-99m-ethyl cysteinate dimer (^{99m}Tc-ECS). From the aforementioned SPECT perfusion tracers, ^{99m}Tc-ECD has been proven to distinguish more and especially smaller functional deficits in mTBI than ^{99m}Tc-HMPAO (Otte et al. 1997).

SPECT scans are available at most major hospitals with a relatively low cost of about US $800 (Anderson et al. 2005). Different reviews on this neuroimaging modality outline the high negative predictive value of the perfusion SPECT scans during the acute phase in mTBI (Cihangiroglu et al. 2002; Davalos and Bennett 2002; Belanger et al. 2007; Lin et al. 2012).

Other additional radiopharmaceuticals have also been utilized to study concussion. CBF measures with iodine-123 *N*-isopropyl-*p*-iodoamphetamine (^{123}IMP) in conjunction with iodine-123 iomazenil (^{123}IMZ), to measure neuronal integrity by binding to benzodiazepine receptors, were used to study nine chronic mTBI patients. In all of these a significant increase in benzodiazepine receptor uptake of the prefrontal cortex could be shown as compared with matched control subjects (Hashimoto et al. 2007). Finally, a study with cobalt-57 chloride SPECT ($^{57}CoCl_2$) (Audenaert et al. 2003), which is suggested to target calcium in the brain, was performed in 8 mTBI patients 2 days after the injury. In this study, a $^{57}CoCl_2$ accumulation in frontal and temporal lobes, with additional accumulation in the posterior parietal occipital region, could be shown in accordance with hypoperfusion measured by ^{99m}Tc-HMPAO. By contrast, CT and EEG did not detect (structural) lesions in any of these cases. The aforementioned studies are only pilot studies, and with the small number of subjects included in them, it is indeed difficult to determine the general validity of their findings. However, they open new avenues to make the SPECT technique a valid alternative for studying mTBI, both for clinical practice and for research.

50.3.2 SPECT in Sports-Related Head Injuries

Although SPECT on concussion in the acute stages of sports-related head injuries is not available to date, some studies have explored the *chronic* stages of repetitive concussions in boxing and American football. In a ^{99m}Tc-HMPAO SPECT study, Kemp and colleagues (1995) have compared the CBF between active amateur boxers and a control group of healthy athletes. They reported that out of 34 boxers, 14 (41 %) had abnormal cerebral perfusion when compared with an “atlas of normality” (database of images obtained from healthy controls) (Houston et al. 1994), while abnormalities were observed only in 5 (14 %) of the controls. They also reported significant correlations between behavior deficits and abnormalities seen by SPECT. The same group of amateur boxers was reanalyzed by Houston et al. (1998), including other groups (undersea divers, schizophrenic patients, and Alzheimer's disease patients) for comparison. Boxers exhibited large regional CBF abnormalities (1.05 % of cortical voxels) and presented at least one large lesion (>10 voxels, each with a side length of 0.64 cm) in eight of the nine regions of interest, including the left and right frontal, parietal, and inferior temporal lobe, right inferior frontal lobe, and occipital region.

More recently, three studies by Amen and colleagues have investigated the chronic stages of repetitive concussion in retired American football players. In their first experiment (Amen et al. 2011a) 100 subjects were recruited from the National Football League (NFL), representing different teams and all positions, and compared with healthy matched controls. The study, using ^{99m}Tc-HMPAO SPECT, revealed a global decrease in CBF, especially in the prefrontal, temporal, and occipital lobes, anterior and posterior cingulate gyrus, hippocampus, and cerebellar region (Fig. 50.3). The use of *Z* scores to analyze the results, instead of the

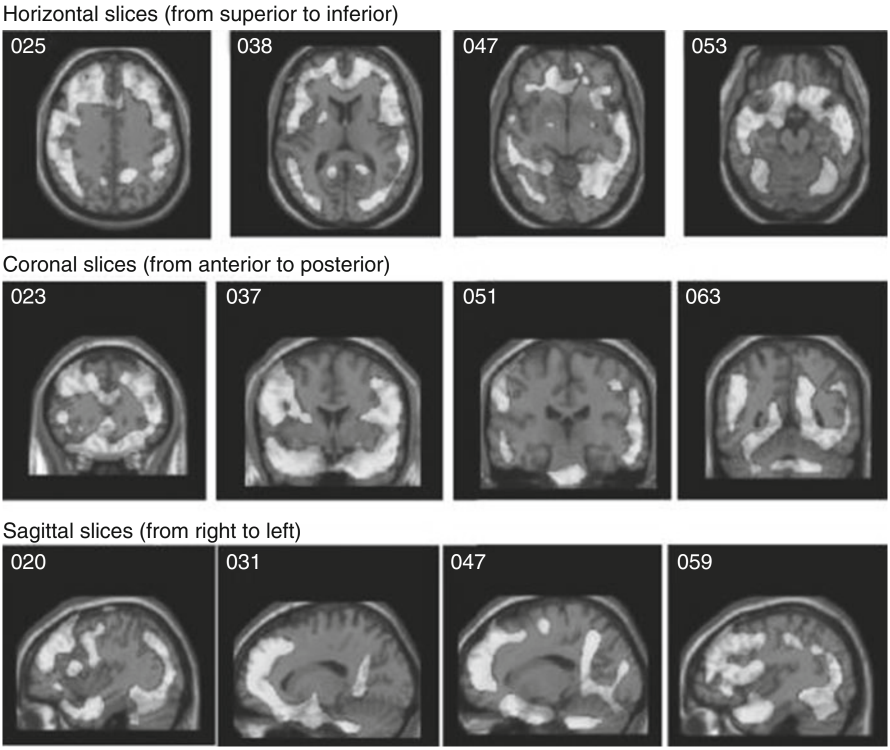

Fig. 50.3 Global brain HMPAO SPECT decrease in NFL players versus healthy subjects. *Light areas* indicate decreased perfusion in the NFL players versus healthy-brain comparison subjects at $p<0.0001$, family-wise error. No increases were seen (Amen et al. 2011a)

generally used number of hypoperfusion regions, makes it difficult to compare the data with other SPECT studies (Lin et al. 2012). However, their findings seem to correspond with CBF changes found in other general studies about mTBI. In a second study, Amen et al. (2011b) examined 30 retired NFL players before and after an intervention based on weight loss and multiple supplements, such as fish oil, vitamins, ginkgo biloba, acetylcholine, and antioxidants. Initial SPECT scans were compared with the follow-up scans using a paired *t*-test. They found increased brain perfusion in the prefrontal cortex, parietal and occipital lobes, anterior cingulate gyrus, and cerebellum. Unfortunately, there was no control group and no randomization in the study, so it is rather difficult to answer the question of whether or not the results are due to the intervention. In the last study (Willeumier et al. 2012), and using the same data pool, the CBF of 38 overweight (waist-to-height ratio = 58.7 ± 4.7) retired NFL players was compared with the same number of normal-weight players (49.34 ± 2.8). The study revealed that overweight athletes present a decreased CBF in the dorsolateral prefrontal cortex (Brodmann areas 8 and 9), the anterior prefrontal cortex (Brodmann area 10), and the left temporal pole. These brain regions are involved in attention, reasoning, and executive function.

50.3.3 SPECT: Discussion and Future Perspective

Advances in SPECT detector systems and hybrid SPECT-CT, development of new tracers, the application of modern methods of image analysis, and the relatively low cost of each scan make the SPECT an interesting technique for the study of concussion. Nevertheless, some issues still remain to be resolved. First, while studies have shown that SPECT is more sensitive in TBI than CT or MRI (Ichise et al. 1994), it may not be highly specific, as there might be other conditions showing changes in the same brain regions (Wortzel et al. 2008). And second, SPECT image analysis tends to rely on the comparison of regions of interest considered "normal," but due to the diffuse nature of the concussion, it may be difficult, if not impossible, to obtain an area not affected. Therefore, implementation of new methods to process the data is needed, such as the use of voxel-based analysis with statistical parametric mapping (SPM, Wellcome Department of Cognitive Neurology, University College London) (Friston et al. 1991, 1995).

The understanding of concussion with the help of SPECT would also benefit with the use of different gamma-emitting radioligands. For example, the combination of ^{123}I-2-β-carbomethoxy-3-β-(4-iodophenyl)tropane (β-CIT) and ^{123}I-iodobenzamide (IBZM): In moderate and severe TBI, these two tracers have shown a nigrostriatal dysfunction, although the striatum was structurally preserved (Donnemiller et al. 2000). Another recent animal study has used a newly developed radiotracer, *N′*,*N′*-diethyl-6-chloro-(4′-[^{123}I]iodophenyl)imidazo[1,2-a]pyridine-3-acetamide (^{123}I-CLINDE), to monitor in vivo neuroinflammation (Mattner et al. 2011). Especially the development of new radioligands may be helpful for the understanding of the pathomechanism of concussion and mTBI.

50.4 PET

One of the main advantages of PET over SPECT is its higher sensitivity that allows generating images of greater resolution (e.g., Otte and Halsband 2006). The usefulness of this technique in the study of traumatic brain injuries was shown in several clinical settings (e.g., Hattori et al. 2003). However, no meta-analyses have clarified its importance due to the heterogeneity of the published studies (differences in the time elapsed between trauma and scan, differences in the TBI classification, use of different radiotracers, or different methodologies for the image analysis). Despite the large number of these studies including moderate and severe injuries, not much research has been done to address expressly the mild injuries or the concussions in sports. Apart from availability and the need for a nearby cyclotron, this can also be explained by the high cost of PET exams, usually ranging between US $1,000 and $3,000 (Rushing et al. 2012).

50.4.1 PET in TBI

The most common radiotracer used in clinical PET imaging is 2-deoxy-2(^{18}F)-fluoro-d-glucose (FDG), with its first studies applied to TBI patients dating back to the 1980s and 1990s (Rao et al. 1984; Langfitt et al. 1986; Alavi 1989; Alavi et al. 1997; Tenjin et al. 1990; Yamaki et al. 1996; Fontaine et al. 1999). In these studies, it was pointed out that abnormalities can be detected by FDG more extensively than those observed by structural images, such as CT, and this applied even to early stages after mTBI, where CT or MRI was still negative. Since these first experiments, the brain metabolism in *acute* phases of TBI was studied, and the existence of a triphasic pattern was found in the cerebral metabolic rate of glucose (CMRglc), measured by FDG PET (Bergsneider et al. 1997, 2000, 2001). These phases, observed also in animal models, are divided into:

1. Hyperacute increase of metabolic activity
2. Prolonged period of reduced metabolism, of about a month
3. Recovery of stable levels within normal limits

It is important to notice that these phases are independent of the TBI severity and the level of consciousness measured by the Glasgow Coma Scale (GCS) (Bergsneider et al. 2001). Therefore, most of what will be described below can be applied to mild head trauma injuries or concussions, although not many specific researches have been undertaken on this group of subjects.

In the acute phase after the trauma, the whole brain maintains a low metabolic state. While brain CMRglc values cannot reflect the level of consciousness, more recent experiments using a new generation of PET scanners with better spatial resolution have demonstrated a direct association between the level of consciousness measured by GCS and particular CMRglc values in the thalamus, brain stem, and cerebellum (Hattori et al. 2003). Some of the subsequent studies have included the radiotracer $H_2{}^{15}O$ to evaluate also the cerebral blood flow (CBF), clarifying the role of glucose metabolism in the acute phases of TBI. A reduction of hexokinase activity in the whole brain was demonstrated, including apparently undamaged brain areas, while glucose transport and CBF were only reduced in pericontusional areas (Hattori et al. 2004). Moreover, a selective reduction of CMRglc and hexokinase activity was found in the gray matter and not in the white matter. Interestingly, this reduction was not observed in the CBF, measured with $H_2{}^{15}O$, and was not related with any evidence of damage based on conventional MRI images (Wu et al. 2004a, b).

While many individuals are capable to recover back to stable functional levels after the acute phase, others develop more chronic stages. The wide variety of chronic cognitive, emotional, and behavioral alterations that configure the so-called post-concussive syndrome cannot be solely explained by these initial changes in glucose metabolism. In this context, it was shown that initial oxidative metabolic dysfunction can lead to chronic brain atrophy, especially in brain areas not directly damaged during trauma (Xu et al. 2010). Neural network connecting cortical and subcortical regions are also crucial to maintain normal cognitive function (Bassett and Bullmore 2009). As previously mentioned, impaired function in the thalamus or brain stem can alter the normal status of these networks, reflected, for example, in the differences in loss of consciousness after a TBI. This disconnection or malfunction between subcortical and cortical levels may persist in more chronic stages. Several studies have shown bilateral hypometabolism in the prefrontal medial region, medial frontobasal region, anterior and posterior regions of the cingulate gyrus, and the thalamus. Each of these areas is an essential part of the cognitive networks (Nakayama et al. 2006). In addition, subsequent studies have shown metabolic deficits in both the temporal lobe and right cerebellum (Kato et al. 2007) and medial region of cingulate gyrus (Nakashima et al. 2007). Like in acute phases, abnormal patterns of the metabolism are similar in patients with or without structural lesions observed by CT or MRI (Lull et al. 2010; Zhang et al. 2010; García-Panach et al. 2011).

50.4.2 PET in Sports-Related Head Injuries

Unlike SPECT, only few PET studies have focused on mTBI. Most of them report similar diffuse cortical-to-subcortical abnormal patterns as those presented in moderate and severe trauma. This includes alterations in glucose metabolism in the frontal, temporal, and parietal lobes, prefrontal cortex, and cingulate gyrus.

Three studies have examined the effect of multiple head injuries as a consequence of boxing using PET. In the first study, published by Turjanski et al. in 1997 (Turjanski et al. 1997), six patients (five boxers and one jockey), who were presumed to have posttraumatic parkinsonism, were investigated with ^{18}F-DOPA PET. Results were compared with a healthy group and a group of patients with idiopathic Parkinson's disease without history of head trauma. In the posttraumatic group, a 40 % reduction of mean ^{18}F-DOPA uptake was found in the caudate and

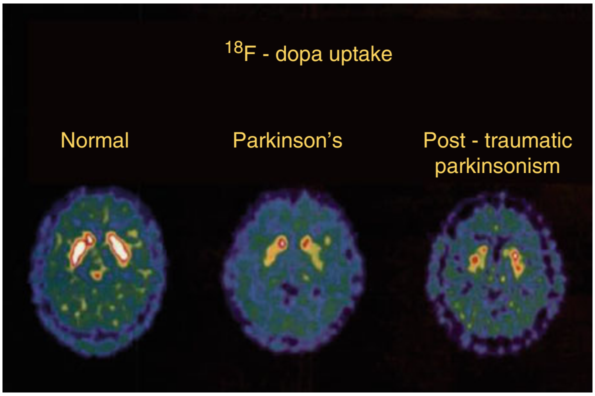

Fig. 50.4 Dopaminergic function in posttraumatic parkinsonism. Transaxial images of striatal ^{18}F-dopa activity accumulated over the last 60 min of the study in a control subject, a patient with Parkinson's disease, and a patient with posttraumatic parkinsonism. Note that putamen uptake is impaired in both patients, while the posttraumatic parkinsonism patient also shows reduced uptake in the caudate (Turjanski et al. 1997)

putamen compared with controls. Their mean putamen uptake was significantly higher than in the Parkinson's disease group, while mean caudate uptake was lower (Fig. 50.4). The authors concluded that – although posttraumatic parkinsonism shares clinical features with idiopathic Parkinson's disease – the uniform loss of nigrostriatal dopaminergic function in the posttraumatic subject suggests a different underlying pathology.

It was not until recently that new PET imaging research was performed in athletes: Provenzano et al. (2010) have examined with FDG the effects of repetitive head injury in a group of 17 boxers compared with those of seven controls. Images were analyzed using both SPM and regions of interest. Both methods showed that boxers have bilateral hypometabolism in the posterior cingulate cortex, parieto-occipital cortex, frontal lobes (Broca's area) bilaterally, and the cerebellum as compared with controls (Fig. 50.5). While these results present a unique pattern of decreased metabolism, the authors suggest that this could be the result of a singular signature of brain injury in boxing. These results partially overlap with the findings of hypometabolism in the cerebellum, vermis, pons, and medial temporal lobe after repeated blast exposure in Iraq war veterans (Peskind et al. 2011). Besides, the reported hypometabolism in the parieto-occipital region interestingly matches with the finding often seen in whiplash injury (Otte et al. 1995; Otte 2012).

The last published study was by Bhidayasiri et al. (2012). They compared dopaminergic function of three retired Thai boxers with parkinsonism with another three patients with idiopathic Parkinson's disease, having no history of significant head injury. In the posttraumatic parkinsonism patients, a higher uptake in putamen was found compared with the Parkinson's disease group. Furthermore, boxers had a significantly lower uptake in the ipsilateral anterior putamen and the contralateral posterior putamen than the Parkinson's disease group (considering the side of predominant symptoms). However, no differences were observed in the caudate nucleus

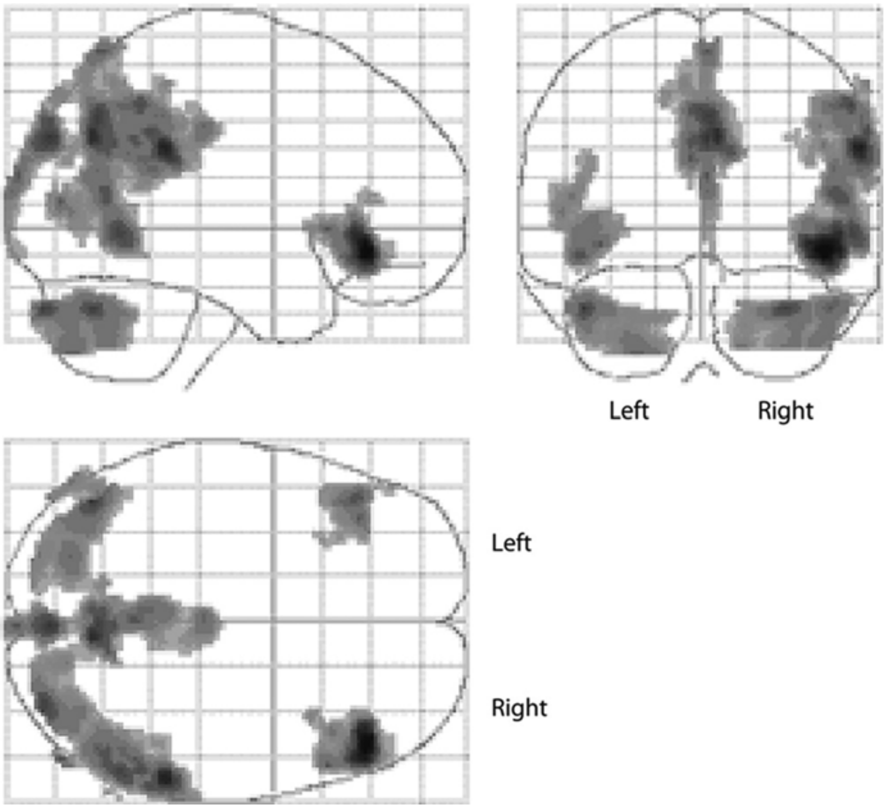

Fig. 50.5 FDG PET imaging of chronic traumatic brain injury in boxers. Statistical parametric mapping analysis showing the group differences between boxers and controls. Regions of decreased FDG uptake displayed on a glass brain are seen in the posterior cingulate cortex and the cerebellum, parieto-occipital, and frontal lobes (Broca's area) bilaterally (*shaded areas*) (Provenzano et al. 2010)

of the two groups. These different findings compared with the previous study of Turjanski et al., where lower uptake was found in the boxers' group compared to the Parkinson's disease group, were explained by the shorter disease duration of the posttraumatic parkinsonism in the Thai boxers (range 1–3 years compared to 6 years in the previous study). While both studies support the idea that cumulative chronic head trauma in boxers is an additional insult to the dopaminergic system, more research needs to be done in this context.

50.4.3 PET: Discussion and Future Perspective

The number of PET studies focusing on the consequences, at short or long term, of concussion in sports is very limited. Most of the research is reduced to the well-established FDG scans. However, the potential to investigate specific cellular processes involved in the pathophysiology of a disease is one of the main advantages of the PET technique and should be used in the future to achieve a better understanding of mTBI, particularly in sports, where people are at high risk to receive repeated concussions. In the last years several papers of interest have been published using different PET radiotracers for TBI, which can be considered as the starting point for its application also in the study of concussion in sports, i.e., mTBI.

One of these tracers is ^{11}C-flumazenil (FMZ), a marker for central benzodiazepine receptor expression. The binding of FMZ is used as an indicator of neuronal viability (Heiss et al. 1998). In the study of Shiga et al. (2006), the existence of lesions showing low uptake of FMZ was confirmed. This damage was always paired with abnormalities on the cerebral metabolic rate of oxygen, measured with ^{15}O-labeled gas ([^{15}O]CO, [^{15}O]CO_2, and [^{15}O]O_2) PET scan, without showing abnormal MRI scans. Areas with alterations in the cerebral metabolic rate of oxygen were also found without relation to FMZ. This suggests that FMZ PET could be useful to differentiate the hypometabolism caused by neuronal loss from the hypometabolism produced by other factors. In a more recent study significant bilateral reduction of FMZ uptake was found in the frontal medial gyrus, anterior cingulate gyrus, and the thalamus (Kawai et al. 2010). While these results are promising for the detection of selective neuronal loss, still more research is needed.

Due to the characteristics of symptoms in chronic stages of PCS and CTE, another interesting cell process to research about is the cholinergic system. A recent study has used [methyl-^{11}C] *N*-methylpiperidyl-4-acetate (^{11}C-MP4A) in patients with cognitive deficits in a chronic TBI stage (Östberg et al. 2011). ^{11}C-MP4A uptake, which reflects the activity of acetylcholinesterase, was shown to be reduced in several areas of the neocortex, more pronounced in the parieto-occipital region. It would be interesting to study athletes exposed to repetitive concussions to evaluate if cholinergic dysfunction correlates with the clinical symptoms of the patients.

Probably one of the most important cellular processes taking place in the pathophysiology of TBI and concussion is neuroinflammation. Microglia and astrocytes react in the acute phases of trauma and can become chronically activated. The role of activated microglia is crucial in the neuroinflammatory cascade after trauma and therefore was suggested as a sensitive biomarker for neuroinflammation detected with nuclear neuroimaging techniques (Cagnin et al. 2007). The most frequently used radioligand for this purpose is (R)-^{11}C-1-[2-chlorophenyl]-*N*-methyl-*N*-[1-methylpropyl]-3-isoquinoline carboxamide (^{11}C-PK11195). In recent studies with chronic TBI patients (up to 17 years after the initial trauma), significant whole brain increase of ^{11}C-PK11195 binding was found bilaterally in the frontal lobe, thalamus, left parietal lobe, right frontal lobe, hippocampus, putamen, midbrain, and pons (Folkersma et al. 2011). In another similar experiment, significant increases were located in the thalamus, putamen, occipital cortex, and posterior limb of the internal capsule (Fig. 50.6) (Ramlackhansingh et al. 2011). Based on the results of these studies, it seems that the use of microglia markers, such as ^{11}C-PK11195 or similar radioligands, could be an attractive method for detecting secondary damage

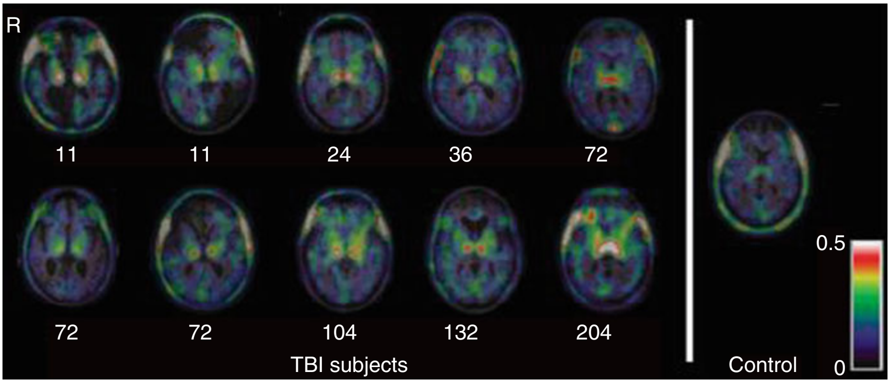

Fig. 50.6 Chronic microglial activation after TBI. Overlay images of the transverse T1 magnetic resonance imaging at the level of the thalamus superimposed with ^{11}C-PK11195 images of all TBI subjects and a representative control subject. *Numbers* indicate time in months from the time of TBI to PET scanning (Images illustrate the greater binding of ^{11}C-PK11195 in the thalamus of all TBI subjects. *R* right (Ramlackhansingh et al. 2011))

after head trauma and serve as an important marker to evaluate interventions toward inflammatory processes.

Overall, the number of studies focusing in concussion of athletes is scarce. However, it seems that the results obtained from the different experiments point to the possible development of functional impairment, even before they can be detected by standard neuroimaging techniques such as CT or MRI. As discussed above, there is a lack of correlation between loss of consciousness and the severity of the trauma. Together with the presence of inflammation even months after the initial trauma, it is recommended to increase the research on the risks of exposure to further head impacts, while the brain is still trying to recover from the previous one. This is especially relevant in the adolescence and young adulthood, where the annual rate of diagnosed concussions over the past 10 years in high school sports demonstrated an increase of 16.5 % annually (Lincoln et al. 2011).

50.5 Amyloid Beta and Traumatic Brain Injury

In recent years there has been a wide discussion on the link between traumatic brain injury and the subsequent onset of dementia of the Alzheimer's type. Deposits of amyloid ß-proteins were not only found in single cases of dementia pugilistica but could be seen in some cases of patients dying after only one episode of severe traumatic brain injury (Graham et al. 1996). Tang and colleagues, 1996, revealed a tenfold increase in the risk of Alzheimer's disease associated with apolipoprotein E ε4 in combination with a history of traumatic head injury, compared to a twofold increase in risk with apolipoprotein E ε4 alone, whereas head injury in the absence of an apolipoprotein E ε4 allele did not increase the risk (Tang et al. 1996).

Some authors do not support a potential relation between dementia and traumatic brain injury: Mehta et al. (1999) performed a larger prospective study of a Rotterdam-based cohort of 6,645 patients. They found no increased risk of dementia for patients with a history of head trauma. In addition, the apolipoprotein E ε4 allele did not modify this relationship.

50.6 Final Discussion

Although it is more than two decades since the first SPECT and PET studies on mild traumatic brain injury, the research involving concussion in athletes has been almost neglected during this time. The association between repeated head injuries and the risk to develop a neurodegenerative disease was pointed out almost in the beginning of the previous century. However, not much is known about the pathophysiology of repeated concussion in athletes. Most of the guidelines for the assessment of concussion in sports, such as the one of the 4th International Conference on Concussion in Sport held in Zurich in November 2012 (McCrory et al. 2013), are constructed based on the neuropsychological assessments, without the support of any neuroimaging techniques. Conventional structural imaging (CT or MRI) contributes little to the concussion evaluation, and PET or SPECT techniques are still in the early stages to be recommended in a different setting than research. Nevertheless, nuclear imaging techniques with access to specialized ligands having the potential to bind to specific receptors involved in the pathophysiology of concussion lie ahead of us for an exciting future.

Some conclusions can be drawn from the research conducted so far in TBI and be extrapolated to concussions in sports. First, in the acute phase of the concussion, there is a global decrease of perfusion in the brain that is not related to the level of consciousness, while CMRglc in the thalamus, brain steam, and cerebellum do relate with consciousness, measured with GCS. Therefore, the severity of a concussion, and the decision to remove an athlete from playing, cannot solely be decided by the loss of consciousness, as this does not represent the severity of the injury. In the same context, the absence of structural abnormal findings in CT or MRI does not reflect the characteristics of the concussion, while FDG PET seems to be more useful to explain neurological states. However, it is necessary to demonstrate the cost-effectiveness validity of FDG PET over other neuroimaging techniques or neuropsychological assessments. Also, the alterations involving hypometabolism (FDG), decrease of neuronal viability (FMZ), and increase of neuroinflammatory response (^{11}C-PK11195) are mostly located in the midbrain and thalamus. These structures are known to be especially susceptible to damage due to the biomechanical characteristics of the concussion (Bigler and Maxwell 2012). Additionally, other brain areas like the prefrontal and cingulate cortex were shown to be damaged or have an abnormal function in different studies. All of these areas are part of a common emotional network, and its dysfunction can be related to some of the cognitive impairments present in the post-concussive syndrome or the chronic traumatic encephalopathy.

As previously mentioned, a huge advantage of nuclear imaging techniques is the possibility to develop specific radioligands capable to address specific characteristics of a metabolic process. Therefore, there is a bright future for PET and SPECT in concussive injuries in sports helping to better understand the cascade of reactions taking place after the injury. Neuroinflammatory processes scanned with ^{11}C-PK11195 or the study of cholinergic systems with ^{11}C-MP4A is only one step in this direction. Many further investigations can be developed if other targets are addressed, such as tau proteins or beta-amyloid deposits, known to be related with the pathophysiology of chronic traumatic encephalopathy (Gavett et al. 2011b).

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Injury Risk in the Olympic Games

51

The Injury and Illness Surveillance During the XXIX 2008 Summer and the XXI 2010 Winter Olympic Games

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Abstract

The protection of an athlete's health is an important task for the International Olympic Committee (IOC). Systematic injury and illness surveillance monitors trends over long periods of time, and the identification of high-risk sports, including their most common and severe injuries and illnesses, provides valuable knowledge to reduce the risk of occurrence. During the XXIX Summer Beijing 2008 and XXI Winter Games Vancouver 2010, comprehensive recording of injuries and illnesses through the medical staff of the participating National Olympic Committees and the sports medicine clinics at the different Olympic venues revealed that at least 7–11 % of all athletes incurred an injury or suffered at least from one illness occurrence during the Games. The incidence of injuries and illnesses varied substantially between sports. In the future, risk factor and video analyses of injury mechanisms in high-risk Olympic sports are essential to better direct injury prevention strategies. Monitoring the athlete's health during the pre-Game period through periodic health exams will be important to optimize health protection.

51.1 Introduction

With over 10,000 expected athletes from more than 200 countries, the XXX London 2012 Olympic Games were the largest sport event ever. More than 2,500 athletes participated in the last XXI Winter Olympic Games held in Vancouver in 2010. The Games are spectacular media events, not just for the audience but probably even more for the participating countries and the athletes themselves (Ljungqvist et al. 2009; Junge et al. 2009; Engebretsen et al. 2010). Protection of an athlete's health is an important task for the International Olympic Committee (IOC) (Ljungqvist et al. 2009). Systematic injury and illness surveillance monitors trends over long periods of time, and the identification of high-risk sports, including their most common and severe injuries and illnesses, provide valuable knowledge to reduce the risk of occurrence (Junge et al. 2009; Engebretsen et al. 2010). Following the four-stage model of van Mechelen et al. (van Mechelen et al. 1992), analyzing the extent of a problem such as high injury and/or illness risk in a specific population, is the first step in the development of effective prevention strategies.

The IOC injury and illness surveillance system, developed in cooperation with the International Sports Federations (IFs) and National Olympic Committees (NOCs), was successfully implemented in the 2008 Beijing (injury surveillance only) (Junge et al. 2009) and in the 2010 Vancouver Olympics (injury and illness surveillance) (Engebretsen et al. 2010) and has been further developed in the 2012 London and 2014 Sochi Olympic Games (Steffen et al. 2011).

Major sport events, such as the Olympic Games, constitute an ideal environment for performing projects like these. The study population is a relatively homogenous group in terms of skill level, and the study period is defined by the event itself, which usually is characterized by a high standard of environmental factors (e.g., safety of venues, optimal preparation of courses/slopes) (Junge et al. 2006; Alonso et al. 2009). As early as in 1998, the Fédération Internationale de Football Association (FIFA) started to survey all injuries incurring during their competitions (Junge et al. 2004a, b, 2006; Yoon et al. 2004), and other major sports federations followed the role model of FIFA's Medical Assessment and Research Centre (F-MARC) (Alonso et al. 2010; Mountjoy et al. 2010; Bahr & Reeser 2003; Fuller et al. 2008; Langevoort et al. 2007). In 2004, an injury surveillance system was applied for all team sports during the Summer Olympic Games in Athens (Junge et al. 2006). Based on these experiences, a group of experts, gathered by the IOC, developed an injury surveillance for multisport events (Junge et al. 2008), and the IOC performed, for the first time, an injury surveillance during the 2008 Beijing Olympic Games (Junge et al. 2009).

For Olympic winter sports compared to summer sports, much less knowledge on injury risk exists. Furthermore, sports such as snowboard and freestyle skiing are relatively recent additions to the traditional Olympic winter sports. In 2006, the International Skiing Federation (FIS) introduced an injury surveillance system for world-class skiing athletes in an attempt to record injuries in all FIS sport disciplines throughout a whole World Cup season and thereby monitor injury trends over time (Flørenes et al. 2011). As the second step in the development of injury preventive strategies is to map the causes of injuries, new projects have been conducted to identify intrinsic and extrinsic risk factors and injury mechanisms (Bere 2011; Bakken 2011; Steenstrup 2011), but many questions on how to protect high-risk athletes earlier in their careers still remain unanswered. Similarly, there is only a limited number of papers available aimed at investigating illnesses during single (Alonso et al. 2010; Mountjoy et al. 2010; Dvorak et al. 2011) or multisport events (Engebretsen et al. 2010; Derman 2008).

Continuous injury and illness surveillance during these major sport events will build a foundation for providing evidence for health development in sports and for the development of injury prevention programs. (Ljungqvist et al. 2009) The aim of this chapter is to summarize the occurrence of injuries and illnesses in the previous two Olympic Games (Junge et al. 2009; Engebretsen et al. 2010) and to enable the national team physicians to be better prepared for the future Olympic Games. Practical implications and suggestions for further research to protect the athletes' health will be given.

51.2 Methods

The IOC injury surveillance system for multisport events was developed in 2008 (Junge et al. 2008). The injury definition and data collection procedures were successfully implemented during the Olympic Games 2008 in Beijing (Junge et al. 2009). Based on the experiences from athletics (Alonso et al. 2010) and aquatic sports (Mountjoy et al. 2010), surveillance was expanded to also include the registration of illnesses occurring during the Olympic Winter Games 2010 (Engebretsen et al. 2010).

In Beijing and Vancouver, all National Olympic Committees' (NOC) head physicians were asked to participate in the Olympic surveillance studies and to report daily the occurrence (or nonoccurrence) of newly sustained injuries (only in Beijing) and illnesses on a standardized reporting form. In addition, information on all athletes treated for injuries and illnesses by the Local Organizing Committee (LOC) medical services were retrieved from the available medical centers located at selected venues.

51.2.1 Implementation of Data Collection

Six months before the 2008 Beijing and the 2010 Vancouver Olympic Games, the NOCs were informed about the study by the IOC. The medical representatives of all participating countries received a booklet with detailed information about the study, including the injury and illness forms to be filled out. Two days before the opening of the Games, NOC physicians, physiotherapists, and the medical representatives of the Summer and Winter Olympic International Sports Federations were invited to a meeting covering the details of the studies. All NOC head team physicians were asked to submit a daily injury and illness form. In addition, athletes seen for an injury or illness in the venue medical stations or the central clinics were reported through the central clinic database. To encourage compliance with the reporting procedures during the Games, members of the study group were in frequent personal contact with the NOCs, having more than 50 (Beijing 2008) or 10 athletes (Vancouver 2010) participating (Junge et al. 2008, 2009; Engebretsen et al. 2010).

51.2.2 Injury and Illness Report Form

The report form required documentation of the following information: athlete's accreditation number, sport discipline/event, date and time of occurrence, time, competition/training, injured body part, injury type, causes, and estimated time loss. The illness part of the report form was located directly below the injury part on the same page and followed a similar design. The illness documentation included the diagnosis, affected system, main symptom(s), and cause of illness, as well as an estimate of time loss. Detailed instructions on how to fill out the form correctly were given in the booklet with example for injuries and illnesses. Daily injury information was also received from the polyclinic in the Olympic Village. Injury and illness report forms were distributed to all NOCs in the following languages of choice: Chinese, English, French, German, Russian, Spanish, and Arabic (Junge et al. 2008, 2009; Engebretsen et al. 2010).

51.2.3 Definition of Injury and Illness

An athlete was defined as injured or ill if he/she received medical attention regardless of the consequences with respect to absence from competition or training. Following the IOC injury surveillance system, an injury should be reported if it fulfilled the following criteria: (1) musculoskeletal complaint or concussion, (2) newly incurred (preexisting, not fully rehabilitated should not be reported) or reinjuries (if the athlete has returned to full participation after the previous injury), (3) incurred in competition or training, and (4) incurred during the XXIX Summer Olympic Games 2008 (August 9–24, 2008) or the XXI Winter Olympic Games 2010 (February 12–28, 2010). The definition of an illness was developed based on the injury definition to ensure compatibility with the existing injury protocol and ease of understanding for the participating physicians. An illness was defined as any physical complaint (not related to injury) newly incurred during the Games that received medical attention regardless of the consequences with respect to absence from competition or training (Junge et al. 2008, 2009; Engebretsen et al. 2010).

All information was treated strictly confidential, and the injury reports were made anonymous after the Olympic Games. Ethical approval was obtained by the Norwegian Regional Committee for Medical Research Ethics, Norway.

51.3 Results

51.3.1 Response Rate and Coverage of the Athletes

All NOCs with more than 50 (Beijing) or 10 registered athletes (Vancouver) were included in the analysis of response rate, and these countries represented more than 94 % of all participating athletes. In Beijing, the head physicians of all the participating NOCs returned a total 1050 injury report forms (72 %). In addition, 264 injury report forms were received from medical stations at the different Olympic venues and through daily reports from the polyclinic in the Olympic Village (Junge et al. 2009). Throughout the 17 days of the Vancouver Olympics, the 33 participating NOCs (with more than 10 athletes) returned a total of 461 out of a maximum of 561 forms to the project group (mean 82 %, range 77–89 %) (Engebretsen et al. 2010). For both Olympic Games, the response rate of completed forms by the NOC head physicians decreased with the size of the NOCs.

Table 51.1 Comparison between 2008 Beijing and 2010 Vancouver (injuries)

	Beijing 2008	Vancouver 2010
Participating athletes	1,0977	2,567
Injuries (per 1,000 athletes)	1,055 (96.1)	287 (111.8)
Most common diagnosis	Ankle sprains (7 %), thigh strains (7 %)	Concussions (7 %)
Most affected locations	Trunk (13 %), thigh (13 %), head/neck (12 %), knee (12 %)	Head/neck (16 %), knee (14 %), thigh (7 %)
Most common mechanisms	Contact with another athlete (33 %) Overuse (22 %) Noncontact (20 %)	Contact with another athlete (15 %) Contact with a stagnant object (22 %) Noncontact (57 %)
Expected time-loss injuries	50 %	23 %[a]
Competition/training injuries	73–27 %	46–54 %
High-risk sports (injuries per 100 athletes)	Football, taekwondo, field hockey, handball, weightlifting	Snowboard cross, freestyle aerials and cross, bob, ice hockey
Low-risk sports (injuries per 100 athletes)	Canoeing/kayaking, diving, rowing, sailing, synchronized swimming, fencing	Nordic skiing disciplines, curling, speed skating

[a]This figure is underestimating the number of time-loss injuries as the response rate to this information was low and many of the injuries were of severe outcome, without estimated time loss registered (more details in the Vancouver paper) (Engebretsen et al. 2010)

51.3.2 Incidence of Injuries

In Beijing, a total of 1,055 injuries were reported among 10,977 athletes, equivalent to an incidence of 96.1 injuries per 1,000 registered athletes (Junge et al. 2009). Among the 2,567 registered athletes (1,045 females, 1,522 males) in Vancouver, a total of 287 injuries were reported resulting in an injury rate of 111.8 injuries per 1,000 registered athletes (Engebretsen et al. 2010). On average 10–11 % of the registered athletes sustained at least one injury (Table 51.1).

51.3.3 Injury Risk in Different Sports

The incidence of injuries varied substantially among the different sports, both in Beijing and in Vancouver (Table 51.2). In relation to the number of registered summer sport athletes, the risk of sustaining an injury was highest for football, taekwondo, field hockey, handball, weightlifting, and boxing in Beijing (all ≥15 % of the athletes) (Junge et al. 2009). In Vancouver, injury risk was highest for bobsleigh, ice hockey, short track, alpine, and freestyle and snowboard cross (15–35 % of registered athletes were affected in each sport). Every 5th female athlete was injured in bobsleigh, ice hockey, snowboard cross, and freestyle cross and aerials, while the highest risk sports for male winter sport athletes were short track (28 % of registered male athletes), bobsleigh (17 %), and ice hockey (16 %) (Engebretsen et al. 2010).

Table 51.2 Injury distribution of injuries from selected sports registered during the 2008 Summer Olympics ($n=1055$ injuries) and 2010 Winter Olympics ($n=287$ injuries)

Olympic sports	Registered athletes	Number of injuries	Percentage of all injuries	Percentage of athletes injured
Athletics	2132	241	18.3	11.3
Swimming	1046	36	2.7	3.4
Rowing	548	10	0.8	1.8
Cycling	518	30	2.2	5.8
Soccer	496	156	11.8	31.5
Ice hockey	444	82	6.2	18.5
Sailing	400	3	0.2	0.8
Shooting	386	3	0.2	7.8
Judo	385	53	4.0	11.2
Field hockey	382	78	5.9	20.4
Wrestling	341	32	2.4	9.4
Handball	334	58	4.4	17.4
Canoeing/kayaking	324	4	0.3	1.2
Gymnastics	318	24	1.8	7.5
Alpine skiing	308	46	3.5	14.9
Cross-country skiing	292	9	0.7	3.1
Volleyball	287	23	1.7	8.0
Basketball	287	38	2.9	13.2
Boxing	281	42	3.2	14.9
Water polo	259	25	1.9	9.7
Weightlifting	255	43	3.3	16.9
Fencing	206	5	0.4	2.4
Biathlon	202	3	0.2	1.5
Equestrian	193	10	0.8	5.2
Baseball	189	21	1.6	11.1
Speed skating	176	5	0.4	2.8
Badminton	172	8	0.6	4.7
Table tennis	172	9	0.7	5.2
Tennis	168	10	0.8	5.9
Bobsleigh	159	32	2.4	20.0
Figure skating	146	21	1.6	14.3
Diving	145	3	0.3	2.1
Archery	128	9	0.7	7.0
Taekwondo	126	34	2.6	27.0
Softball	119	16	1.2	13.4
Triathlon	109	10	0.8	9.2
Short track	109	5	0.4	9.0
Luge	108	2	0.2	1.9
Synchronized swimming	104	2	0.2	1.9
Curling	100	4	0.3	4.0
Beach volleyball	96	8	0.6	8.3
Modern pentathlon	71	4	0.3	5.6
Snowboard half pipe	69	9	0.7	13.0
Freestyle cross	68	13	1.0	19.0

(continued)

Table 51.2 (continued)

Olympic sports	Registered athletes	Number of injuries	Percentage of all injuries	Percentage of athletes injured
Ski jumping	67	3	0.3	4.5
Snowboard slalom	59	4	0.3	6.8
Freestyle moguls	57	1	0.1	1.8
Snowboard cross	57	20	1.5	35.0
Nordic combined	52	1	0.1	1.9
Skeleton	47	3	0.3	6.4
Freestyle aerials	47	9	0.7	19.1
Total	*1,3544a*	*1,320b*	*100*	*10.8*

[a]Missing 20 athletes
[b]Missing 22 injuries (Beijing)

51.3.4 Injury Location and Type

In Beijing, the distribution of injuries was as followed: about half of the diagnoses ($n = 600$; 54 %) affected the lower extremity, 20 % were related to the upper extremity ($n = 218$), 13 % to the trunk ($n = 149$), and 12 % to the head/neck ($n = 133$). The thigh (13 %) and knee (12 %) were most commonly injured, followed by the lower leg, ankle, and head injuries (9 %), mainly diagnosed as skin lesions or contusions (Junge et al. 2009).

In Vancouver, for both genders, the face, head, and cervical spine (female 20 %, male 21 %) and knee (female 16 %, male 11 %) were the most prominent injury locations, followed for female athletes by wrist (8 %) and for male athletes by thigh (10 %). Contusions (female 32 %, male 26 %), ligament sprains (female 20 %, male 11 %), and muscular strains (female 8 %, male 16 %) were the most common injury types. In alpine and freestyle snowboarding, 22 out of 102 injuries (22 %) affected the head/cervical spine, and one fourth of all injuries the knee (24 %). Twenty concussions were reported, affecting 7 % of the registered athletes. These athletes participated in the snowboard (boarder cross and half pipe) and freestyle disciplines (ski cross and aerials), in bobsleigh, in short track, in alpine skiing, and in ice hockey. A catastrophic injury with death as outcome occurred in luge (Engebretsen et al. 2010).

51.3.5 Injury Mechanism and Circumstances

In Beijing, one third of the injuries ($n = 282$; 33 %) were caused by contact with another athlete. Noncontact trauma ($n = 172$; 20 %) and overuse either with gradual ($n = 78$; 9 %) or sudden onset ($n = 110$; 13 %) were also frequent causes of injury (Junge et al. 2009). In Vancouver, the three most common reported injury mechanisms were a noncontact trauma ($n = 57$, 23 %), contact with a stagnant object ($n = 54$, 22 %), and contact with another athlete ($n = 36$, 15 %) (Engebretsen et al. 2010).

While 73 % of the injuries in Beijing occurred in the competition (Junge et al. 2009), injuries in Vancouver were evenly distributed between official training

(54 %) and competition (46 %) ($P = .18$). However, a specifically high proportion of training injuries was found for the three snowboard disciplines, freestyle cross skiing, short track, figure skating, skeleton, and biathlon. In these sports, three out of four injuries occurred outside of the competition (Engebretsen et al. 2010).

51.3.6 Injury Severity

In Beijing, about half of the injuries were expected to prevent the athletes from further training or competition ($n = 419$; 50 %). Physicians estimated that one third of the injuries would result in an absence from sport with up to 1 week (Junge et al. 2009). In Vancouver, of the 287 injuries, 65 (23 %) were expected to result in a time-loss situation for the athlete. Of those with expected time loss, 11 injuries (17 %) had an estimated absence from training or competition of more than 1 week (Engebretsen et al. 2010).

51.3.7 Incidence and Distribution of Illnesses (Registered in Vancouver Only)

Among 173 out of 2,567 athletes (7 %) in Vancouver, a total of 185 illnesses were reported, resulting in an incidence of 72.1 illnesses per 1,000 athletes. Illnesses were reported from a variety of sports. In skeleton, figure and speed skating, curling, snowboard cross, and biathlon, every 10th athlete suffered from at least one illness. The majority of the illnesses ($n = 113$, 63 %) affected the respiratory system, mostly observed in the ice skating and Nordic skiing disciplines. As a consequence, the illness cause was most often classified as an infection ($n = 111$, 64 %) affecting athletes in mainly the same sports as mentioned above. The most frequent diagnosis was upper respiratory tract infection (pharyngitis, sinusitis, tonsillitis) ($n = 61$, 54 %) (Engebretsen et al. 2010).

51.4 Discussion

This presentation summarizes the first two IOC surveillance projects on the injury and illness occurrence of athletes during the 2008 Beijing Summer and 2010 Vancouver Winter Olympic Games with all sports of the Games included. The principle findings were that at least 10–11 % of the athletes incurred an injury during the Olympic Games and 7 % of the athletes an illness. Although variations in injury risk have been detected, it can be concluded that specifically some team sports (such as soccer, ice hockey, field hockey, handball, and basketball), martial art or weight class sports (such as taekwondo, boxing, and weightlifting), and speed sports (such as bob and the skiing and snowboard disciplines) have a relatively higher injury risk. Upper respiratory tract infections, the major cause of reported illnesses in Vancouver, were specifically suffered by Nordic skiing and skating athletes.

51.4.1 Incidence and Distribution, Type, and Cause of Injuries

In Vancouver, the injury incidence was with 111.8 injuries per 1,000 athletes (11.2 %) slightly higher than reported from the Summer Olympics in Beijing 2008 (96.1 injuries per 1,000 athletes, 9 2009.6 %) (Junge et al. 2009). This observed difference is most likely due to the differences in the sports themselves, since both IOC surveillance projects were conducted by the same research group using the same methodology to obtain data (Engebretsen et al. 2010).

As illustrated for winter sports by Torjussen and Bahr (Torjussen & Bahr 2006) and for summer sports by Junge et al. (2006, 2008), choosing the appropriate method to report the risk of injury in sports is a challenge if the aim is to compare the risk between different sports or disciplines where exposure may differ considerably. During major sport events, such as the Olympics, athletes can have, for example, 15 jumps in a high jump competition; 8 throws in a javelin competition; 1 ski run in a 50 km cross-country race; 5 runs in snowboard cross, several matches in ice hockey, soccer, or basketball; and only 1–4 starts in a 100 m sprint competition. Thus, as an alternative to relative injury risk where the risk is expressed as rate corrected for exposure, for example, injuries per run/matches, using the absolute injury risk is highly relevant for the present summary, where injuries and illnesses are expressed as the total number of injuries/illnesses per registered athletes for each sport/discipline (Engebretsen et al. 2010).

Having this in mind, athletics, soccer, and ice hockey caused the greatest portion of injuries in the 2008 Summer (Junge et al. 2009) and 2010 Winter Olympics (Engebretsen et al. 2010). Out of all injuries registered during both Games, 18 % of injuries occurred in athletics, 12 % in soccer, and 6 % in ice hockey. However, this does not mean that athletes in these sports are at the greatest risk of injury. The explanation is that these sports have a great number of competing participants.

The picture was slightly different when the number of injuries was calculated in relation to the number of participating athletes. In Beijing, the risk of sustaining an injury was highest for soccer, taekwondo, field hockey, handball, weightlifting, boxing, triathlon, and athletics (Junge et al. 2009). These findings are in accordance with literature (Junge et al. 2006; Alonso et al. 2010; Dvorak et al. 2011; Junge & Dvorak 2007, 2010; Greene & Bernhardt 1997; Martin et al. 1987). In Vancouver, freestyle and snowboard cross, bobsleigh, ice hockey, short track, and alpine skiing were the sports with the highest injury risk (Engebretsen et al. 2010).

Compared to high-risk summer sports, wherein, for instance, team sports, many of the injuries are expected to result from player-to-player contact, a lot of the winter sports are characterized by a high speed. Injury risk has also been documented to be high in freestyle and snowboard cross. To position themselves in the front through their heats while competing against three other skiers/riders, athletes had to pass several challenges, for example, turns, jumps, and waves (Flørenes et al. 2010a). Combined with the speed component, competing in heats may promote a risk-taking attitude for the athletes. In addition, body contact within the rules of the sport occurs and may force the athlete to unanticipated reaction, loss of control, and probably higher-risk situations (Flørenes et al. 2009).

On the other hand, the lowest injury risk during the Beijing Olympics was observed for water sports such as sailing, canoeing/kayaking, rowing, synchronized swimming, diving, and swimming (Junge et al. 2009), which is also in agreement with the literature (Greene & Bernhardt 1997; Martin et al. 1987; Cunningham & Cunningham 1996). The low injury risk for athletes competing in the Nordic skiing disciplines compared to alpine, freestyle, and snowboard athletes is not surprising as they are not exposed to high speed on icy surfaces with minimal protection (Flørenes et al. 2010a).

In line with a previous report (Flørenes et al. 2009), the knee and the head were the most frequent body parts injured among alpine and freestyle skiers and snowboarders, and the same picture was seen among summer sport athletes, too, where thigh, knee, lower leg, ankle, and head injuries were most commonly injured (Junge et al. 2009). Also, a concern should be that every 5th registered injury in the Winter Olympic Games affected the head, neck, and cervical spine, mainly diagnosed as abrasion, skin lesion, contusion, fracture, or concussion. In many cases, head and knee injuries result in long absence from training and competition, and the prevention of concussions and severe knee ligament sprains, including anterior cruciate ligament ruptures, is of significant importance. In Vancouver, a total of 20 concussions, constituting 7 % of all participating athletes, were diagnosed (Engebretsen et al. 2010). These figures are twice as high as reported from the Summer Olympic Games (Junge et al. 2009). In a national cohort, Emery et al. (Emery et al. 2010) found a high rate of concussions among young elite ice hockey players. To sum up, except for skiing (Flørenes et al. 2009, Bere), snowboarding (Torjussen & Bahr 2006; Flørenes et al. 2010a), freestyle skiing (Steenstrup), and ice hockey (Gröger et al. 2010) [Emery], there is little data available on winter sports regarding elite athletes' injury risk.

51.4.2 Incidence and Distribution, Type, and Cause of Illnesses (Registered in Vancouver Only)

The illnesses incidence in Vancouver was 72.1 illnesses per 1,000 athletes (7.2 %). These findings are consistent with data from athletics (7 %) (Alonso et al. 2010), aquatics (7 %) (Mountjoy et al. 2010), and football (12 %) (Dvorak et al. 2011). Almost two thirds of the illnesses affected the respiratory system (62 %) and caused by infections (64 %), which is a higher rate than reported in swimming (respiratory system 50 %, infection 49 %) (Mountjoy et al. 2010).

Elite athletes are repeatedly exposed to cold air during winter training and competitions in addition to many inhalant irritants and allergens all year round, situations which may expose them to an increased risk for upper respiratory tract infections (Helenius et al. 2005; Spence et al. 2007). Airway inflammation has often been shown to affect elite swimmers, ice hockey players, and cross-country skiers (Helenius et al. 2005). Improving the education of athletes and their entourage on infectious disease prevention strategies as well as the provision of more hand sanitization stations at training and competitive venues should lead to a decrease in this problem.

51.4.3 Practical Implications and Further Research

Before preventive measures can be suggested, risk factors and mechanisms need to be characterized (van Mechelen et al. 1992). For example, whether an injury in freestyle cross occurs in a landing after a jump, resembling the boot-induced anterior drawer mechanism with deep knee flexion, or is due to collisions with other skiers or the skier coming out of balance by fighting for a better positioning in the course needs to be investigated (Flørenes et al. 2010b). In addition, slope, snow, and weather conditions, the athlete's speed, as well as equipment may play an active role in the inciting event of an injury (Bere 2011 events). A recent report describing situations leading to ACL injuries in World Cup alpine skiing revealed that individual technical errors and inappropriate tactical choices were the dominant risk factors (Bere 2011). In another systematic video analysis of 19 injury cases among elite snowboard riders, jumping appeared to be the most challenging situation in snowboard cross, where a technical error at takeoff was the primary cause of the injuries (Bakken 2011). These studies implicate that close evaluations are necessary on course design and setting, race conditions, visibility and speed, and other technically difficult obstacles, such as height and distance between jumps. Future research should also aim to explore the physiological and psychological requirements for these athletes (Steenstrup 2011). Also, by using video analysis and a model-based image-matching technique, detailed information on joint kinematics can be obtained from uncalibrated injury video recordings (Krosshaug et al. 2005). This approach will help to better understand injury mechanisms. The IOC research group is now analyzing the most serious injuries in Vancouver in an effort to improve the knowledge on injury risk factors and mechanisms in high-risk sports. A similar project will be started after the London Games to analyze high-risk summer sports.

As the cause of injury varied substantially between sports, successful preventive strategies need to be tailored to the respective sport and athlete at risk (Junge et al. 2009; Steffen & Engebretsen 2010). Based on the experiences from the Vancouver Olympics, where more than half of the injuries in the bobsleigh run and skiing/snowboarding slopes incurred as a result of contact with a stationary object, preventive measures need to address the importance of creating safe sports arenas (optimal preparation of the skating ring, bobsleigh run, freestyle, and snowboard courses/pipes). In addition, the high proportion of training injuries in the skiing and snowboarding speed disciplines may suggest additional training runs and optimizing training facilities. The effect of these potential measures to reduce injury risk has to be monitored in upcoming Games.

The IOC and other major international sports federations, such as the International Football Association (FIFA) (Dvorak 2011), the International Aquatic Federation (FINA) (Junge et al. 2004b), and the International Association of Athletics Federations (IAAF) (Alonso 2010), have extended their injury surveillance in a second step to also include illnesses monitoring. In addition, the IOC is currently developing a periodic health exam (PHE) system, which will be offered to the NOCs prior to future Olympic Games. This should improve pre-Game knowledge both on injuries and illnesses and will help NOCs to maximize the health protection of their elite athletes (Ljungqvist et al. 2009).

After the 2010 Olympic Games in Vancouver, the IOC has initiated a new project together with the IFs and the NOC (Ljungqvist et al. 2009; Steffen et al. 2011). The aim of the Health, Safety and Security (HSS) survey is to identify and, in turn, eliminate risk factors which could potentially be harmful for Olympic athletes. Each federation shared their data on athletes' risk exposure, technical development and equipment evolution, venue safety procedures, rule change mechanisms, and determination of athlete eligibility. The IOC and the IFs are optimistic that this survey will not only increase the awareness on injury prevention but also facilitate the introduction of tailored measures to prevent injuries and illnesses in each sport and discipline. A new IOC consensus statement on thermo and altitude challenges in the elite athlete will be published soon.

As a new initiative to early address the next generation of future Olympic athletes, the IOC has created a new sporting event for young athletes. The first Summer Youth Olympic Games (YOG) were held in Singapore in August 2010, and the first Winter Youth Olympic Games have been arranged in Innsbruck, Austria, in January 2012. These and future major youth sport events will bring together around 5,000 athletes, aged 14–18, from all over the world to participate in high-level competitions. The program of the recent YOGs included all the sports scheduled on the 2012 and 2014 Olympic Games, but with a limited number of disciplines and events. A recent literature review revealed that little is known about the injury risk of the young athlete competing at high-level sports (Steffen & Engebretsen 2010). Consequently, a comprehensive injury and illness surveillance, based on the IOC model for previous Olympic Games, has been initiated during the 9 days of the 2012 first Winter Youth Olympic Games.

In London 2012, the IOC with the NOC and IF continued running the injury and illness surveillance system. As in Beijing (Junge et al. 2009) and Vancouver (Engebretsen et al. 2010), the monitoring of the athletes' health will enable researchers and clinicians to follow the injury and disease trends in the various sports and continue the premier goal of the IOC: to protect the health of the athlete. The message from this and other long-term projects initiated by the IOC and the IFs is that *we* need to monitor the development of injury and illness rates over several years to identify potential risk factor and mechanisms for injury and illnesses in disciplines and sports. By acquiring new knowledge on injury trends, we can optimize and target future research on injury risk factors, mechanisms, and, finally, prevention. The key to a meaningful study of epidemiology lies in a well-organized procedure for data collection with coordinated efforts from sports medicine professionals, coaches, and athletes, combined with systematic subsequent analyses.

Conclusion

The present data collection procedures were accepted by the medical staff of the National Olympic Committees as demonstrated by the high response rates of returned injury and illness forms. At least 10–11 % of the athletes incurred an injury during the XXIX Summer or XXI Winter Games, and 7 % of the winter sport athletes suffered at least from one illness occurrence. The incidence of injuries and illnesses varied substantially between sports. In the future, risk factor and video analyses of injury mechanisms in high-risk Olympic sports are essential to better direct injury prevention strategies. Pre-Game monitoring will be an essential part of athlete's medical support.

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The Paralympic Athlete

52

Herman Holtslag and Rienk Dekker

Contents

Abstract

This chapter discusses elite sports participation by people with a (motor) disability. Successively, the history of the Paralympic Summer and Winter Games, as the main elite sporting events, which also focus on the International Paralympic Committee (IPC), and counseling of athletes with a disability are discussed. Furthermore, injuries in the disabled athlete, doping, and classification of athletes are described.

52.1 History of the Paralympic Games

In 1948, Sir Ludwig Guttmann, a neurologist from England, organized the Wheelchair Games in the British Stoke Mandeville, at the time of the London Olympics. By organizing these games, Sir Guttmann aimed to improve the quality of life of the British

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wounded from World War II (Vanlandewijck and Thompsonl 2011). In 1952 the games evolved into an international event. Besides participants from Great Britain, Dutch athletes also took part. This effectively marked the beginning of the International Paralympic Games. At the Olympic Summer Games in 1960 in Rome, a definitive link was established with the Paralympics. Immediately after the Olympics Games, 400 disabled athletes from 23 countries participated in eight sports. From 1988, the Paralympics was held in the same accommodation and cities as the Olympics. At the Paralympic Games in London 2012, there were 4,200 active athletes.

The Paralympic Winter Games were first held in 1976 and took place in Omsköldsvik, Sweden. Since then, these games are also held every 4 years.

The international organization, since 1989, responsible for the Paralympic Games is the IPC. The IPC is a nongovernmental organization based in Bonn, Germany, and has as one of its main responsibilities the organization of the Paralympic Games and Paralympic Winter Games (www.paralympic.org).

52.2 Counseling of Elite Athletes with a Disability

Counseling and helping athletes with a disability essentially does not differ from counseling and helping able-bodied athletes. However, specific knowledge and skills are required that not every physician has mastered. Often a sports physician is involved. In addition to his or her expertise in the field of injuries of the musculoskeletal system, the sports physician may act as a general practitioner, treating everyday illnesses, and can offer some psychological support. The sports physician is also a team player and coordinates, from the health perspective, the effort of the physiotherapy, sports technician, trainer, coach, and athlete itself. Furthermore, in addition to the role and capacities of the sports physician, there are a number of other requirements concerning the counseling of elite athletes with a disability. Expertise and knowledge of the specific diagnosis and the concomitant disabilities are conditional and can be contributed by a rehabilitation physician. This predominantly concerns the diagnoses: spinal cord injury (33 %), cerebral palsy (20 %), amputation (10 %), visually impaired (20 %), and the so-called les autres or others (17 %). The latter category includes athletes with a physical disability which do not strictly fall under a specific category, such as athletes with dwarfism, multiple sclerosis, or limb defects caused by "thalidomide."

The rehabilitation physician coordinates a large multidisciplinary team, aiming to solve all possible issues concerning diagnosis-specific problems, concerning orthotics and prosthetics, as well as other sports-specific aids. Also the rehabilitation physician is involved in classification (see paragraph 52.5).

Cooperation between a sports physician and a rehabilitation physician serves as the ultimate solution to optimally counsel and help the elite athlete with a disability. In addition, there are often a team manager, a trainer, and in some cases a video analyst involved. In the Paralympic Village, there is also an orthopedic workshop available and accessible for all athletes.

The formal roles of the sports physician and/or the rehabilitation physician are comprehensive. Important aspects in preparation phase toward the games are to:

- Conduct medical examinations of elite athletes with a disability.
- Provide a source of information and expertise in injury treatment.
- Control classification and medication as well as doping (prevention).
- Offer medical advice to other physicians, coaches, physiotherapists, etc. involved.
- Liaise with physicians and medical committees of the sports unions.
- Visit centralized training for building and maintaining the network with athletes and coaching.
- Compose and manage an adequate pharmacy.
- Prepare thematically structured meetings with supervisors.
- Occasionally participate in meetings of the project team (i.e., *Chef de mission* and his/her team).

  During the games the tasks of the sports physician and rehabilitation physician are to:

- Make an on-site inventory of the possibilities for medical treatment.
- Have knowledge of the different sporting venues.
- Organize daily consultations, discussing issues like climate, acclimatization (jet lag), nutrition, hydration, hygiene, whereabouts, doctor's bag, pharmacy, and materials (cooling vests, scales, massage tables, sports drinks, etc.).
- Visit games with a high risk of injuries for the athlete.
- Perform surgery.
- Be available for 24 h a day, 7 days a week for counseling in case of medical problems.
- Assist athletes in their classification, doping, etc.

  After the games the physicians contribute by:

- Providing information of injuries of athletes to other involved physicians
- Contributing to the evaluation

52.3 Injuries

Besides many advantages, sports participation also has disadvantages, like the occurrence of sports injuries. Epidemiological data on injuries in athletes with disabilities are not widely available. From the scarcely available literature, however, it can be deduced that the incidence of sports injuries and the injury patterns in the disabled population are comparable to the able-bodied population. In addition, there are specific injuries, linked to the nature of the disability of the athlete. For example, in wheelchair athletes, frequent shoulder pain occurs, and the severity of the symptoms seems to be related to the frequency of sports and the chosen type of sports. Intensive sports thereby increases the likelihood of injury. The treatment of these injuries focuses on optimizing the wheelchair ergonomics, exercise therapy to improve function of shoulder muscles and improve mobility of the shoulder girdle. Finally, in the case of impingement, injection treatment or eventually a surgical therapy may be applied.

Wheelchair athletes also frequently suffer from hand injuries. Bruises, wounds, and blisters occur repeatedly following sudden intense contact with the wheels or tires. Use of appropriate gloves is essential. Also regularly impingement of nerves are identified, especially the median and ulnar nerves. Optimal wheelchair ergonomics, good movement techniques, well-dosed splint therapy, and, under a strict indication, use of injection therapy with corticosteroids or surgical release may serve as a treatment option (Goosey-Tolfrey 2010).

Finally, also skin problems (wounds and pressure sores) may occur, for example, resulting from sports practice. These skin problems can be caused by the action of high shear and compressive forces during exercise, in combination with a higher body temperature and high sweat production. Regularly lifts (lifting body) and optimal wheelchair ergonomics are of preventive value.

An example of the specific problems occurring during sports participation by paraplegic concerns heatstroke. As a result of dysregulation of the autonomic nervous system, resulting in a reduced skin blood flow and sweating, and also the absence of muscle pump function in the legs, there is a risk of hyperthermia on exertion (heatstroke) (Brukner and Kahn 2007). Dizziness, overall (muscle) weakness, headache, and (other) autonomic dysregulation phenomena occur. Prevention is possible by a good fluid intake and acclimatization to the environment in case of climate change. In case of an actual heatstroke, cooling the athlete is important in combination with loosening tight clothing and rehydration, where possible, orally, if necessary by infusion.

Another category of athletes with disabilities that has to deal with sports injuries is amputees (Bragaru et al. 2011). Muscle pain and skin irritation of the stump and pain in the non-amputated leg may occur. The use of optimal prosthesis, specifically designed for sports participation, is important in the prevention and treatment of these problems. Sometimes application of specific physiotherapy, exercise therapy, or injection therapy is indicated.

Treating sports injuries in people with a disability requires insight into mechanisms of sports injuries, but also knowledge of the specific pathology that underlies the disability is conditional. Therefore, it is preferable to carry out the treatment by a multidisciplinary team, in which at least a rehabilitation physician, a sports physician, a sports physiotherapist, and orthotist participate.

52.4 Doping

Doping is a term for the use of performance-enhancing drugs in sports often to improve athletic performance. Another short and simple description of doping is "*prohibited substances and methods prohibited by the World Anti-Doping Agency* (*WADA*)." The WADA is an independent foundation created through a collective initiative led by the International Olympic Committee (IOC). WADA's mission is to lead a collaborative worldwide campaign for doping-free sports by publishing annually (January first) an updated list of prohibited substances and methods.

A third, practical, definition of doping is "a violation of one or more provisions of the doping regulations." These are:

- Presence of prohibited substance(s) and/or method(s)
- (Attempted) use of prohibited substance(s) and/or prohibited method(s)
- (Attempted) poor cooperation
- Poor information provision
- (Attempted) manipulation and (attempted) possession
- (Attempted) trade
- (Attempted) administration
- Boosting (Eijsden-Besseling 2007). For handicapped sporters "boosting" is forbidden. Boosting is a method of inducing autonomic dysreflexia with the intention of enhancing performance in sports. It can be used by an athlete with a spinal cord injury to increase their blood pressure and is performed by causing a painful stimulus in the lower part of the body.

Since 2004, WADA is responsible for the preparation and publication of the list (www.wada-ama.org). The use of any prohibited substance by an athlete for medical reasons is possible by virtue of a therapeutic use exemption (TUE). It is an international standard identifying substances and methods prohibited in competition, out of competition, and in particular sports. Doping controls can be performed before and after the competition, essentially involving every athlete.

"Out-of-competition doping control" can be performed in athletes of national teams. Every athlete who wins a medal or breaks a national record should go through a doping control.

A confirmed abuse or offense of the doping regulations will lead to exile for competition for one or two years, sometimes for a lifetime.

52.5 Classification

First published in November 2007, the International Paralympic Classification Code helps support and coordinate the development and implementation of accurate, reliable, and consistent sports-focused classification systems and to detail policies and procedures common to classification in all sports.

A major component of sports for people with a physical disability is classification. The main goal of classification is to determine eligibility to compete equitably with other athletes with other kind of disabilities. The same dividing in groups for competition happens in elite sports, like gender differences, leagues, age categories, and weight classes like in judo and boxing.

Each sport for disabled has its own specific classification system which forms part of the rules of the sport. Classification is undertaken to ensure that an athlete's impairment is relevant to sports performance. An athlete must have an impairment that leads to a permanent and verifiable activity limitation (minimal disability) and be aware that pain syndromes are not eligible. As a consequence of these differences, an athlete may meet eligibility criteria in one sport, but may not be eligible to compete in another sport. For example, a cervical spinal cord lesion is a minimal disability in wheelchair rugby, and in tennis an amputation.

There are three international standards: athlete evaluation, procedures for the assessment of athletes and the allocation of sports class and sports class status; protests and appeals, procedures for the management of classification-related protests and appeals; and classifier training and certification, management of classifier training and certification.

The rules per sport differ completely and are the responsibility of each international sports federation. In general, the athletes are classified through a variety of processes depending on their disability and the sports they are participating in. Evaluation may include a physical or medical examination, a technical evaluation of how the athlete performs certain sports-related physical functions, and observation in and out of competition. The classification of team consists of three persons (minimal two): medical, paramedical, and sports technician (ex-sporter, trainer, or orthotist).

The original classification is in medical diagnoses: e.g., amputation, spinal cord lesion, cerebral palsy, visual handicap, and "the others." But again, it is the functional limitation being sports specific which determines in which class the athlete should compete. After an evaluation of athlete's classification, there are four different possibilities of their status: not eligible (NE), this designation indicates an athlete does not meet the minimal limitation for that specific sport; new (N), this designation indicates an athlete who has not undergone evaluation in order to obtain a sports class for international competition; it is the first time and often a national classification; review (R), this designation indicates an athlete who has obtained a classification, but may require further evaluation; and confirmed (C), this designation indicates an athlete who has undergone evaluation and has obtained a sports class for international competition and does not require further evaluation according to the classification rules of the international federation for that sport. Protests and appeals can be made by the athlete himself/herself or the accompanying team or other athletes. A reevaluation can be done after the competition.

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Official website of the paralympic movement. www.paralympic.org

World Anti-Doping Agency. www.wada-ama.org

Retraction Note to: The Expert View on Bicycling Injuries

48

Guy De Schutter

Retraction Note to:
Chapter 48 in: A.W.J.M. Glaudemans et al. (eds.), *Nuclear Medicine and Radiologic Imaging in Sports Injuries*, DOI 10.1007/978-3-662-46491-5_48

This chapter has been retracted at the request of the volume editor in agreement with the author. The chapter was examined following the COPE guidelines with regard to suspected plagiarism. The chapter was found to contain a substantial amount of verbatim material, without referencing, from the published article entitled "Bicycling Injuries" by Marc R. Silberman published 2013 in Current Sports Medicine Reports.

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