Chapter 6
Musculoskeletal Imaging

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Introduction

This chapter covers imaging of diseases that constitute the majority of musculoskeletal pathology: trauma, infection, neoplasm, metabolic bone disease, and arthritis. Uncommon musculoskeletal pathology, i.e., endocrine, genetic, dysplastic, and congenital disease, also require imaging but will not be discussed in this chapter. Despite a multitude of technologies available to image the musculoskeletal system, the starting point for bone pathology is typically conventional radiography (CR). Evaluation of soft tissue pathology is generally much better served by more advanced techniques, particularly magnetic resonance imaging (MRI), ultrasound (US), and at times computed tomography (CT), although occasionally CR provides significant value as well. Nuclear medicine studies are also useful in the evaluation of some musculoskeletal diseases. As with imaging any organ system, the choice of the appropriate study will depend on the clinical question to be addressed, the availability of the imaging modality, contraindications both absolute and relative, and the accuracy of the modality in balance with its risks and financial cost. With this in mind, we approach issues of imaging along lines of clinically suspected pathology. We start by reviewing the imaging armamentarium as it applies to the musculoskeletal system, including strengths and limitations, indications, and alternatives modalities.

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Imaging Modalities: Overview

Conventional Radiography/Plain Radiography

Although sometimes viewed as outdated and of little utility, radiographs serve as the starting point in the imaging diagnosis of many categories of suspected musculoskeletal pathology, especially trauma, osteomyelitis, focal mass lesions, and arthropathies. Plain radiographs are inexpensive, widely available, and rapidly and readily obtainable, even by the bedside if necessary.

Ultrasound

US can be used to visualize tendon pathology to good advantage, e.g., pathology of rotator cuff tendons and ankle tendons. US also is becoming a valuable tool in early inflammatory arthritis, particularly in cases of undifferentiated, unclassified inflammatory arthritis. Ultrasound can demonstrate inflammatory changes in the soft tissues, e.g., synovitis, tenosynovitis, enthesitis, and show evidence of joint destruction, i.e., erosions. In addition, application of Doppler US permits visualization of a lesion's vascularity.

US permits real time imaging, which allows for provocative maneuvers to detect pathology that is not well shown on static imaging studies. Examples of such provocative maneuvers using dynamic real time US include elbow flexion to elicit ulnar nerve subluxation at the cubital tunnel, hip flexion to show snapping of the iliopsoas tendon in the groin or the iliotibial band at the greater trochanter, and eccentric muscle contraction in the diagnosis of myofascial herniation.

US can also be used to guide interventional procedures for infection, arthritis, or soft tissue trauma (especially athletic overuse syndromes). Specifically, US can facilitate joint aspiration, drainage of fluid collections, and tissue biopsy, as well as injection of tendon sheaths, joints, bursae, and peritendinous soft tissues, e.g., the common extensor tendon origin at the lateral epicondyle of the elbow (tennis elbow), the gluteal tendons in the hip, and the plantar fascia at the foot.

US is operator-dependent, and nowhere is this more important than with musculoskeletal studies. This means that specifically trained imagers are needed for this type of examination. As mentioned in Chap. 1, US transducers have a narrow field of view, and so with today's scanning methods it is possible to overlook pathology. Despite these limitations, the role of musculoskeletal US continues to expand, especially the use of ultrasound guided procedures.

Computed Tomography

With the introduction of MRI, CT's role in musculoskeletal imaging has declined, particularly for soft tissue imaging. Nonetheless, CT has certain positive characteristics that make it a commonly used tool for some musculoskeletal pathology.

CT is most commonly used to evaluate bone trauma, particularly for acute fractures of the spine and pelvis, to plan operative reduction of complex fractures and fracture-dislocations, and to diagnose osseous nonunion of fractures. After intravenous contrast administration, CT also may be employed for diagnosis of soft tissue abscess. It should be noted, however, that MRI is generally better for abscess diagnosis, and so CT should be used only when MRI is unavailable or contraindicated. CT is highly sensitive for the presence of calcium and so can be used to detect and characterize matrix mineralization in osseous and soft tissue space occupying lesions.

Magnetic Resonance Imaging

MRI is a commonly performed musculoskeletal examination because it depicts soft tissue structures that cannot be resolved by other modalities. Specifically, these include ligaments, muscles, tendons, fibrocartilage, and fascia. MRI is thus the preferred modality to evaluate suspected internal derangement of joints, and certain types of extra-articular soft tissue pathology including traumatic muscle strains and contusions, soft tissue tumors and tumor-like entities, and soft tissue infectious processes most commonly abscess.

MRI has no imaging peer with respect to its ability to evaluate bone marrow. This permits diagnosis and characterization of pathology ranging from traumatic bone contusion and occult osseous fracture to marrow proliferative and marrow replacement diseases, both diffuse and focal. MRI also has the ability to demonstrate very early cortical abnormalities in cases of acute osteomyelitis, often earlier than other imaging modalities. While nuclear medicine bone scintigraphy performs almost as well, MRI has a slight edge, is more specific, and shows accompanying soft tissue abnormalities. Furthermore, MRI can visualize all of the features involved in soft tissue inflammation and joint damage in patients with inflammatory arthropathies, including active pathology early in the disease course that allows for administration of disease-modifying agents that may slow down progression and even reverse pathology.

Nuclear Medicine

Bone scintigraphy (BS), labeled WBC study, and PET and PET/CT are used most commonly in the evaluation of musculoskeletal pathology. These studies all routinely use very large fields of view that permit whole body evaluation for multifocal disease. As with numerous other nuclear medicine (NM) exams, a major advantage of BS, labeled WBC study, PET, and PET/CT is high sensitivity and high negative predictive value. On the other hand, these studies have low specificity, somewhat long exam length (especially with labeled WBC studies), and relatively limited ability to anatomically localize pathology. However, both specificity and anatomic localization of abnormalities have improved for both BS and PET with the addition

of co-registered CT. Single photon emission CT (SPECT) has aided in localizing lesions on BS. NM studies employed for musculoskeletal applications are generally less expensive than MRI, with PET and PET/CT being exceptions.

Trauma

Osseous Trauma

In most cases, the imaging evaluation of acute or subacute musculoskeletal trauma commences with plain radiographs. Although CR provides little useful information about the soft tissues, it is sufficient to diagnose most fractures. In addition, radiographs obtained in different positions can be used to exclude instability, e.g., flexion and extension views of the spine to exclude ligamentous abnormalities [1].

At times, clinical suspicion of a fracture may persist despite negative radiographs. In this case, there are several options depending upon the body part in question and the age of the patient. For example, in the case of adult elbow trauma, it is usually reasonable to treat a patient suspected of having a radial head fracture but with negative radiographs conservatively using presumptive immobilization and have the patient return for repeat radiographs a week to 14 days later [2]. At this time the bone resorption related to early healing would make the previously occult fracture more apparent [3].

A conservative strategy is inadvisable for some occult fractures, particularly in weight-bearing bones. Instead, depending upon the patient's age and the time delay between the traumatic event and their presentation, other modalities, though more costly, may speed diagnosis and allow earlier definitive treatment. Two imaging studies fall into this category, radionuclide BS and MRI. While it may be tempting to do a CT scan when plain radiographs are negative, CT has relatively poor performance for diagnosis of radiographically occult acute fractures compared with BS and MRI.

BS is less expensive than MRI, but the time delay between the traumatic event and patient presentation will affect its diagnostic accuracy. In younger patients, where the vascular supply to bone is unimpeded by atherosclerosis, BS will show at least 95 % of fractures at approximately 24 h after the trauma. In older patients 48–72 h may be required to achieve this type of sensitivity [4]. So, if not enough time has passed between the traumatic episode and evaluation, it is advisable to wait before obtaining the scan or to use MRI for diagnosis.

MRI has an excellent track record with respect to diagnosing occult fractures. Nearly all compression-type fractures are visible within a few hours on MRI. It should be pointed out, however, that avulsion-type fractures may be problematic because identification of osseous trauma on MR relies heavily on visualizing marrow space edema, much more so than trabecular discontinuity. Avulsion fractures are typically small and so commonly generate little edema and hemorrhage in the marrow space of either the parent bone or the avulsed fragment [5]. Furthermore,

since the avulsed fragment is often small and primarily cortical in nature, it may be difficult to identify on MRI. For example, MRI has relatively poor accuracy for diagnosis of Segond fractures of the lateral tibial rim at the knee. It is important that the requesting physician provide a detailed clinical history so that small avulsion fractures are not overlooked when an MRI has been chosen to evaluate the patient.

Although MRI is excellent for diagnosing acute occult fractures, it is by a large margin the most expensive modality in the diagnostic armamentarium. While some institutions have adopted a limited sequence, less expensive MR examination protocol to assess for fractures, this practice has not become widely used, at least in part because of constraints in billing and insurance reimbursements in today's medical practice environment.

In cases where initial radiographs are negative but there remains high clinical suspicion for occult fracture, both MRI and to a slightly lesser degree BS have a high degree of sensitivity for this diagnosis. The specificity of MRI is significantly greater given its ability to display other types of bone (e.g., osteoarthritis, bone contusion) [2] and adjacent soft tissue (e.g., muscle strain, muscle contusion, hematoma) pathology. American College of Radiology (ACR) appropriateness criteria very strongly favor MR over BS. For scaphoid and distal radius fractures, CT is recommended over BS when MRI is unavailable or contraindicated and the clinician is unable to or does not desire to immobilize the wrist and obtain 7–14 day follow-up radiographs [2] (Table 6.1).

Another problem with both BS and MRI is that many institutions, for economic reasons, do not offer these modalities 24 h a day or even every day of the week. If neither BS nor MRI is available, CT is the next best examination.

In contrast to extremity fractures, CT is used routinely in the initial evaluation of acute spine trauma. According to the National Emergency X-Radiography Utilization Study (NEXUS) criteria or Canadian C-Spine Rule (CCR) for cervical spine injury (CSI) criteria, MDCT with sagittal and coronal reconstructions is generally the preferred first imaging study for patients at high risk for fracture [1, 6]. This migration from CR to CT has occurred in part because CR only has 70 % sensitivity for cervical spine fractures. In pediatric patients less than 14 years of age where the incidence of spinal injury is lower, CR remains the initial imaging procedure of choice for acute spinal injury, in the cervical, thoracic, and lumbar spine in order to minimize radiation exposure [1, 6].

Generally, in cases where MDCT is used for initial assessment of acute spinal trauma, the entire spine should be imaged because severe trauma patients have a high incidence of multiple, noncontiguous injuries [1, 6]. It should be noted that thoracic and lumbar CT reconstructions derived from thoracic-abdomen-pelvic examinations are adequate substitutes for primary spine imaging, obviating the need for additional, formal spine CT imaging and thus avoiding unnecessary radiation dose to the patient.

Spine MRI is excellent for evaluation of patients in which there is clinical suspicion for spinal cord injury, cord compression, or ligamentous instability. Thus, MDCT of the cervical spine should be supplemented with an MRI in patients with posttraumatic myelopathy, with clinical or imaging findings worrisome for ligamentous injury,

Table 6.1 Fractures: efficacy of imaging modalities

Imaging modality	Sensitivity	Limitations
CR		Radiation exposure
		May take 7–10 days after injury to diagnose fracture
		2-D representation of 3-D information
		Sensitivity varies widely depending on anatomic location of injury
		Assumes technically well done studies that use proper MAs, kVp, etc., and include all pertinent views
CT		Radiation exposure
		Limited effectiveness in diagnosis of incomplete and non-displaced, complete fractures
MRI	95 %	Specificity less for small avulsion-type fractures that are often better detected with CR or CT
BS	95 %	Imaging not performed until 3–4 h after injection
		Usually takes 2–3 days after injury to diagnose fracture with high sensitivity in elderly adults
		Specificity less for non-acute fractures

or with a mechanically unstable spine for presurgical planning [1, 6]. In cases with clinical or imaging findings suggestive of arterial injury, MDCT of the cervical spine should typically be accompanied by CTA or MRA of the head and neck [1, 6].

In both pediatric and adult populations, the major role of CT in evaluation of extremity fractures is for surgical planning. CT provides extensive information on the 3D anatomy and spatial relationships of fracture fragments. It is able to assess whether or not a fracture involves a joint and show how much diastasis and step off is present at the articular surface [2, 3, 7, 8]. CT may occasionally provide information about tendon entrapment. Typically, it is at the orthopedist's discretion to request a planning CT once the decision has been made to operatively reduce the fracture. CT angiography can be useful to confirm arterial injury in cases where vascular compromise is clinically suspected from signs and symptoms such as abnormal pedal pulses, skin pallor, parathesias, and coolness of the extremity [9].

MRI can occasionally be of use in preoperative planning of extremity fracture reduction. Its role relates to identifying accompanying soft tissue injury [9], typically after fracture-dislocations caused by high-energy trauma, e.g., dislocation of the femorotibial joint of the knee. Here, MRI not only displays the status of the ligaments, but also of the menisci, tendon insertions, and focal articular cartilage defects.

Stress fractures frequently are difficult to visualize using CR, particularly insufficiency type stress fractures because of the associated osteopenia. The sensitivity of CR for early stress fracture detection may be as low as 15 % on initial imaging, with follow-up X-rays sensitivity increasing to only 50 % [10, 11]. Nonetheless, it is reasonable to begin the patient's evaluation with CR primarily to exclude other pathology. Often, however, an alternative study, either BS or MRI, will be required to diagnose the fracture. Both have a high degree of accuracy for this diagnosis, but MRI is generally the preferred examination because it depicts all of the anatomy and it uses no ionizing radiation. Of course, MRI is more expensive than BS, and this difference should be taken into consideration.

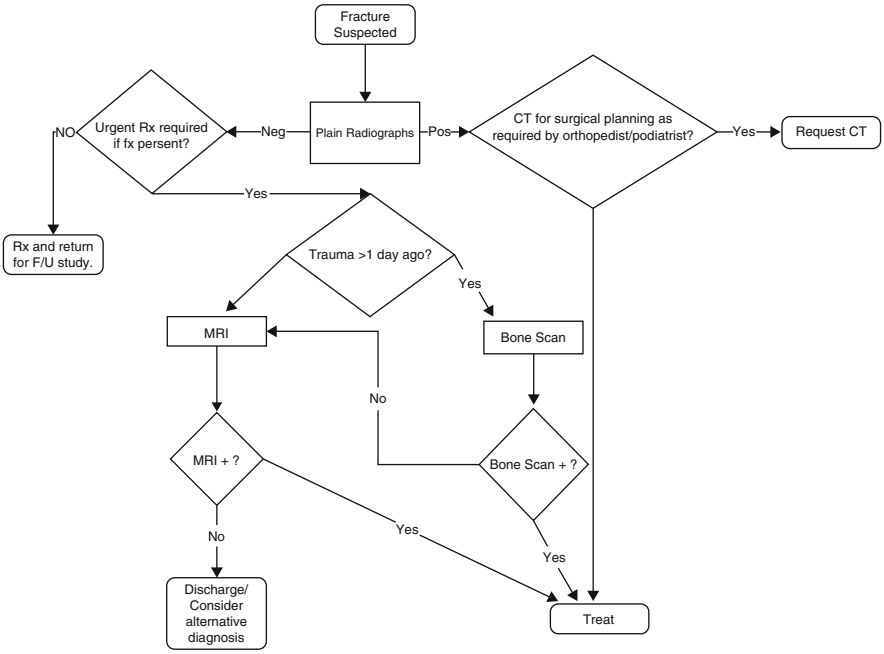

Fig. 6.1 Workup of osseous trauma

Because BS only shows abnormal metabolic activity, findings are nonspecific and always should be compared with recent CR [11, 12]. This practice will prevent incorrectly interpreting a BS abnormality as a presumed clinical diagnosis. For example, an osteoid osteoma and a stress fracture will have similar BS appearances, but these are very different entities, requiring different therapy.

US plays a limited role in initial fracture diagnosis. US, using CR as a standard, has a sensitivity and specificity of 94 % for lipohemarthrosis and hence detection of occult fractures with intra-articular extension (Fig. 6.1).

Soft Tissue Trauma

Trauma to muscles, ligaments, and tendons may occur acutely as with a sudden muscle strain or from chronic repetitive trauma, as with overuse syndromes like "tennis elbow." Other common soft tissue injuries include muscle contusions and intramuscular hematomas, cruciate ligament injury and meniscal tears in the knee, rotator cuff tears of the shoulder, shoulder glenoid and hip acetabular labral tears, carpal intrinsic ligament tears, sprains of the ankle, ankle and wrist tenosynovitis, and plantar fasciitis in the foot. Tendons, e.g., the rotator cuff, biceps at the shoulder and elbow, gluteal, hamstring, adductor, quadriceps, and Achilles tendons, may tear as a result of either acute and/or chronic trauma or as a result of other infiltrating pathology that causes degradation of the tendon's integrity, e.g., fluquinolones, xanthomas, or tophi.

Regardless of whether the trauma is acute or chronic, MRI and US are the preferred imaging modalities for diagnosis. CR may be helpful initially to exclude underlying pathology masquerading as trauma and to provide information about the adjacent osseous structures that MRI or US might not show. For instance, an avulsion fracture from the dorsal triquetrum at the attachment of the ulnotriquetral ligament will be better depicted on CR and aid the underlying soft tissue diagnosis.

MRI easily distinguishes among several different types of soft tissue, displaying a high level of anatomic detail for the evaluation of muscles, tendons, ligaments, fat, fascia, hyaline articular cartilage, and fibrocartilage, e.g., joint labra and menisci, the triangular fibrocartilage complex (TFCC) of the wrist, and the articular disc of the temporomandibular joint (TMJ). It can image any part of the body as long as there is no contraindication to placing a patient in the magnet and there is no artifact inducing material near the part to be imaged.

US is useful in evaluation of tendons and ligaments when the target structure is accessible to the penetrating US waves. The exam is usually most efficacious when applied to specific clinical questions that require focused imaging performed in a small anatomic area. Suspected tears of the Achilles, patellar, quadriceps, hamstring tendons, and rotator cuff fall into this category.

As discussed above, US shows anatomy in real time, allowing for visualization of motion. This can be useful in trauma to elicit extensor tendon subluxation in the fingers related to ligament tears, ulnar nerve subluxation-dislocation in and out of the cubital tunnel at the elbow, ankle tendon dislocations at the hind foot, and myofascial tears of muscles.

CT, in some cases, can diagnose trauma to tendons, muscles, and ligaments, but compared with MRI, its capability is limited. CT suffers from poor contrast resolution in evaluating the musculoskeletal system.

Although soft tissue abnormalities, both traumatic and non-traumatic, occasionally can be detected on BS, this study is not accurate enough to warrant its use for this purpose. In fact, these findings typically are noted incidentally on a BS obtained for a different purpose (Fig. 6.2).

Infection

Osseous Infection (Osteomyelitis)

Osteomyelitis is common in certain populations, e.g., diabetics. The vast majority (>90 %) of pediatric cases of osteomyelitis arise through hematogenous dissemination of the infectious agent, usually *Staphylococcus aureus* [13, 14]. Adult osteomyelitis, on the other hand, overwhelmingly (>90 %) results from contiguous spread of adjacent soft tissue infection, whether from a soft tissue ulcer or less commonly pyomyositis [13]. A small proportion of osteomyelitis in adults results from hematogenous spread [13]. This occurs most commonly in patients who have large intravascular boli of organisms, e.g., intravenous drug users (IVDA) in whom the spine

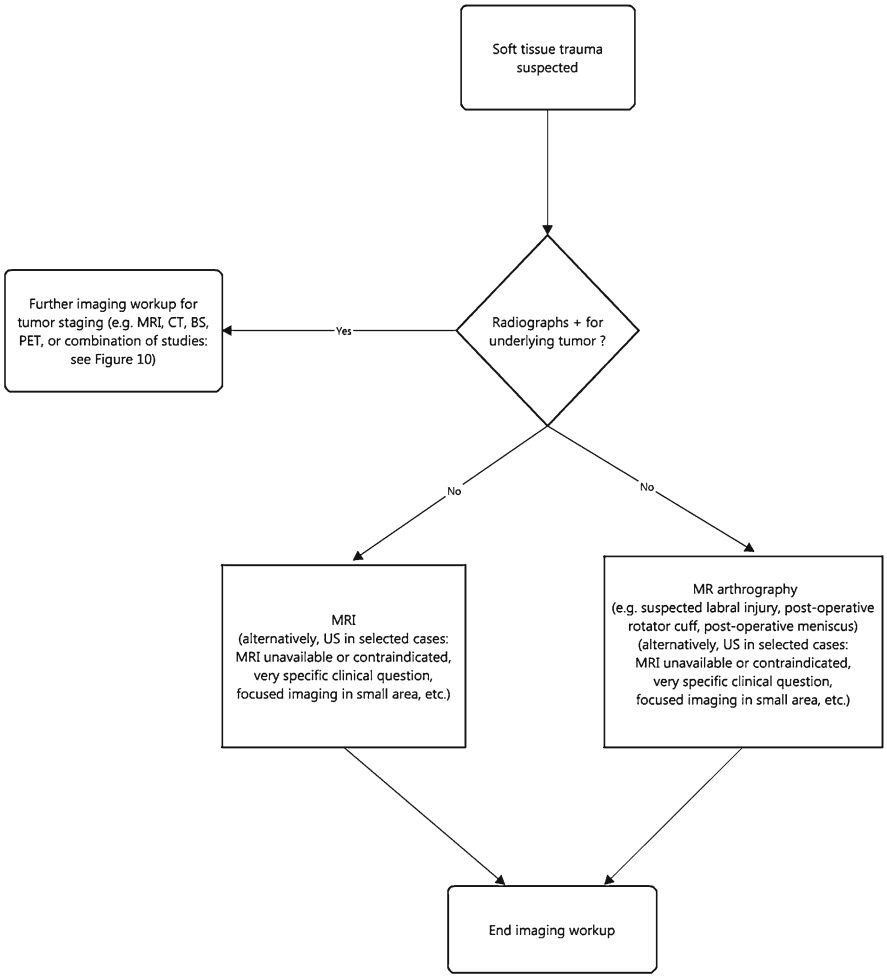

Fig. 6.2 Workup of soft tissue trauma

and sternoclavicular and acromioclavicular joints are common sites of infection [13, 15]. Osteomyelitis in any bone can spread to adjacent joints and cause septic arthritis [13, 16].

Of course, imaging can be employed not only to diagnose osteomyelitis, but also to evaluate healing in response to treatment. Finally, CR is valuable in defining postoperative anatomy in patients who have had normal anatomy altered either surgically or from neuropathic arthropathy.

Although the specificity of CR for osteomyelitis is moderately high (80 %), its sensitivity is low (54 %). The low sensitivity results from the fact that there must be substantial trabecular bone destruction for osteomyelitis to be evident on plain radiographs, usually 50–70 % [14]. As a result, the destructive changes associated

with osteomyelitis typically are not demonstrated by radiographs until 10–14 days after the start of the infection [13, 14, 17]. CR's sensitivity for sequestra (10–15 %) and cloacae is also low [18]. As with acute fractures, the delay between infection's onset and visibility on CR is more prolonged in the elderly population.

Although CR may have a lower sensitivity than some other modalities, it is inexpensive. If CR reveals osteomyelitis, the work up can stop there in most cases. Furthermore, if additional imaging is required, a plain radiographic study of the same body part is essential for comparison, especially when there is confusing or altered anatomy, e.g., patients with amputations [17].

MRI and NM have equivalent high sensitivity for diagnosis of osteomyelitis, but the former is able to detect the infection slightly earlier in its course, at most a day or two. As with occult fractures, BS may not show osteomyelitis in elderly adults until 2–3 days from the onset of infection. Once again, BS is less expensive than MRI.

Thus, while CR is the initial imaging modality of choice in the diagnostic workup for osteomyelitis, MRI is usually the second imaging study chosen if CR is nondiagnostic [13, 14]. MRI is exquisitely sensitive to cortical destruction and also can show bone marrow and soft tissue edema. Typically, IV contrast does not increase MRI's sensitivity for acute osteomyelitis. On the other hand, contrast often can be helpful in detection of findings typically associated with osteomyelitis such as soft tissue and intra-osseous abscesses and bony sequestra [13]. MRI with added IV contrast plus fat suppression has been reported to raise specificity for osteomyelitis from 81 to 93 % [19]. Furthermore, contrast can aid in the differentiation of nonviable necrotic soft tissues from viable tissue, thus aiding operative planning [17, 20].

Unfortunately, the specificity of MRI for acute osteomyelitis drops in complicated cases that involve acute or chronic osteomyelitis; patients who are recently postoperative; patients who have had a recent fracture; or who have underlying conditions such as neuropathic or inflammatory arthropathy [14, 17]. In some cases, particularly in patients with neuropathic arthritis, labeled WBC radionuclide scans or FDG-PET scans are more efficacious than MRI to diagnose associated osteomyelitis [14]. Occasionally, bone biopsy will frequently be required to make the diagnosis or if an unusual organism is suspected.

Findings on follow-up MRI studies in patients with osteomyelitis routinely lag the clinical picture, and so can give an incorrect impression of the status of patients who are undergoing or recently had treatment. Findings on MRI such as marrow edema and marrow enhancement may worsen during the treatment phase, not showing improvement until later on. Regardless, evidence of progressive bone destruction should not be evident and indicates worsening infection.

In patients who are unable to have MRI, whether due to unavailability of or contraindication to the exam, BS may be used instead. As mentioned, BS has equally high sensitivity for detection of osteomyelitis as MRI and as a result has extremely high negative predictive value; a negative study virtually excludes osteomyelitis [14]. In addition, BS allows imaging of the entire skeleton, making it valuable in cases of suspected multifocal infection such as chronic recurrent multifocal osteomyelitis. The main drawbacks of BS are its inability to detect infection as early

as MRI, and its lower specificity compared with MRI, CR, and other studies [14]. The development of single photon emission CT (SPECT) in registration with standard CT has mitigated some of these issues but also has increased the cost of nuclear medicine studies substantially. In some special circumstances, such as cases of multifocal osteomyelitis and osteomyelitis around prostheses, BS combined with labeled WBC study can be particularly beneficial; the labeled WBC study improves the low specificity of BS alone [17]. Labeled WBC studies are most useful in the appendicular skeleton. Many studies have shown problems with false negatives and low sensitivity for osteomyelitis of the spine evaluated with labeled WBC [21].

Diagnosing ongoing chronic osteomyelitis can be difficult. Early studies using FDG-PET showed higher sensitivity and specificity than other NM studies and MRI both [14]. A recent meta-analysis that reviewed the accuracy of multiple imaging modalities for the diagnosis of chronic osteomyelitis showed FDG-PET to be the most accurate, with a sensitivity of 96 % and specificity of 91 %. In comparison, the sensitivity and specificity of MRI was 84 % and 60 %, respectively. Labeled WBC study had a sensitivity of 84 % and a specificity of 80 %, but these values decreased considerably when cases involving the axial skeleton were included [22]. Relative unavailability and high cost are significant stumbling blocks for FDG-PET.

Although MRI often can diagnose a sequestrum, CT is slightly more sensitive because it is exquisitely sensitive for detecting calcification and ossification [13]. CT is especially applicable if the suspected sequestrum is small or IV contrast cannot be administered with the MRI [13, 14]. On the other hand, if a patient can tolerate IV contrast, MRI is superior to CT in determination of the viability of infected bone, and even more accurate than CT in the detection of necrotic soft tissues that may require surgical debridement [13, 17].

In selected locations in the body where radiographs do not display the anatomy clearly CT is the preferred initial examination in cases of suspected osteomyelitis, e.g., sternoclavicular joints [13, 14]. CT also may be preferred in areas where respiratory motion may degrade MRI image quality, e.g., the chest and abdominal walls [23, 24]. CT, if positive, is capable of providing precise anatomic localization of osteomyelitis. It also is able to guide bone biopsy. CT is very limited in evaluation of the marrow space compared with MRI [14, 17] (Table 6.2).

US plays a minor role in the diagnosis of osteomyelitis. The modality cannot detect intra-osseous pathology such as medullary bone destruction, sequestrum, and intra-osseous abscess [14, 17]. US does have very good utility in the detection of infection of the soft tissues adjacent to infected bone and periosteal abnormalities primarily in children. For instance, US can identify periosteal elevation and accompanying subperiosteal fluid collections such as abscess, and it also is able to demonstrate neighboring soft tissue abscesses in patients with osteomyelitis [14]. In addition, in cases where osteomyelitis is intra-capsular in location, such as the femoral neck, US has high sensitivity in detection of joint effusion, but it cannot distinguish whether the effusion reflects complicating septic arthritis or is merely reactive in etiology [14]. US, like CT, can provide guidance for aspiration of fluid collections and joint effusions related to osteomyelitis (Fig. 6.3).

Table 6.2 Osteomyelitis: efficacy of imaging modalities

Imaging modality	Sensitivity	Specificity	Accuracy	Advantages	Limitations
CR	54 % (22–93 %)	80 % (50–94 %)		May demonstrate an alternative diagnosis (i.e., fracture nonunion, tumor)	Radiation exposure
				Excellent overview and delineation of anatomy (especially beneficial in postoperative and neuroarthropathy patients)	2-D representation of 3-D information
				Aids characterization of the distribution of arthritic changes (including neuropathic osteoarthropathy)	Usually takes 10–14 days after infection onset to diagnose osteomyelitis
				Useful in detection of soft tissue gas	Bone destruction needed for visualization of the abnormality may be 60 %
				Specificity moderate	Sensitivity low to very low
					—
					Endplate cortical destruction in osteomyelitis-discitis usually not evident until at least 4–6 weeks after infection onset
					Specificity in spondylodiscitis reduced by other causes of disc space narrowing (e.g., DDD), endplate erosive changes (e.g., severe DDD), and gross bone destruction (e.g., neuropathic spondyloarthropathy, amyloid arthropathy)

CT	Helpful in evaluation of deep structures and assessment of atypical and irregular bones and joints, and complex joint anatomy (e.g., sternum, sternoclavicular joint, spine, pelvis)	Radiation exposure
	Precise anatomic localization of findings	Soft tissue contrast moderate, but lower than MRI
	Depicts subtle, early bone cortex erosion	Much less sensitivity for marrow infection (vs. MRI)
	Very good for sequestrum detection	Insensitive, inadequate assessment of degree of marrow involvement
	Can guide bone biopsy	Accuracy in determination of viability of infected bone and soft tissues lower than MRI
		—
		Inferior soft tissue contrast resolution results in decreased sensitivity for epidural abscess complicating spondylodiscitis

(continued)

Table 6.2 (continued)

Imaging modality	Sensitivity	Specificity	Accuracy	Advantages	Limitations
MRI	92 % (29–100 %)	84 % (78–89 %)	89–98%[a]	Comprehensive assessment of entire spectrum of bone and soft tissue infection pathology	Not always (easily) available
	84%[a]	60%[a]		Excellent bone marrow evaluation	Expensive
				Outstanding soft tissue contrast aids diagnosis of coexisting pathology (e.g., soft tissue abscess, sinus tract, devitalized soft tissue)	Long study length may result in image quality degraded by motion artifact (difficult for severely ill patients to remain in scanner entire study)
				Superb anatomic detail	Nephrogenic systemic fibrosis (NSF) risk from IV gadolinium-based contrast agents (GBCAs)
				Provides surgeon with preoperative anatomic "road map" of pathology	Specificity decreased in setting of recent fracture, recent surgery, neuropathic osteoarthropathy, and inflammatory arthritis
				Sensitivity and specificity high (>90 %)	Nonspecific result is not uncommon but may help in evaluation of complex cases of chronic osteomyelitis
				May help in evaluation of complex cases of chronic osteomyelitis but nonspecific result is not uncommon	—
				—	Limited ability to accurately differentiate pyogenic vs. mycobacterial etiology in osteomyelitis-discitis
				Highest sensitivity (96 %), specificity (92 %), and accuracy (94 %) modality for spondylodiscitis	
BS	91 % (69–95 %)	46 % (38–100 %)		Allows for evaluation of entire body (particularly helpful with multifocal osteomyelitis)	Usually takes 2–3 days after infection onset to diagnose osteomyelitis in elderly adults
				Sensitivity high (equal to MRI)	Moderate study length (images obtained 3–4 h after radiotracer injection)
				Negative predictive value (NPV) high	Specificity very low
					Low resolution, suboptimal anatomic localization (but improved by SPECT or CT)

Labeled WBC	86 % (45–100 %)	84 % (67–89 %)	78–90 %	Allows for evaluation of entire body (particularly helpful with multifocal osteomyelitis)	Very long study length (imaging performed 2–4, 24, and possibly 48 h after injection)
	84%[a]	80%[a]		Sensitivity high	Specificity reduced in setting of recent fracture, recent surgery, neuropathic osteoarthropathy, and inflammatory arthritis
				Negative predictive value (NPV) high	Sensitivity for vertebral osteomyelitis much lower than for bone infection in the extremities
				—	
				NM commonly favored in setting of postoperative spondylodiscitis because of reduced specificity of MRI	Low resolution, suboptimal anatomic localization (but improved by SPECT or CT)
BS + labeled WBC	88 % (73–100 %)	82 % (55–91 %)	81 %	Allows for evaluation of entire body (particularly helpful with multifocal osteomyelitis)	Very long study length (imaging performed 2–4, 24, and possibly 48 h after injection)
				Sensitivity high	Specificity reduced in setting of recent fracture, recent surgery, neuropathic osteoarthropathy, and inflammatory arthritis
				Negative predictive value (NPV) high	Low resolution, suboptimal anatomic localization (but improved by SPECT or CT)
				Specificity of BS increased by addition of labeled WBC study, and vice versa	
				—	
				NM commonly favored in setting of postoperative spondylodiscitis because of reduced specificity of MRI	
FDG-PET	96%[a]	91%[a]	94 %[a]	Allows for evaluation of entire body (particularly helpful with multifocal osteomyelitis)	Relative lack of availability
				Sensitivity and specificity high	High cost
				Negative predictive value (NPV) high	—
				Particularly useful in difficult, complex cases of chronic osteomyelitis (vs. any modality)	Not reliable for osteomyelitis-discitis even though addition of CT increases specificity
				—	
				NM commonly favored in postoperative spondylodiscitis setting because of reduced specificity of MRI	
Probe to bone	66 %	85 %			Presence of granulation tissue over ulcer very uncommon but may give false negative result

[a]Chronic osteomyelitis

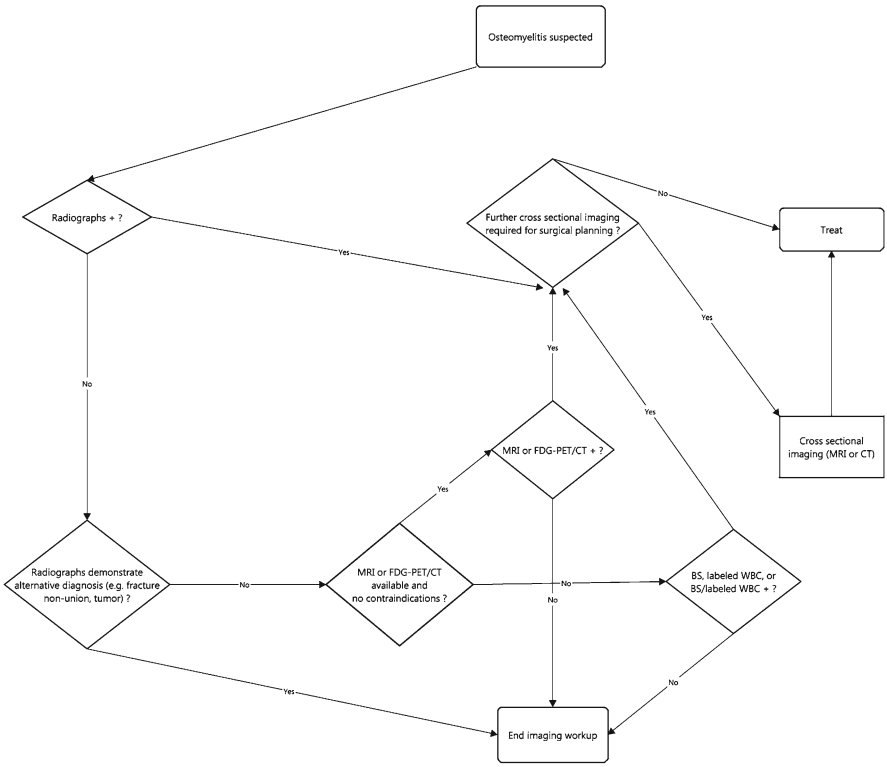

Fig. 6.3 Workup of osseous infection (osteomyelitis)

Spinal Infection (Osteomyelitis-Discitis, Spondylodiscitis)

Spinal osteomyelitis and discitis represents only approximately 5 % of all cases of osteomyelitis. Spondylodiscitis occurs most frequently in the lumbosacral spine. Cervical spine involvement is least common. Epidural spread is not uncommon but is a source of significant morbidity and mortality. Rarely, the infection spreads to the meninges and spinal cord, usually with devastating results [25]. As in the case of patients with extra-spinal osteomyelitis, bacterial infection is much more common than fungal or parasitic etiologies, and again *S. aureus* is the most common causative organism, accounting for more than half of cases (60 %) [25]. Gram negative pyogenic and polymicrobial infection is also frequently seen. *Mycobacterium* infection, including *M. tuberculosis,* is another common etiology, particularly in developing countries, where it is widespread and even endemic [25].

As with evaluation of osteomyelitis elsewhere, CR is the first study for imaging patients with suspected osteomyelitis-discitis. As with other locations, the sensitivity of X-rays for spondylitis is low, especially early in the course of the disease.

In adults, endplate cortical destruction, the most specific finding for pyogenic infection, is usually not evident on radiographs until at least 4–6 weeks after the onset of infection [25]. The sensitivity of radiographs for spinal infections for non-pyogenic osteomyelitis-discitis is worse—minimal to none. CR also has limited specificity for discitis-osteomyelitis [25]. Overall, disc space narrowing is most frequently the result of degenerative disc disease and occasionally even erosion and irregularity may be seen in severe degenerative disc disease. Gross bone destruction and osseous fragmentation can be the result of amyloid spondyloarthropathy and neuropathic arthropathy [25].

MRI is the gold standard in imaging of spinal infection [13, 25]. Numerous studies have shown that MRI has very high sensitivity, specificity, and accuracy for osteomyelitis-discitis, approximately 96 %, 92 %, and 94 %, respectively. These figures exceed those of any other imaging modality [25]. MRI's performance in detection of bone and disc infection stems from its excellent depiction of disc fluid, endplate cortical erosion, overt bone destruction, and bone marrow edema. It is also sensitive for identification of associated inflammatory phlegmon and abscess, usually either epidural or retroperitoneal within the psoas muscle. These usually require drainage for successful treatment. IV contrast can provide additional value, providing better delineation of fluid collections and improved detection of necrotic tissue and sequestra.

CT is sometimes beneficial in the workup of osteomyelitis-discitis. Like MRI, CT is capable of providing precise anatomic localization and detail in osteomyelitis-discitis. As expected, however, CT is beset by the same disadvantages relative to MRI as in the diagnosis of osteomyelitis outside the spine. Unless MRI is unavailable or contraindicated, CT is generally no longer used for this diagnosis.

NM studies play a small role in the initial diagnosis of osteomyelitis-discitis except in postoperative patients where distinction between operative changes and infection is difficult on MRI [25]. As with extra-axial infection, BS and labeled WBC studies either alone or in combination are typically used in postoperative patients. PET has not proven to be dependable in the diagnosis of spondylodiscitis, although the addition of CT improves anatomic localization and specificity (Fig. 6.4).

Joint Infection (Septic Arthritis)

In the clinical setting of a single acutely painful joint, septic arthritis should be strongly considered and evaluated emergently to avoid rapid irreversible destruction of the joint [26]. Septic arthritis in children typically arises from hematogenous inoculation of the joint, while in adults it arises from direct inoculation of the joint. Osteomyelitis that is intracapsular to a joint also can give rise to septic arthritis [13, 16].

Certain patient populations have a predilection to develop septic arthritis, in particular anatomic locations. For instance, in IVDA, the acromioclavicular joints,

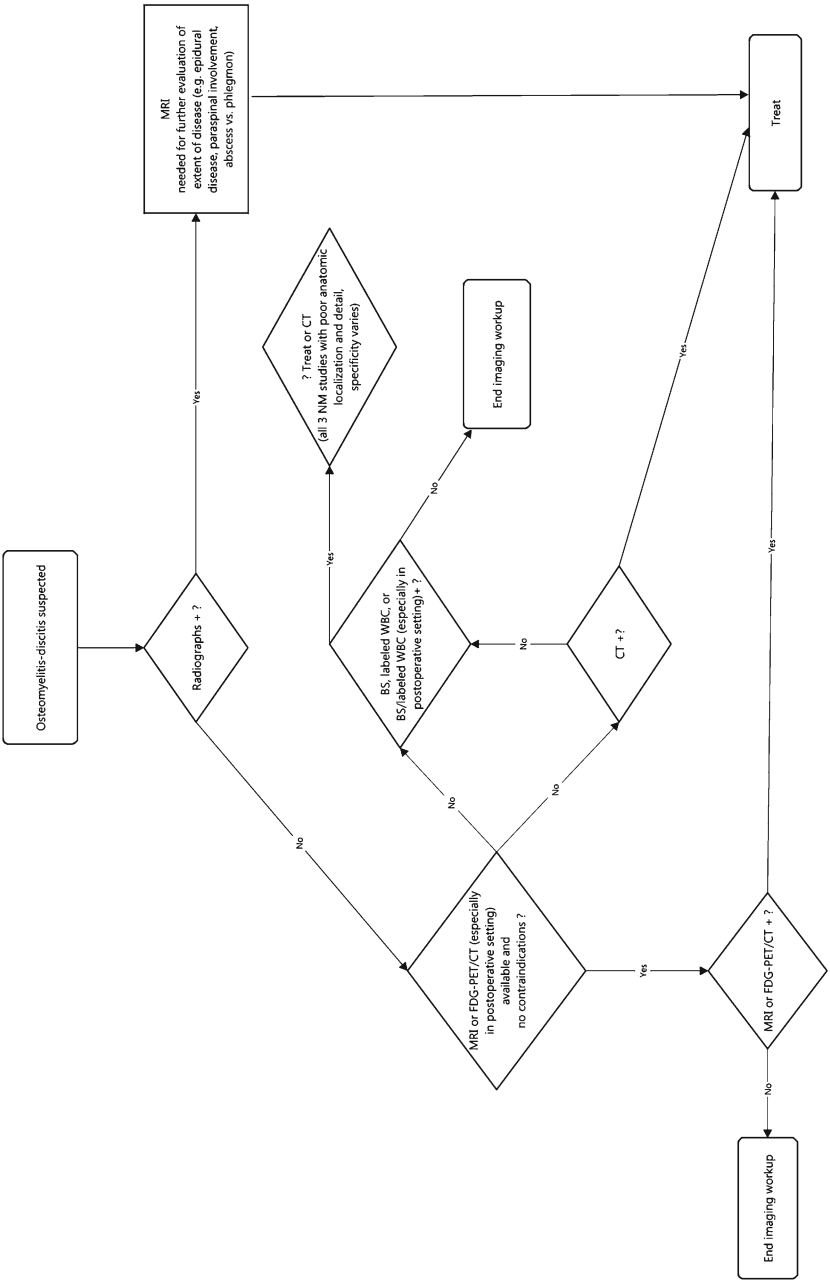

Fig. 6.4 Workup of spinal infection (osteomyelitis-discitis, spondylodiscitis)

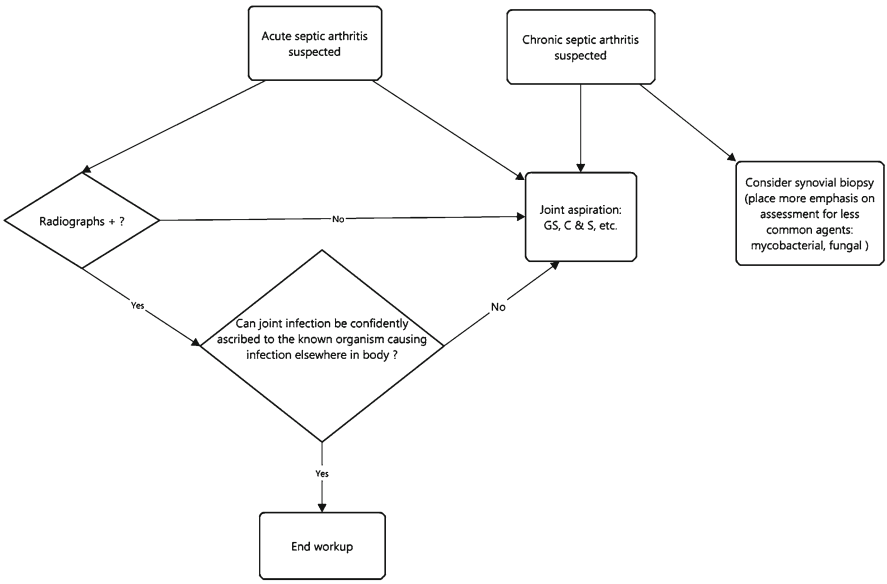

Fig. 6.5 Workup of joint infection (septic arthritis)

sternoclavicular joints, vertebral discs, and sacroiliac joints are commonly involved [15]. Patients within 6 months of arthroplasty are also prone to infection.

Joint aspiration remains the gold standard in the diagnosis of acute septic arthritis [13, 26]. MRI and US can confirm the presence of joint fluid prior to joint aspiration, but they cannot reliably distinguish sterile joint fluid from infected joint fluid [26]. In fact, routine imaging cannot exclude septic arthritis even with a normal examination [13]. Regardless, both MRI and US are only occasionally performed and almost always are unnecessary since they do not obviate the need for joint aspiration [13]. On the other hand, fluoroscopy and US can be useful to guide joint aspiration procedures. When there is clinical concern for chronic septic arthritis, in the majority of patients joint aspiration remains the initial examination. However, one should at least consider performing synovial biopsy, placing more emphasis on evaluation for less common infectious agents such as mycobacteria and fungi [26].

To summarize, although laboratory results may be normal in an acutely infected joint, clinical data, i.e., elevated CRP, sedimentation rate, leukocytosis, fever, systemic infection, and joint pain, should be emphasized over and pursued earlier than most imaging studies. Judicious use of advanced imaging techniques such as MRI, US, and nuclear medicine may help exclude alternative diagnoses, but joint aspiration and culture is the examination of choice in cases of septic arthritis (Fig. 6.5).

Soft Tissue Abscess

Soft tissue abscesses may arise through multiple pathways: direct implantation, infection in the adjacent soft tissues, or most commonly hematogenous spread of infectious organisms (usually bacteria) [13]. These fluid collections are generally seen more often in patients who have depressed immune systems, bacteremia, sepsis, infectious endocarditis, or a history of recent surgery or penetrating trauma. In the IVDA population, abscesses in the soft tissues are commonly related to the use of unsterilized needles and injectates, and so they tend to arise in areas where users inject.

Although CR has very low sensitivity for soft tissue abscess, this is the standard first imaging study, usually to exclude foreign bodies and soft tissue gas [17]. Radiographs rarely demonstrate a discrete appearing mass in the soft tissues. They more frequently will show focal soft tissue swelling and edema.

MRI and CT, both with IV contrast, routinely detect fluid collections in the soft tissues. Although MRI without IV contrast can detect abscesses, contrast enhanced MRI has greater sensitivity, particularly for smaller abscesses as may be seen with pyomyositis [13]. The soft tissue contrast resolution of CT with IV contrast is moderate and inferior to that of MRI. Moreover, depending on the timing of CT image acquisition relative to administration of the IV contrast, the fluid collection may have poor conspicuity and go undetected. Therefore, MRI with IV contrast is the preferred examination for diagnosis of a soft tissue abscess [13, 17, 26]. In addition to its utility in evaluation for soft tissue abscesses, MRI can characterize the extent of tissue devitalization and so facilitate operative planning for soft tissue debridement or amputation [17, 20].

Abscesses are also easily diagnosed with targeted US. Using color Doppler, US can add further value in some cases by assessing the vascularity of the wall of the collection and adjacent soft tissues. The presence of hypervascularity in the wall and surrounding soft tissue favors a diagnosis of abscess over a noninfected collection such as seroma or hematoma [17]. It should be cautioned, however, that there can be significant overlap in the vascularity and central echogenicity of these different types of fluid collections because seromas and hematomas can become superinfected. As a result, fluid aspiration often is needed for definitive diagnosis. Both CT and US can provide excellent guidance for this procedure [17, 27].

The differential diagnosis of soft tissue abscess on MRI, CT, and US includes muscle infarction and necrotic tumor [28]. Differentiating between abscess and necrotic tumor often can be done clinically. On the other hand, distinguishing between abscess and muscle infarction, most commonly seen as a complication of diabetes, typically requires aspiration to determine the cause of the collection.

Labeled WBC study for soft tissue abscess is less often utilized than MRI, CT and US because it provides limited anatomic localization of abscesses [29]. Furthermore, labeled WBC exams take much longer to perform than other modalities, and this can be a problem in acutely ill patients or because it can increase an inpatient's length-of-stay. Nonetheless it has high sensitivity and excellent specificity for abscess (Table 6.3, Fig. 6.6).

Table 6.3 Soft tissue abscess: efficacy of imaging modalities

Imaging modality	Sensitivity	Specificity	Limitations
CR	+	+++++	Radiation exposure Poor soft tissue evaluation Finding of discrete soft tissue fluid collection/mass only occasionally seen, with collection + internal air or air fluid level rare
US	++++/+++++	++++	Specificity mildly reduced by other possible fluid collections (e.g., hematoma, seroma)
CT (with IV contrast)	+++/++++	++++	Radiation exposure Soft tissue contrast less than MRI Peripheral, rim-like wall enhancement dependent on appropriate timing of IV contrast injection
MRI (without and with IV contrast)	++++/+++++	++++	Not always (readily) available Expensive Long study length may result in image quality degraded by motion artifact (difficult for very ill patients to remain in scanner for complete study) Nephrogenic systemic fibrosis (NSF) risk from IV gadolinium-based contrast agents (GBCAs) Sensitivity reduced if no IV contrast (particularly with small, less conspicuous fluid collections)
Labeled WBC	++++	++++	Very long study length (imaging at 24 and possibly 48 h postinjection of labeled WBC) Limited precise anatomic localization of pathology due to low contrast resolution (better with SPECT, more recent unequivocal improvement with CT)

Pyomyositis

Known also as infectious myositis, pyomyositis is rare with higher incidence in immunocompromised patients, e.g., diabetes and AIDS [15, 16]. The disorder most often afflicts the thighs and buttocks and is multifocal in approximately 50 % of cases [15]. A minority of patients develop one or more intramuscular abscesses, often small in size [13]. If pyomyositis is not complicated by soft tissue abscess, MRI, CT, and US will typically show features of nonspecific edema and distortion of soft tissue planes, analogous to what is seen on CR.

Necrotizing Fasciitis

Necrotizing fasciitis is a fulminant and rapidly spreading infection of the tissues around the deep fascia, associated with a high degree of morbidity and mortality.

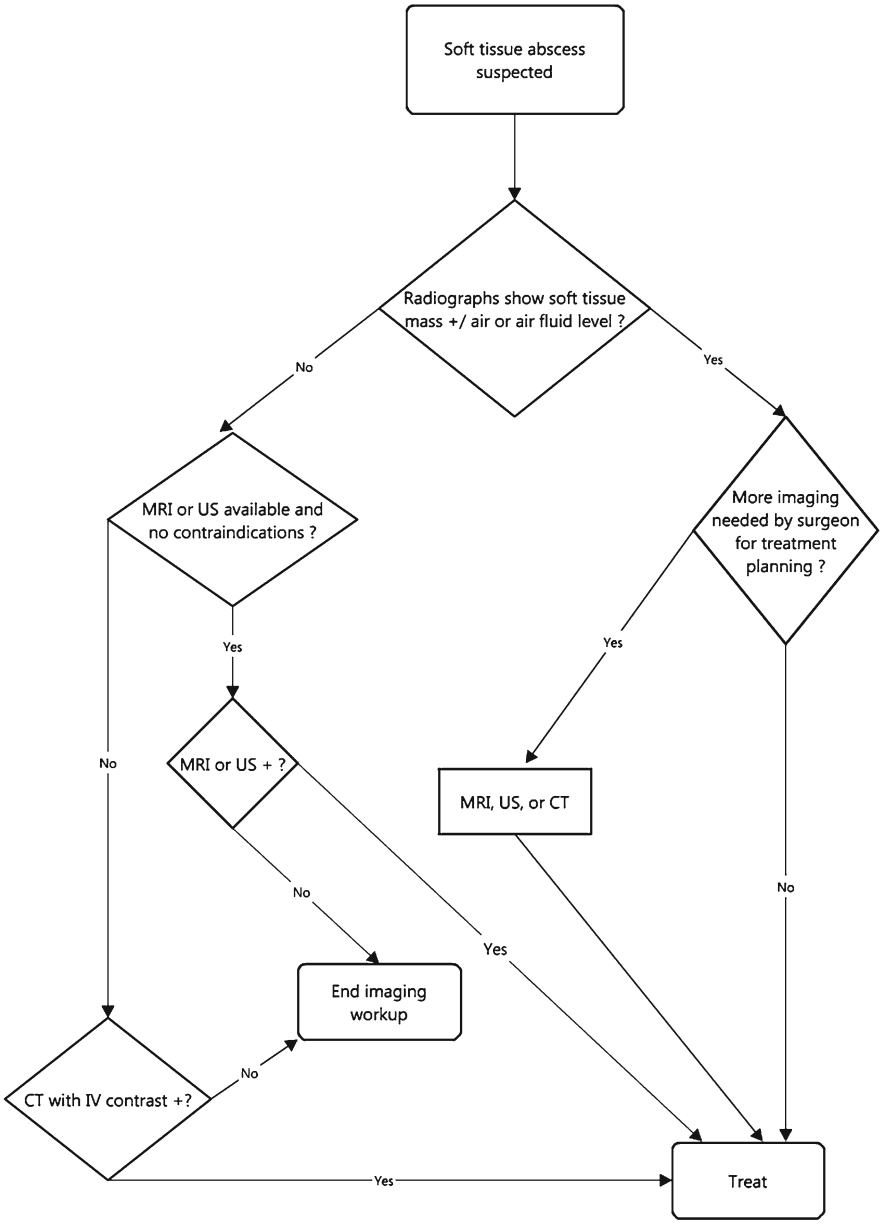

Fig. 6.6 Workup of soft tissue abscess

Given its virulent nature, prompt treatment is essential. Findings on cross-sectional imaging tend to be nonspecific until late in the disease. As a result, necrotizing fasciitis is primarily a clinical diagnosis and imaging plays a limited role in diagnosing this entity.

Neoplastic and Non-Neoplastic Space Occupying Lesions

Focal Lesions of Bone

Radiographs are indispensable in the evaluation of focal lesions of bone, whether primary neoplasms, secondary neoplasms, or non-neoplastic. In the majority of cases analysis of radiographic findings allows either a definitive diagnosis or a narrow differential diagnosis [30, 31]. In fact, radiographs are often diagnostically superior to more advanced imaging modalities, and they are invariably less expensive. Today, CR remains the gold standard for establishment of the appropriate diagnosis of tumor and tumor-like bone lesions [32]. In some cases, however, MRI and CT may provide additional information that narrows the differential diagnostic considerations. For example, a finding of multiple fluid-fluid levels in a lesion on MRI may suggest a diagnosis of aneurysmal bone cyst.

Often focal bone lesions are asymptomatic and incidentally noted on radiographs that were obtained for unrelated reasons. Many of these lesions have classic radiographic appearances and correlate with nonaggressive, benign entities that may not require additional work up, e.g., non-ossifying fibroma, mature osteochondroma, and bone island. Some lesions, although benign, may require further evaluation as they may enlarge and cause symptoms or threaten the integrity of the bone, e.g., unicameral bone cysts, aneurysmal bone cysts, giant cell tumors, and chondroblastomas. In these cases, evaluation with MRI or CT provides the anatomic detail needed for surgical planning to define the size of the lesion and what adjacent anatomic structures it impacts [32].

Sometimes a focal bone lesion is suspected clinically. If radiographs are negative, depending upon the lesion suspected, a BS, CT, or MRI may be the next imaging choice. Whether suspected or incidentally discovered on advanced imaging, CR is usually obtained to further define the nature of the lesion. If the radiographs do not adequately show the lesion or fail to make the diagnosis, CT or MRI may be required. Although most primary lesions of bone are best evaluated with MRI, CT is preferred over MRI for lesions that are juxtacortical-periosteal, located in flat bones that have thin cortices and little marrow space, and for detection and characterization of tumor matrix mineralization [32] (Fig. 6.7).

Metastases to Bone

Metastases to bone are common, occurring much more often than primary bone tumors. From 30 to 70 % of cancer patients will develop osseous metastases during the course of their illness [33]. Although many epithelial neoplasms metastasize to bone, lung, breast, prostate, renal, and thyroid malignancies are the most common.

Some malignancies, e.g., prostate cancer, have laboratory tests that can suggest progression or spread of disease, but no laboratory test is specific enough to predict

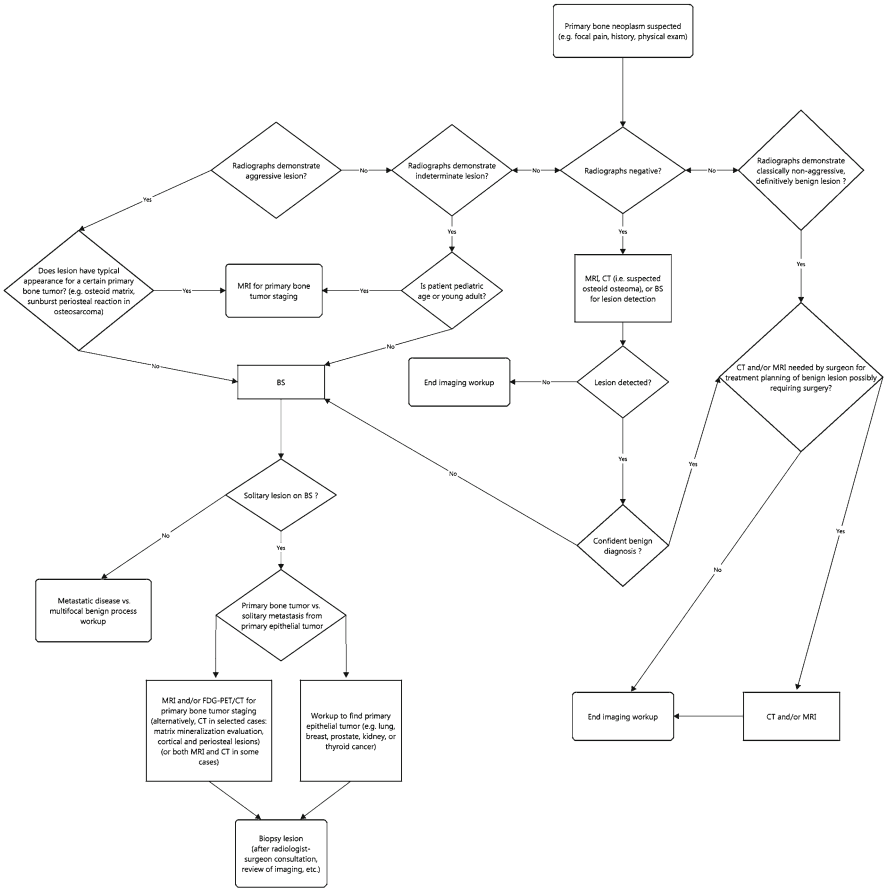

Fig. 6.7 Workup of focal lesions of bone

metastases to bone. In addition, many skeletal metastases are asymptomatic and are detected only on routine screening or when a patient presents with a complication of a metastasis such as a pathologic fracture [12, 33].

In general, a minimum of about 30 % bone destruction is required before CR will depict osteolytic lesions [34]. Some studies report even higher threshold values, 50 % [35] or even 70 % destruction. Thus, radiographs have low sensitivity for bone metastases, particularly early ones. As a result, the imaging workup for osseous metastatic disease from most epithelial malignancies begins with BS, which has been shown to have high sensitivity for this use. BS is most effective for osteoblastic metastases, the majority of which arise from breast or prostate cancer. The sensitivity of BS for osteolytic metastases is lower than for blastic metastases, particularly with renal and thyroid cancer where the lesions are often highly destructive. Nevertheless, BS's sensitivity for detection of osteolytic metastases is high (86 %) [33].

For primary malignancies that uncommonly or rarely metastasize to the skeletal system, e.g., gastrointestinal and gynecological malignancies, BS is usually obtained at time of initial presentation only when there is evidence of advanced disease [36]. Thus, BS currently forms the mainstay of initial screening for metastatic disease as well as a part of routine follow-up of cancer patients.

BS has the advantage of imaging the entire skeleton. This is important since nearly 15 % of bone metastases occur in locations in the appendicular skeleton not routinely imaged on a skeletal survey [12]. Today, newer imaging techniques such as whole body (WB) MRI, PET, and PET/CT are able to evaluate nearly the entire skeleton on a single study. On meta-analysis BS has moderate to high specificity in detection of osseous metastases on a per-patient basis with overall sensitivity and specificity of 86 % and 81 %, respectively. Even so both MRI (91 and 95 %) and FDG-PET (90 and 97 %) exhibit higher sensitivity and specificity than BS [33]. Thus far, however, BS remains the mainstay of work up because it is low cost and is nearly as sensitive as more expensive examinations.

Although some patterns of abnormality on BS clearly indicate metastases, others are nonspecific. As a result, when areas of abnormal radionuclide uptake are discovered on a BS done to exclude metastases, comparison radiographs are required to exclude benign pathology, such as degenerative disc disease, as the etiology of the BS abnormality [33]. This means that if no benign explanation or no abnormality at all is visible on CR, the BS lesion is taken to represent a metastasis, and further work up must be pursued.

A solitary lesion on BS in patients with a known primary epithelial malignancy is common. The frequency varies with the type of primary malignancy and the location of the BS abnormality. For example, such a finding in the rib cage reflects a bone metastasis approximately 25 % (range: 10–40 %) of the time [37]. More often than not, the BS finding will require additional evaluation with radiographs. If these are unrevealing, MRI, PET, and/or PET-CT may be required [12]. Similarly, this protocol can be applied to BS studies showing multiple foci of abnormal uptake. Biopsy may be necessary in some of the cases in which imaging is diagnostically inconclusive [12].

Most primary malignancies of bone, as opposed to epithelial cancers, do not metastasize to other skeletal sites and so BS is not indicated. On the other hand, both osteosarcoma and Ewing's sarcoma often do spread to other skeletal sites, and so BS is a necessary part of the evaluation in patients with these tumors [12].

The main role of CT in the evaluation of a bone metastasis is to determine whether the lesion has caused enough cortical destruction to put the bone at risk for pathologic fracture [32]. CT is insensitive at detecting malignant marrow infiltration and so has only low to moderate sensitivity for osseous metastatic involvement [33]. As a result, it is not used for screening or evaluation of most lesions.

MRI is an excellent imaging choice for assessment of the bone marrow [32, 38] and will show osseous metastases that do not involve the cortex. In fact, as mentioned above, (WB) MRI has specificity and sensitivity that is equal to or greater than that of BS and FDG-PET/CT. Even so, BS is favored by current ACR guidelines over MRI [12]. As such, MRI is a good staging tool, but has little value in screening.

MRI, because of its high sensitivity to bone infiltration, has a tendency to overestimate the amount of cortical destruction a metastasis has caused. As a result, it poorly predicts if a metastasis is of orthopedic significance. Also, conventional MRI has a poor track record when it comes to distinguishing acute traumatic or osteoporotic compression fractures from pathologic fractures in the spine. Some have suggested that MRI with diffusion-weighted imaging may be more effective at differentiating between benign and malignant vertebral collapse, but this technique is still under investigation [12].

Finally, ACR Appropriateness Criteria state that MRI for metastatic bone disease does not require administration of IV contrast. Vertebral metastases form an exception because here IV contrast can help to outline soft tissue extension. Regardless, IV contrast tends to be useful in the evaluation of primary soft tissue lesions [12, 39].

FDG-PET has high contrast resolution and allows for whole body evaluation. In addition, unlike most other imaging modalities, it provides information about metabolic activity [32]. As such, it provides both morphologic and physiologic information. FDG-PET is better at identifying osteolytic or mixed lytic and blastic metastases than those that are purely blastic. This explains why BS remains the screening test of choice for osteoblastic bone metastases [33, 40, 41] (Table 6.4, Fig. 6.8).

Multiple Myeloma

Multiple myeloma (MM), including its cousin plasmacytoma, is the most common primary malignancy of bone. Although MM commonly causes lytic lesions in bone, it has some unique features that deserve elucidation. Histomorphometric studies have shown uncoupled or severely imbalanced bone remodeling with increased bone resorption and decreased or absent bone formation in patients with multiple myeloma. Specifically there is stimulation of osteoclast formation and activity in close proximity to myeloma cells. Concurrently, myeloma cells suppress osteoblasts and thereby inhibit bone formation. In addition to blocking osteoblast formation and inhibiting osteoblast function, myeloma cells have also been reported to up-regulate osteoblast apoptosis [34]. Nearly 10 % of MM patients present with diffuse osteopenia on CR at the time of diagnosis [34]. The remaining patients are either radiographically normal or have visible lytic lesions. Eventually, as many as 90 % of MM patients will develop osteolytic lesions [34].

Only about 50 % of myeloma lesions are detected by BS, making it inappropriate as a screening tool for active MM. As a result, skeletal survey (SS), a radiographic technique that images nearly the entire skeleton, traditionally has been the test used to diagnose and follow patients with MM. As in the case of osseous metastatic disease, extensive destruction of bone, between 30 and 75 %, must be present before myeloma lesions become evident on SS [42, 43]. Despite the diagnostic limitations of SS, as recently as in 2009, the International Myeloma Working Group (IMWG) issued a consensus statement on the role of imaging techniques in multiple myeloma in which whole body X-ray, i.e., SS, was considered the standard for initial staging of MM [34, 42].

Table 6.4 Bone metastases: efficacy of imaging modalities[a]

Imaging modality	Sensitivity[a]	Specificity[a]	Limitations
CR			Sensitivity very low
			Especially limited in areas of overlapping structures, deep locations, and anatomically complex bones and joints
CT	73 % (77 %)	95 % (83 %)	Insensitive, inadequate assessment of marrow involvement
			Sensitivity moderate but comparatively low (vs. MRI, BS, FDG-PET)
MRI[b]	91 % (90 %)	95 % (96 %)	Whole body (WB) MRI specificity and sensitivity equal to or greater than each of BS and FDG-PET/CT separately, but either BS (i.e., initial presentation breast cancer) or FDG-PET/CT (i.e., initial presentation breast cancer with negative BS, or known bone metastases with pathologic femur fracture) may be favored by current ACR guidelines over MRI in some instances
			Limited quantification of cortical bone destruction (vs. CT)
BS[c]	86 % (75 %)	81 % (94 %)	Sensitivity reduced by false negatives resulting from rapidly growing, near purely osseous metastases (e.g., renal, thyroid)
			Specificity reduced by high false positive rate caused by increased turnover of bone in numerous benign primary bone tumors, non-neoplastic lesions, fractures, and degenerative disease
			Worse accuracy than FDG-PET/CT overall
			Preferred over FDG-PET for osteoblastic metastases
			"Flare" effect on follow-up imaging after therapy can be misleading in patients with positive response to treatment
FDG-PET[d]	90 % (87 %)	97 % (97 %)	Sensitivity for detection of osteoblastic metastases lower than for osteolytic and mixed lytic/blastic lesions
			FDG-PET/CT better than FDG-PET

[33] Meta-analysis—67 articles, 145 studies, 1995–2010

[a]On per-patient basis (per-lesion basis)

[b]Includes both conventional axial and whole body MRI, and both unenhanced and contrast enhanced MRI

[c]Includes BS both with and without SPECT

[d]Includes both FDG-PET and FDG-PET/CT

IMWG guidelines recommend initial staging of patients with either multiple myeloma or monoclonal gammopathy of unknown significance (MGUS) but normal SS with (WB) MRI. This same technique also is recommended for the initial evaluation of patients with an apparently solitary plasmacytoma [34, 44].

FDG-PET has a higher sensitivity for myeloma bone lesions compared with SS [42], but FDG-PET appears to be less sensitive than MRI (particularly in the spine

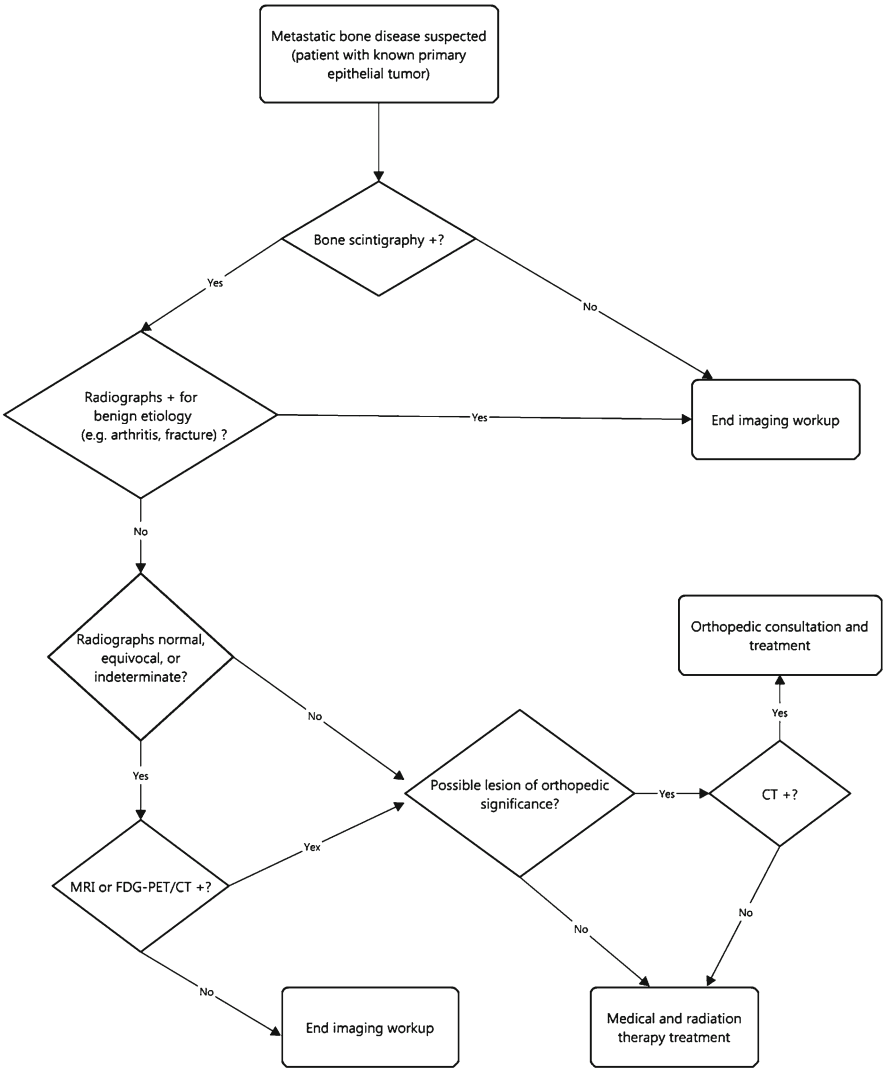

Fig. 6.8 Workup of metastatic bone disease

and pelvis), especially in cases of diffuse bone infiltration instead of localized lytic lesions [42, 45, 46]. Although more study is needed, at the current time MRI appears to be a better choice than FDG-PET for the initial staging of MM [42]. On the other hand, FDG-PET, with its ability to provide information about the physiologic activity of disease, may be preferable to MRI for follow-up imaging since treated lesions may still be evident on MR after therapy [45].

In summary, despite the limitations of SS and evidence in the literature of much higher sensitivity for more advanced imaging techniques such as (WB) MRI,

FDG-PET, and FDG-PET/CT, skeletal survey presently remains the gold standard in imaging workup of MM [34]. In addition, since according to current guidelines of the IMWG, only symptomatic MM patients receive treatment, skeletal survey remains the mainstay of radiological evaluation of myeloma patients (Table 6.5, Fig. 6.9).

All in all, radiographs form the lynch pin of accurate diagnosis of focal osseous lesions. They serve as the first line of imaging, except in a few specific clinical situations as described above. In cases where radiographs are non-diagnostic, in younger patients and in patients who have no history of epithelial neoplasm, MRI is usually the next study chosen to evaluate an osseous lesion [47]. On the other hand, if the lesion's appearance is consistent with a metastasis from an epithelial tumor, BS is usually the next study chosen in order to determine if there are other metastases elsewhere in the skeleton [12, 47]. Overall, CT is used less frequently than MRI, but it is the correct choice in selected circumstances: some specific entities, e.g., osteoid osteoma, certain anatomic locations, e.g., juxtacortical or location in a flat bone, to evaluate tumor matrix, i.e., osteoid, chondroid, and to evaluate if a lesion is of orthopedic significance [32].

Soft Tissue Lesions

Typically, patients present for evaluation of a soft tissue mass because they have noted a palpable lesion, a new localized asymmetry in the appearance of their body, or pain in a specific area. Sometimes clinicians may detect the masses or asymmetries on physical examination. Benign tumors of the soft tissues are overwhelmingly more common than malignant soft tissue tumors (100:1) [48], the most common being a lipoma.

While CR is typically the first examination to evaluate bone lesions, it has little utility for soft tissue masses other than occasionally to show evidence of fat or some calcification or ossification within a mass. More advanced imaging, particularly MRI, but also US and CT, is required to visualize and characterize soft tissue mass lesions [23].

MRI is the gold standard for evaluation of soft tissue masses, again because of its inherent soft tissue contrast resolution [23, 32, 39, 48, 49]. Because MRI can show bone marrow and cortical bone destruction, it readily depicts when a mass involves or arises from the marrow space to secondarily involve the adjacent soft tissues and vice versa.

In cases where a lesion is suspected on physical examination, MRI can confirm whether or not a lesion is actually present [39]. The technique can also distinguish between cystic and solid masses. MRI is the preferred imaging modality to evaluate spontaneous soft tissue hemorrhage in middle age and elderly adults as this is often a sign of an underlying neoplasm [23].

In the majority of cases, MRI findings will characterize the mass, what adjacent structures the mass involves and in some cases whether the mass is benign or

Table 6.5 Multiple myeloma: efficacy of imaging modalities

Imaging modality	Sensitivity	Advantages	Limitations
CR/Skeletal survey	80 %	Widely available	Extended acquisition time (minimum 20 films)
		Allows for screening evaluation entire body	Limited evaluation of ribs, sternum, and scapula
			At least 30 % trabecular bone destruction needed for detection
			Gold standard inferior to each of FDG-PET, FDG-PET/CT, and MRI but still most common initial imaging study
CT		Helpful in evaluation of deep structures and assessment of atypical and irregular bones and joints, and complex joint anatomy (e.g., sternum, sternoclavicular joint, spine, pelvis)	Insensitive, inadequate assessment of marrow involvement
			Lower sensitivity (vs. MRI, FDG-PET)
		Precise anatomic localization of findings	
		Depicts subtle, early bone cortex erosion	
MRI (without IV contrast)		Excellent bone marrow evaluation	Inferior assessment of mineralized bone damage (vs. CT)
		Superb anatomic detail	
		Sensitivity and specificity high	
BS	50 % (35–60 %)	Widely available	Sensitivity very low (worst of any modality)
			High false negative rate due to rapidly growing, near purely osteolytic lesions (e.g., renal, thyroid)
FDG-PET	90 %	Allows for evaluation of entire body	Most likely more for problem solving instead of routine staging
		Physiologic information	FDG-PET/CT more accurate than FDG-PET
		Most likely preferable to MRI for follow-up imaging, response to treatment, etc. (further studies needed)	Good coregistration of physiological and anatomical information in hybrid FDG-PET/CT raises localization ability of imaging

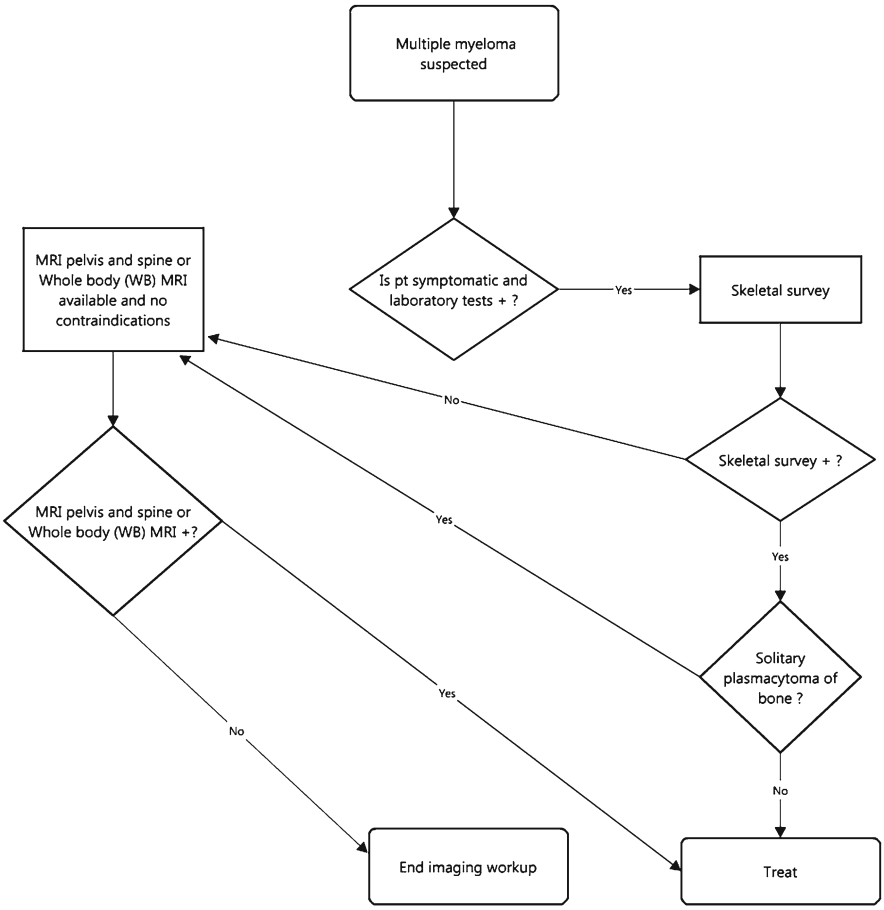

Fig. 6.9 Workup of multiple myeloma

malignant. Some lesions have a characteristic MRI appearance, permitting a confident diagnosis, e.g., various types of cysts, soft tissue hemangioma, lipoma, Morton's neuroma, plantar fibroma, elastofibroma, and fibrolipomatous hamartoma [39, 48, 49].

In the majority of cases, however, MRI findings will not yield a single diagnosis or sometimes even a confident determination that a lesion is benign [39, 48]. Because MRI can differentiate between necrotic/cystic and more viable, solid areas of a tumor, it may be used to direct where a lesion should be biopsied [23, 32].

Historically, CT was a front line imaging study for detection and characterization of soft tissue masses. As noted above, MRI has largely replaced CT in this capacity. In specific situations CT still has a role in evaluation of focal soft tissue lesions, for example to detect and characterize calcifications within a lesion or in anatomic

locations where motion artifact can degrade MRI image quality, e.g., lesions in the chest wall [23, 32]. CT, with its exquisite sensitivity for detection of calcium, may show lesion calcifications that are otherwise radiographically occult. This is valuable, for example, to differentiate myositis ossificans from a soft tissue malignancy. In its earlier stages, myositis ossificans can appear aggressive on MRI and so be mistaken for a malignant lesion [39, 50]. Here, CT has an advantage over MRI because it shows the organization of the newly ossifying tissues to better advantage, and this usually suffices to exclude malignancy [23].

US has a problem solving role in the evaluation of soft tissue lesions. As mentioned previously, its two main diagnostic strengths are its ability to differentiate between a cystic and solid mass [23, 49] and to show the level of vascularity of a lesion. For example, many lesions located around joints are cystic, e.g., ganglion cysts, synovial cysts, paralabral cysts, parameniscal cysts, Baker's cysts, or distended bursae. US not only can demonstrate that a lesion is cystic, but it also may show communication between the lesion and the adjacent joint space. US also can detect tiny calcifications, but CT is better for this application. As with other modalities US is unable to distinguish reliably between benign and malignant lesions, since there is significant overlap in findings [51].

US examinations have been developed for other specific indications such as evaluating Morton's neuromas and plantar fibromas in the feet or to diagnose rotator cuff tears in the shoulder. Regardless, because US is time-consuming and has limited fields of view, MRI is the main modality used for these applications at most institutions.

Even though most soft tissue malignancies are ^{18}FDG avid, ^{18}FDG-PET (/CT) currently does not play a large part in the imaging evaluation of soft tissue masses [23, 32, 52, 53]. Several studies have shown correlation between FDG uptake and the grade/aggressiveness of soft tissue sarcomas [54]. PET also has not been shown to reliably distinguish between benign and malignant lesions [23, 32], and so it adds little new clinically useful information to the patient's initial evaluation. It can provide value, however, in directing tissue biopsy to more metabolically active portions of a lesion [13, 55]. PET imaging also is valuable to follow treated lesions since it displays a measure of metabolic activity in the former tumor bed [53].

As expected, BS has limited utility in the evaluation of soft tissue lesions. Only a small minority of lesions can be seen on BS, largely because most soft tissue lesions lack the osteoblastic activity that BS is designed to detect.

In summary, the detection and characterization of soft tissue lesions is usually not as straightforward as with primary bone tumors. In contrast to focal bone lesions, only a small percentage of soft tissue masses will be visible on CR. Regardless, CR is generally the initial diagnostic imaging study [48]. In selected cases, plain radiographs serve as a useful adjunct to more advanced imaging modalities [23]. MRI is the current gold standard for evaluation and diagnosis of soft tissues lesions, mainly because of its superb soft tissue contrast resolution [39, 49]. In certain circumstances, however, CT may be preferable to MRI [25]. PET may have greater importance in the future, but it needs additional vetting before it becomes a routine part of the imaging armamentarium [23, 49] (Fig. 6.10).

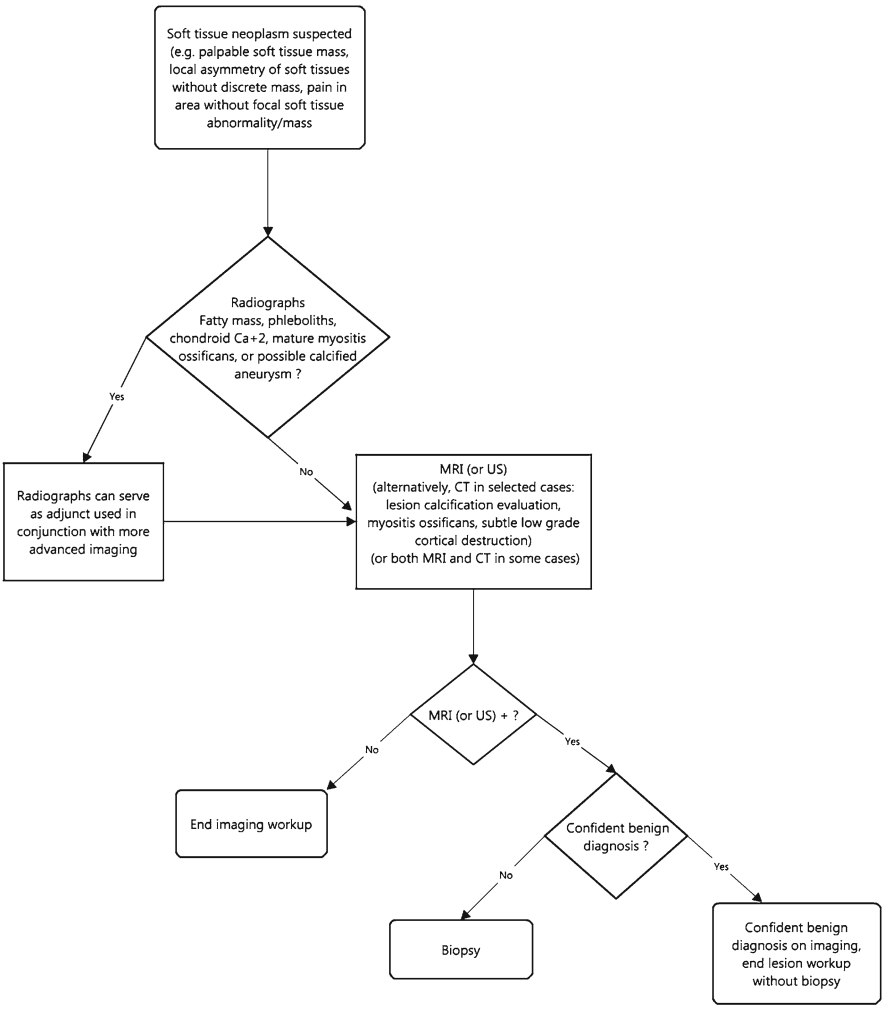

Fig. 6.10 Workup of primary soft tissue lesions

Arthritis

Although there are numerous well-known arthropathies, only three account for the vast majority of arthritis cases: osteoarthritis (OA), reflecting approximately 80 % of patients, rheumatoid arthritis (RA) and gout, each representing about 8 % of cases [13]. Regardless of the type of arthropathy, the initial evaluation of the patient is the same.

Clinical information including history, physical examination, symptoms, and laboratory data (serology, joint aspirate, etc.) plays an important role in the

diagnosis of arthritis. Newer laboratory tests, e.g., anticyclic citrullinated peptide (anti-CCP) antibody, have made serologic diagnosis of some arthritides possible without having to rely on imaging [56]. Imaging is nonetheless important to diagnose many arthropathies and remains an integral part of following a patient's course.

The advent of disease-modifying antirheumatic drugs (DMARDs) has dramatically changed the management of RA and seronegative spondyloarthropathies. It has been shown that DMARDs can slow or halt the progression of RA, psoriatic arthritis, and ankylosing spondylitis. Furthermore, there are data supporting existence of a therapeutic window of opportunity for patients with these inflammatory arthropathies early in the course of the disease when these drugs are apt to be most beneficial to the patient [57]. This is changing the role of imaging in the evaluation of inflammatory arthritis.

Traditionally, the most commonly used and important modality in the evaluation of arthritis is CR, but CT, US, and MRI also play important roles. BS has little or no application to imaging arthritis because of its low specificity. MRI and US provide the best overall assessment of disease, showing findings of both soft tissue inflammation and structural joint damage [56, 58]. They are, however, more costly and time-consuming than CR, making them more applicable to answering specific clinical questions than for use in routine screening. On the other hand, in early inflammatory arthritis when DMARDs have greater treatment potential, MRI and US may serve as first line imaging examinations.

Currently, the first imaging study performed for the evaluation of suspected arthritis is CR [58]. High resolution radiographs obtained with proper positioning are essential. As with focal lesions of bone, CR analysis often will suggest a single diagnosis or a narrow differential diagnosis. The sites imaged depend upon the type of arthritis suspected and, of course, where the patient has pain.

CR is performed routinely for degenerative disc disease in the spine and also for OA which tends to affect large weight-bearing joints and the smaller joints in the hands and to some degree the feet. When imaging large joints in the lower extremities, CR performs best when weight-bearing views are obtained. This is because loss of articular cartilage, the underlying etiology of OA, is reflected by joint space narrowing on CR and this is best evaluated when the joints are under load.

During early stages of arthritis, radiographs do not correlate well with clinical measures such as pain and disability. This is related to the relative insensitivity of CR, and so it is not until the patient has progressed to later stages that radiographs correlate with functional outcome measures. In addition, CR rarely identifies synovitis, bursitis, and inflammatory soft tissues changes such as tenosynovitis that characterize the early phases of inflammatory arthritis [58].

Such findings are all easily seen on MRI and US. In addition, MRI can detect marrow edema which is the strongest predictor of future development and progression of erosions and subsequent loss of articular cartilage [56]. Synovitis and marrow edema, in particular, often precede and predict later bone erosions and the chondral loss that result in irreversible joint damage. As a result, MRI, and to a

lesser extent, US are gaining popularity in evaluation of inflammatory arthropathies early in the course of disease [58].

CT is helpful in evaluating joints where anatomic complexity, joint orientation, or joint obscuration by adjacent structures limit the efficacy of radiographs, e.g., the sternoclavicular, temporomandibular, and sacroiliac joints. The main advantage and utility of CT is its ability to demonstrate cortical erosions, even those that are very small and subtle, and also to quantify total bone erosion volumes [59].

CT is at least equal to and possibly superior to MRI and US in erosion identification [58–60]. Unlike MRI, however, it cannot identify the bone marrow edema that precedes development of erosions, and it is also poor at detection of synovial proliferation and soft tissue inflammatory changes. Thus, CT is comparatively insensitive for detection of early arthritis, and so is rarely used in clinical practice except occasionally as a problem solving tool used in regions of difficult anatomy and some cases of septic arthritis and gout [58].

The sensitivity of US in detecting bone erosions is site-dependent, high in easily accessible joints but reduced in anatomically complicated joints [25, 58]. Where accessibility is optimal, US shows high agreement with MRI and possibly even CT at detection of bone erosions [58, 59]. Some studies suggest that US using color Doppler is more sensitive than MRI in showing the presence of synovitis and better in characterizing the synovitis by showing increased vascularity in inflamed tissue. As might be expected, joint effusions and synovitis which present clinically as periarticular soft tissue swelling are more easily identified using US than by physical examination [58]. Thus, given the importance of instituting DMARDs in a timely manner, US with its high sensitivity for identification of synovitis, bursitis, and inflammatory soft tissues changes has had an increasing role in early stage inflammatory arthropathies [58].

MRI can not only show erosions and joint space narrowing associated with inflammatory arthritis, but it also depicts both extra- and intra-articular soft tissue inflammatory changes early in the course of disease. As mentioned, not only does it show synovitis, but it also shows bone marrow edema that occurs in early disease [56]. This marrow edema histologically represents true osteitis consisting of active bone inflammation with cellular inflammatory infiltrates, but there is no free water making the term edema somewhat of a misnomer. Bone marrow "edema" on MRI predicts future erosions better than any other imaging finding [56]. Ultimately, the main goal of MRI is to identify precursor lesions before arthritis progresses to bone erosion, cartilage destruction, and joint structural damage [56]. Early imaging diagnosis of inflammatory arthritis will thus allow the clinician to institute prompt, effective treatment with DMARDs and so slow or even halt progression of the disease.

Regrettably, serologic testing, with the possible exception of anti-CCP antibody for RA, does not predict the future severity of an arthropathy [56]. This has led MRI to become a commonly used tool for the early diagnosis of clinically suspected undifferentiated inflammatory arthritis. The great disparity in cost and time of

Table 6.6 Inflammatory arthropathies: efficacy of imaging modalities for findings in early and late disease

Imaging modality	Early (joint effusion, synovitis, tenosynovitis)	Early (bone marrow edema)	Late (erosions)	Limitations
CR	+	–	++	Radiation exposure 2-D representation of 3-D information Very poor detecting early disease findings such as inflammatory soft tissue changes Sensitivity very low in demonstrating even findings of late disease (e.g.,) erosions-stage where therapeutic window for DMARDs has likely passed
US	+++++	–	++++	Operator-dependent Limited availability of well-trained, experienced, skillful MSK sonographers
CT	++	–	+++++	Radiation exposure Not adequate for detection of inflammatory soft tissue pathology and bone marrow findings of early disease
MRI	++++/+++++	+++++	++++	Not always (easily) available Expensive Long study length may result in image quality degraded by motion artifact (difficult for severely ill patients to remain in scanner for complete study) Nephrogenic systemic fibrosis (NSF) risk from IV gadolinium-based contrast agents (GBCAs) Less effective than CT in demonstrating early cortical bone erosion

acquisition between CR and MRI relative to the additional benefit provided by MRI militates against routine use of MRI over radiographs [58] (Table 6.6).

In summary, considerable advances have been made over the past decade in the application of advanced imaging techniques to diagnosing early RA and seronegative spondyloarthropathies, with an aim toward achieving improved clinical outcomes. Although CR is still the most frequently used imaging study for diagnosis of arthritis and is viewed as the "gold standard" [58] by the majority of the medical community, other more advanced imaging modalities are clearly more effective in detection of inflammatory changes in the soft tissues and identifying joint destruction. Radiographs have extremely low sensitivity in detection of non-osseous findings such as synovitis and tenosynovitis, and they are non-diagnostic in detection of bone marrow "edema"/osteitis, all findings of early disease in inflammatory

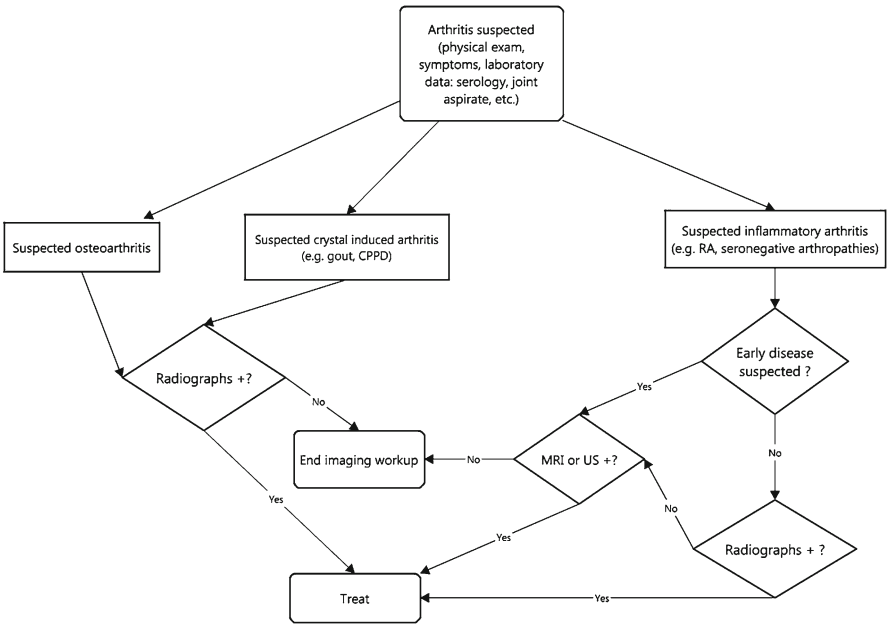

Fig. 6.11 Workup of inflammatory arthritis

arthropathies. US offers high sensitivity assessment, especially with regard to inflammatory soft tissue findings and for erosions related to joint damage. MRI and US are increasingly used in clinical practice with good benefit. CT, on the other hand, has a limited role in the clinical evaluation of arthritis [58]. The advent of DMARDs and hence the ability to arrest progression of disease has brought these more sophisticated studies to the fore (Fig. 6.11).

Metabolic

Osteoporosis

Osteoporosis is the loss of bone mass such that the skeleton becomes pathologically prone to fracture. Today, with people living longer lives, these fractures are a substantial source of morbidity and mortality. While previously the diagnosis of osteoporosis required occurrence of a fragility type fracture, we now are able to employ techniques that quantitatively determine bone mineral density (BMD). In the assessment of BMD, dual energy x-ray absorptiometry (DXA) is currently

the preferred examination. This is one of many available techniques, including techniques that are based on CR, US, CT, and MRI. Each of the available techniques has advantages, but none are as inexpensive, have as low a radiation dose, and are as precise, i.e., repeatable, as DXA [61]. CT techniques, for example, provide higher accuracy, i.e., true measurement of bone mass than DXA, but the added accuracy is not worth the increased expense and radiation exposure. Furthermore, it should be noted that none of the available techniques, with perhaps the exception of some MRI techniques, evaluate bone architecture, only bone mass. This greatly hampers the effectiveness of any available examination in the prediction of osteoporotic fractures.

World Health Organization (WHO) criteria for diagnosing osteoporosis are based only on DXA and single photon absorptiometry (SPA) measurements. Preferably, BMD measurement using DXA is performed at two anatomic sites, most commonly, the hip (femoral neck) and spine. In some cases, such as patients with hyperparathyroidism, measurement of BMD in the forearm with SPA is used as one of the two locations [61].

When DXA is unavailable, quantitative computed tomography (QCT) is the favored alternative technique to measure BMD. Since QCT evaluates only trabecular bone which has higher turnover than cortical bone, it is thought to be more sensitive at detecting early bone loss. Also because the volume of tissue that it evaluates is directly measured and based on a projection like DXA, it is not prone to accuracy error from osteophytes and vascular calcifications in the path of the beam. Unfortunately, QCT cannot be used to diagnose osteoporosis based on the quantitative BMD value obtained, since it has never been validated for WHO criteria. However, through comparison of BMD values to a reference database for the technique, QCT can identify patients with low bone mass who are at risk for fracture [61].

Several other tests for BMD are also reliable in detection of those patients at risk for fracture. Techniques such as peripheral quantitative computed tomography (pQCT), peripheral quantitative ultrasound (pQUS), single X-ray absorptiometry (SXA) [62], and radiographic absorptiometry are less expensive and may be able to identify a larger percentage of the population at risk for osteoporotic fractures. Unlike DXA and QCT, these other technologies are not approved for following treatment [61].

BS, while it provides no information about BMD, is valuable in osteoporotic patients since it provides a whole body survey of the skeletal system for insufficiency fractures. This is particularly advantageous since osteoporosis-related fractures often occur in multiple locations, and some may be asymptomatic.

In conclusion, DXA is the current gold standard for measurement of BMD because it is both inexpensive and precise. Diagnosis of osteoporosis using WHO criteria is only possible with DXA and SPA. Many techniques, including MRI, pQCT, pQUS, SXA [62], and radiographic absorptiometry, are available to measure BMD, each with its own strengths and weaknesses (Tables 6.7 and 6.8).

Table 6.7 Imaging investigations for specific types of musculoskeletal pathology

Diagnosis	Imaging modality of choice in initial evaluation	Second most preferred imaging modality	Other imaging modalities (including role)	Additional points
Fracture	CR	MRI without contrast (occult acute traumatic fracture, stress fracture)	BS (diagnosis)	CR may take up to 7–10 days after injury to diagnose fracture
			CT (presurgical planning: e.g., complex fracture-dislocation)	MRI diagnosis within a few hours typically Usually takes 1–3 days after injury for high sensitivity fracture diagnosis on BS
Meniscal tear	MRI without contrast	CT arthrography (if MRI unavailable or contraindicated)		Conventional arthrography as last resort
Rotator cuff tear	MRI without contrast	US	CT arthrography (if MRI unavailable or contraindicated and US not offered)	MR arthrography preferred over conventional MRI without contrast for glenohumeral instability Conventional arthrography as last resort
Osteomyelitis	CR	MRI without and with IV contrast	MRI without IV contrast	CR sensitivity low
			BS	BS sensitivity high, specificity low
			Labeled WBC	Usually takes 2–3 days after start of infection for BS to diagnose
			BS + Labeled WBC	BS sensitivity increased by addition of labeled WBC study. Bone probe results may obviate need for imaging
			CT (assess pathologic fracture risk by identifying lesions of orthopedic significance)	Biopsy required in some cases (indeterminate, equivocal imaging)
Soft tissue abscess	CR	MRI without and with IV contrast US	MRI without IV contrast	CR sensitivity low
			CT with IV contrast	US, MRI with IV contrast, and labeled WBC sensitivity and specificity high
			Labeled WBC	US and CT can guide aspiration

(continued)

Table 6.7 (continued)

Diagnosis	Imaging modality of choice in initial evaluation	Second most preferred imaging modality	Other imaging modalities (including role)	Additional points
Primary bone tumor	CR	Aggressive or indeterminate lesion on CR: BS (To determine if there is multifocal disease) Thyroid cancer		
Bone metastases	CR (specific site clinically suspected)	CR (1 or more indeterminate or equivocal lesions on screening BS)	CT (assess pathologic fracture risk-identify lesions of orthopedic significance)	CR insensitive (at least 30 % bone destruction needed for detection)
	BS (screening for multifocal disease)	BS (CR normal)		BS sensitivity moderate to high, specificity moderate
	FDG-PET/CT	FDG-PET/CT (BS or CR normal)		Total body survey possible using BS, FDG-PET/CT, or WB MRI
	Whole body (WB) MRI	MRI (BS abnormal then CR normal, indeterminate or equivocal)		WB MRI specificity and sensitivity equal to or greater than each of BS and FDG-PET/CT separately, but in virtually all ACR appropriateness criteria clinical scenario variants these two modalities are favored over MRI
Multiple myeloma	Skeletal survey (if symptomatic), and laboratory tests abnormal	Whole body MRI MRI spine/pelvis if SS normal or with solitary plasmacytoma of bone	CT (assess pathologic fracture risk-identify lesions of orthopedic significance)	BS lacks sensitivity
Early rheumatoid arthritis	MRI without and with IV contrast US	MRI without and with IV contrast US	CT (erosions)	CR insensitive to identify findings of early disease (e.g., tenosynovitis, synovitis, bone marrow edema)
Established rheumatoid arthritis	CR	MRI without and with IV contrast US (if CR negative for RA, OA, gout, etc.)	CT (erosions)	CR sensitivity limited for findings of late disease, e.g., erosions

Table 6.8 2012 Medicare global reimbursement of various imaging modalities

Imaging modality	2012 Reimbursement ($)
CR	35
Skeletal survey	75
US limited (mass)	45
US complete (tendons, muscles, etc.)	130
CT (w/o, w/)	245–300
BS	275
BS (3 phase)	315
Labeled WBC study	375
MRI (w/o, w/ and w/o)	430–675
PET/CT	1,225

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