# Textbook of Polytrauma Management

## A Multidisciplinary Approach

Hans-Christoph Pape
Joseph Borrelli Jr.
Ernest E. Moore
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*Editors*

*Third Edition*

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# Foreword

In this comprehensive textbook, experts in the field of various systems pathology, inflammatory and immune response, pediatrics, and gerontology address the issues that may affect the clinical course in patients with severe multiple injuries.

Most standard textbooks that deal with simple or complex fractures have focused on anatomy, pathology, and occasionally complications of the musculoskeletal injury. Likewise, those that focus on the aspects of general surgery demonstrated a certain lack of management principles for fracture care. This textbook overcomes this particular issue and emphasizes on clinical decision-making.

This is important, as certain situations, such as extremes of age, extremes of soft-tissue or osseous injury, and other special situations, such as pregnancy, represent the true challenge for a good outcome.

These "associated" elements of the clinical decision-making process are the most difficult to teach and the most dependent on the clinical experience and have rarely been centralized and addressed in a single course. It has become evident that along with the centralization of trauma care in Western societies and the associated certification processes, the technical aspects to address acute hemorrhage and fracture fixation strategies are not necessarily the primary issue in most clinical scenarios.

As trauma training of a musculoskeletal surgeon evolves, he/she may be the most senior physician on the trauma team, and the need for a reference to validate the opinions of those comanaging the patient may evolve acutely in the absence of a full team of expertise.

This compilation of special situations and discussion in this single source will serve as a reference for the traumatologist, whether the basis of his/her training is general or orthopedic surgery and whether the practice is entirely trauma or they give part of their time outside of their clinical interest to cover the call burden of an active trauma hospital.

The sections on epidemiology, costs, and outcomes of these injuries to the lives of our patients and the society that shares the costs of those injuries are humbling to those of us who provide care and remind us that a good outcome is more than a good X-ray.

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# Preface

This book focuses on the multidisciplinary management of a patient with multiple injuries. The third edition of this book has been modified with a continued emphasis on the concept of including all subspecialties involved in trauma care.

Certain changes in trauma care—such as improved resuscitation, management of coagulopathy, selective role of damage control, knowledge about the risks for complications, and new scoring systems—have been added. Also, the part on trauma system changes and their influence on rescue conditions has been updated. The selection of authors continues to be twofold. All of them are experts in their particular fields. In addition, we have sought to include contributions from all over the world, thus respecting the fact that trauma is a global challenge.

This textbook has also been expanded in terms of outcome assessment for certain injury types known to be responsible for long-term issues. Among these are bone infections, bone defects, and certain fracture types.

We hope that these changes will improve trauma care and challenge all to continue research to optimize outcome.

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# General Aspects of Trauma Care

# Impact of Trauma on Society

1

Hans-Peter Simmen, Carina Eva Maria Pothmann, Hans-Christoph Pape, and Valentin Neuhaus

**Learning Objectives, Learning Goals, Questions Covered in the Chapter**

- Health care costs, special consideration of polytraumatized patients, outcome following severe trauma, what types of injury, workplace accident vs. leisure time accidents, restitutio ad integrum vs. permanent disability, posttraumatic stress disorder, long-term follow-up of severe trauma

## 1.1 Introduction

Trauma has become a major cause of fatality and disability worldwide and therefore a major public health problem. For instance, every year across England and Wales, with a population of 57 million, 10,000 people die after an injury. According to the WHO, nearly 6 million people die after an injury each year. This represents 10% of the world's death. Trauma is the leading cause of death among children and young adults under the age of 45.

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Approximately 1.35 million people die each year as a result of road traffic crashes. The 2030 "Agenda for Sustainable Development" has set an ambitious target of halving the global number of deaths and injuries from road traffic crashes by 2020. Road traffic crashes cost most countries 3% of their gross domestic product. More than half of all road traffic deaths are among vulnerable road users: pedestrians, cyclists, and motorcyclists. 93% of the world's fatalities on the roads occur in low- and middle-income countries, even though these countries have approximately 60% of the world's vehicles (Figs. 1.1 and 1.2).

In addition, there are many millions of nonfatal injuries each year. These injuries cause serious health care costs, posing a tremendous burden on society. Additionally to health care costs, productivity loss due to injury adds up to the costs.

Injuries range from a great variety of injury types and severity levels, from frequent minor injuries (e.g., superficial injuries) to rare major injuries (e.g., polytrauma). Trauma may have lifelong physical and psychological effects on its survivors and families [1–4].

The knowledge about health care in societies outside Europe, North America, and Australia is scarce, in particular, there are no sophisticated rescue systems available in wide areas of Asia, Africa as well as South America. Even the emergent global world power China does not offer a comprehensive trauma statistic. Therefore, it is


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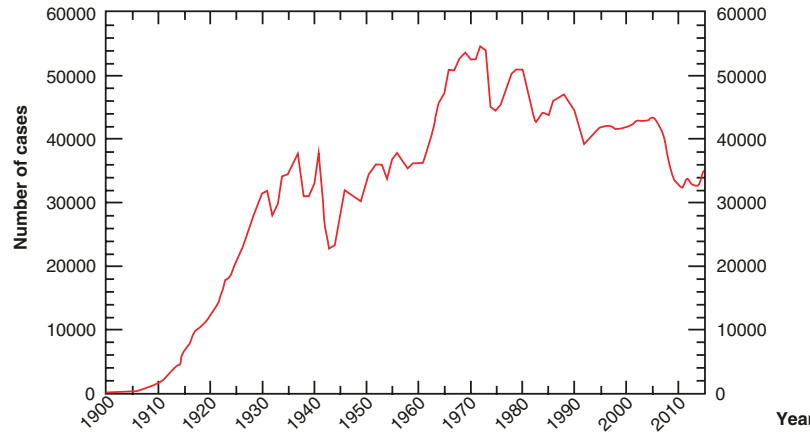


**Fig. 1.1** Deaths in road raffic accidents in the USA [5]

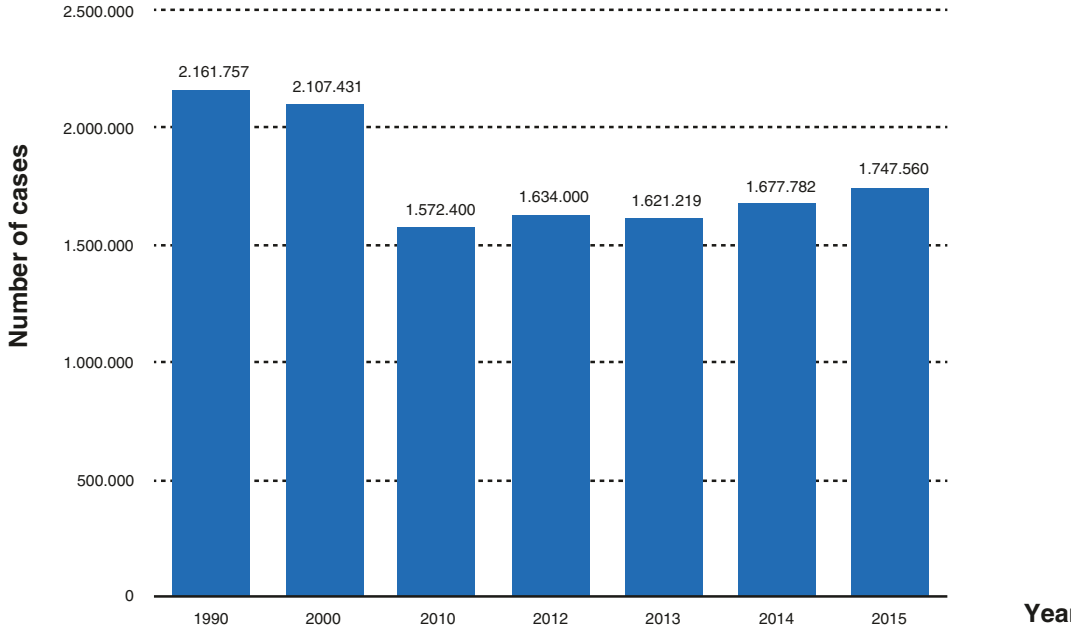


**Fig. 1.2** Road traffic accidents in the USA [5]

much more difficult to draw any conclusions of the impact of trauma in these regions.

### 1.1.1 Definitions

An injury is any damage to the human body of external cause. It is a general term that refers to harm caused by accidents, falls, hits, acts of violence, and more and may occur at home, work, referred to traffic accidents or during leisure activities. It can be due to impact from blunt objects or from objects that penetrate the body. Common types of injury include abrasions, lacerations, hematomas, broken bones, joint dislocations, sprains, strains, and burns. An injury is usually regarded as an unintentional bodily lesion at the organic as well as at the mental level, resulting from acute exposure to energy (mechanical, thermal, electrical, chemical, or radiant) that exceeds the threshold of physiologic tolerance [5].

### 1.1.2 Case Load of Trauma

Switzerland, a small industrialized country in the heart of Europe with nearly 9 million inhabitants (working population 5 million), may be regarded as an European example. According to a summary statistic of the accident insurers, there were 855′000 damage events registered in 2018, 610 of these resulting in death. Total costs were as high as 4550 million EUR (medical costs 1797 million EUR, wage loss 2571 million EUR). Follow-up costs were not included [3].

According to the United States CDC-statistics unintentional injuries accounted for 169′936 deaths with a population of 325 million in 2017, which is "cause of death" rank 3 besides heart diseases [rank 1] and malignancies [rank 2] [6].

### 1.1.3 What Type of Trauma/Injury? Polytrauma—Potentially Life-Threatening Combination of Injuries

Mild, moderate, severe, critical, and fatal can be distinguished. The most common types of unintentional injury belong to the categories "mild and moderate", where a "restitutio ad integrum" may be expected. Major trauma describes serious and often multiple injuries that have the potential to cause prolonged disability or death. There are many causes of major trauma, blunt and penetrating, including falls, motor vehicle collisions, stabbing, and gunshot wounds. The most typical injuries in the German and Swiss polytraumatized patients are blunt traumas (90%–95%) caused by direct collision (e.g., an external blow or force (extrinsic causes)), whereas 5%–10% are penetrating due to stab or gunshot wounds.

The internationally recognized "Injury severity score" (ISS) helps to categorize injuries. Sixteen points or more in this score are regarded a severe injury with potential danger of life [6, 7]. Several trauma registries were established to understand the benefits and risks associated with different types of treatment with the goal of continuous improvement of therapeutic options [3, 8, 9]. The German trauma registry [10] recorded 32,580 patients (out of about 83 million people) in 2018 with an ISS ≥ 16, whereas in Switzerland (about 9 million people) 1817 patients were registered during the same period [9] (Figs. 1.3, 1.4, 1.5). The injury pattern of the polytraumatized patients in the German trauma registry is shown in (Fig. 1.4). The most common injured body regions include head 47%, chest 45%, spine 30%, upper extremities 29%, lower extremities 24%, abdomen 18%, pelvis 15%, and face 10%.

Due to legislation in many countries such as speed limits on roads, safety requirements of

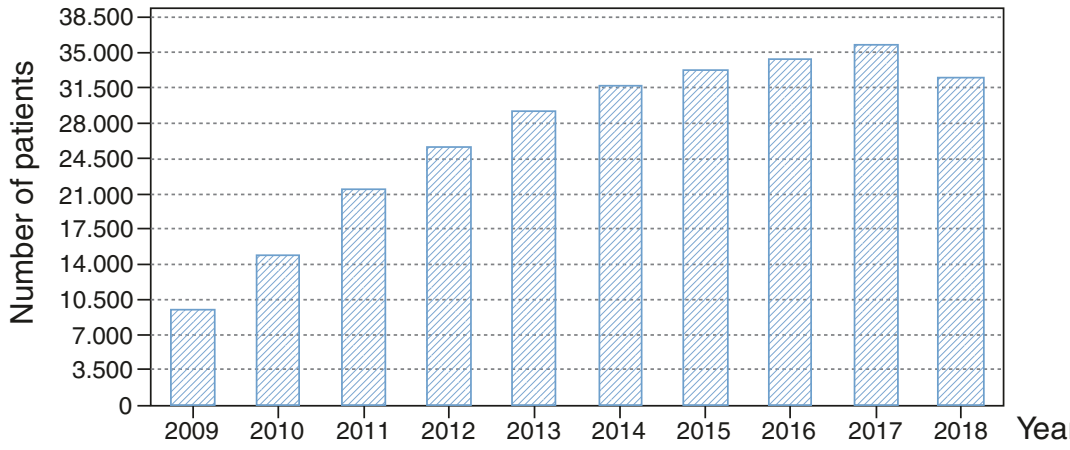


**Fig. 1.3** German trauma registry 2019 [8]

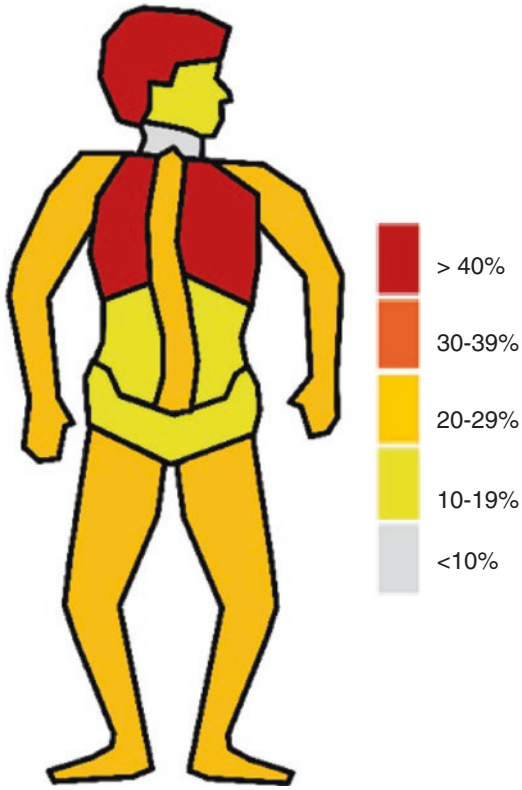


**Fig. 1.4** German trauma registry 2019: injury pattern [8]

cars, reduced allowed alcohol consumption, road traffic accidents could be reduced in recent years, as well as accidents at working places. However, leisure time accidents are steadily increasing. This may be attributed to the so-called fun society. Many people, especially younger ones, live their credo "no risk - no fun."

### 1.1.4 Sport and Fun

Sports accident in high- and middle-income countries is becoming more and more important (so-called fun society accidents). According to the Swiss summary statistics football (soccer) accounts for 38% of accidents, whereas skiing and snowboarding account for 25% [8]. The top sports injuries: An estimated 60% are knee injuries (patellofemoral syndrome, meniscal tears, cruciate ligament ruptures) followed by shoulder injuries including dislocations, concussion, tennis elbow, hamstring muscles, lumbago with sciatica, shin splints, groin pain, heel inflammation [9].

Several types of athletic injuries are recorded:

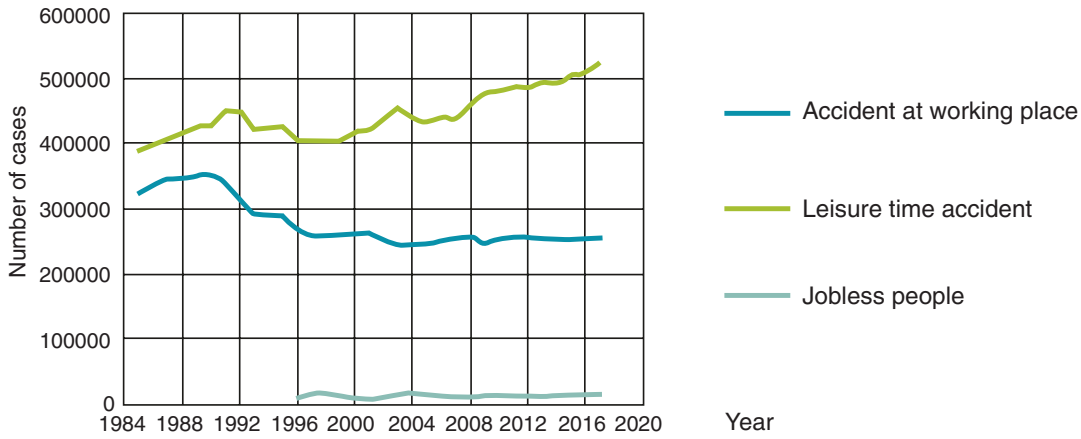


**Fig. 1.5** Summary statistics swiss accident insurers 2019 [9]

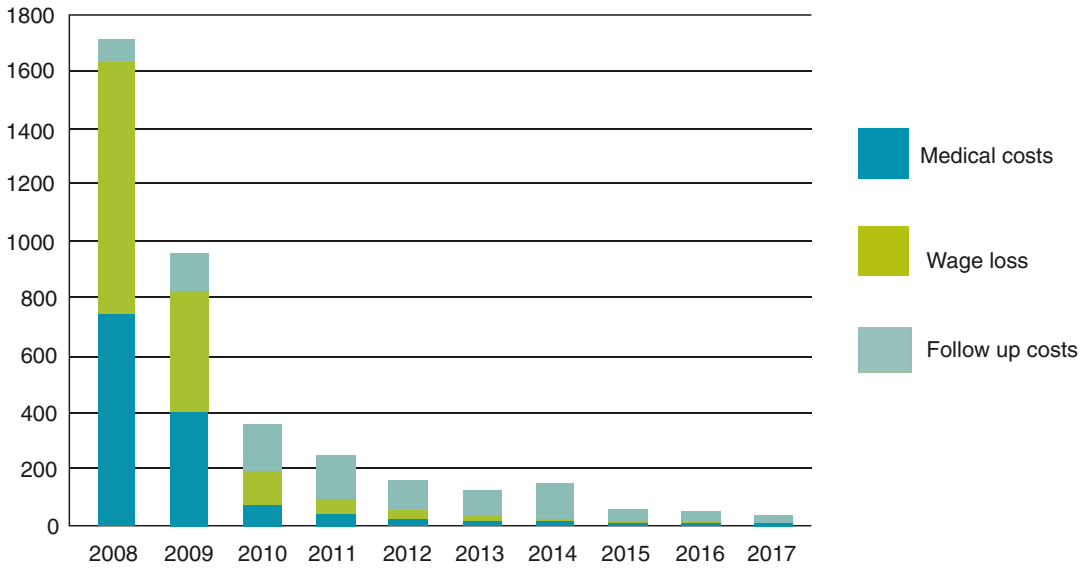


**Fig. 1.6** Total costs in million EUR for all 800,000 patients who had an accident in 2008 Summary statistics swiss accident insurers 2019 [9]

*Acute*, usually a result of a single traumatic event, e.g., fractures, ankle sprains, shoulder dislocations, and hamstring muscle strain

*Overuse of a body area*, subtle and occur over time.

*Chronic*, usually lasting 3 months or even longer, e.g., tennis elbow, shin splint, runner's knee, and heel inflammation

*Strain, sprain* of muscles

*Tears* in meniscal structures and cruciate ligaments

### 1.1.5 Impact

The impact of trauma on the individual including her/his family as well as on the society depends clearly on the severity of injury. Getting back to daily activities, focusing on personal well-being, minimizing productivity loss, disability following injury, chronic pain, psychologic implications have to be considered. Losing control over personal well-being as well as social environment may be the worst-case scenario.

In the majority of unintentional injuries a "restitutio ad integrum" is achieved. Such good results may not be possible in polytraumatized patients. Many of these are disabled for the rest of their private as well as their professional life. This group of patients need financial and social support, which is an extraordinary burden for insurances and taxpayers. In Switzerland, it is estimated, that a polytraumatized patient accounts for total costs of about 2 million EUR [9] (Fig. 1.6).

Productivity costs and return to work should be considered when assessing the economic impact of injury in addition to medical costs. Prognostic factors may assist in identifying high cost groups with potentially modifiable factors for targeted preventive interventions, hence reducing costs and increasing return to work rates [11].

Even in the scarce reports from China the authors declare that injury causes more productivity losses than any disease group in China, hence injury control and prevention merits are high priority in China's health agenda [12].

Steel et al. investigated polytraumatized patients 10 and more years following injury. They found that patients with multiple injuries who sustained a traumatic brain injury (TBI) were more likely to be female, younger in age at the time of injury, have higher injury severity scores and a greater number of upper extremity injuries when compared with those without TBI. Patients

with TBI reported poorer psychological functioning and more frequently reported chronic pain as well as poorer psychological functioning [13].

In a recent longtime follow-up study Halvachizadeh et al. noticed that at least 20 years after injury, no correlation was found between the development of psychiatric complications and the severity of injury. While the rate of full-blown posttraumatic stress disorder (PTSD) was low, nearly half the study population regularly suffered from at least one psychiatric symptom attributable to the initial trauma. Awareness for the development of psychiatric complications and early initiation of psychiatric counseling are advisable [14].

Economic consequences are reported by polytraumatized patients even ten or more years after injury. Financial losses appear to be common in patients between 19 and 50 years. In contrast, social deprivation appears to be most pronounced in the younger age groups. Early socio-economic support and measures of injury prevention should focus on these specific age groups [15].

If patients survived, traumatic lower extremity amputation in combination with a high initial maximum AIS (MAIS) spine score was a strong predictive parameter for an increased odds of adverse clinical outcomes late after trauma [15, 16].

However, in many polytraumatized patients the traumatic event results in a PTSD. This is one of the very few mental disorders that, by definition, requires an environmental context as a precondition for diagnosis. Both trauma sequelae and recovery always occur in the context of social interpersonal contexts, for example, in interaction with a partner, family, the community, and the society [17].

### 1.1.6 Conclusion

The traditional view of injuries as "accidents," or random events has resulted in the historical neglect of this area of public health. However, the most recent estimations show that injuries are among the leading causes of death and disability in the world. They affect all populations, regardless of age, sex, income, or geographic region. Injuries affect mostly young people, often causing long-term disability. Decreasing the burden of injuries is among the main challenges for public health in the next century. Injuries are preventable, and many effective strategies are available.

Much of this chapter focused on trauma victims themselves. However, do not forget the psychological as well as the economic stress and financial constraints for family members. Unintentional injuries, such as road traffic accidents (car, motorbike, bike, pedestrian), leisure time accidents, workplace accidents, and burns are increasingly significant public health issue. Comprehensive care of trauma victims including family members is essential.

**Take Home Messages**

- Trauma is a major cause of fatality and disability worldwide.
- The impact of trauma on the individual including his family as well as on the society depends on the severity of injury and the resilience to cope with the injury and the consequences.
- Getting back to daily activities, focusing on personnel well-being, minimizing productivity loss, disability following injury, chronic pain, psychologic implications have to be considered.

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# Economic Aspects of Trauma Care

2

Yousif Atwan and Emil H. Schemitsch

**Learning Objectives**

- Understand the incidence and major causes of trauma and associated mortality.
- Understand the direct and indirect costs of trauma on society.
- Understand the utility and effectiveness of preventative measures in reducing the economic burden of trauma.
- Understand and evaluate the disparity in road traffic safety across nations.
- Understand the effectiveness of osteosynthesis in decreasing costs and mortality associated with trauma.

## 2.1 Introduction

Trauma and injuries are substantial causes of mortality and morbidity worldwide. It is estimated that over 5 million trauma related deaths occur on an annual basis [1, 2]. This represents 9.6% of global mortality and has been increasing over time [2]. The upward trend is largely attributed to a 46% increase in death due to road traffic trauma worldwide [2]. Alarmingly, despite their substantial economic burden, trauma accounts for 32% more deaths than tuberculosis, malaria, and HIV/AIDS combined (Fig. 2.1) [3]. Furthermore, trauma is the leading cause (40%) of death among young people (under 44 years of age) who often are economically essential members of society [4]. Furthermore, the Global Burden of Disease study group demonstrated that injuries account for 11.2% of disability adjusted life years (DALYs) worldwide [5]. Therefore, trauma and injuries are an economic burden due to healthcare expenditures as well as reduction in economic productivity of patients due to prolonged hospitalization, rehabilitation, disability and death [6].

## 2.2 Cost of Injury

The total economic burden placed on society by trauma can be divided into direct and indirect costs. Direct costs include health care expenses to the individual and health care system due to the traumatic events. Indirect costs include expenses related to the decline of productivity due to disability, rehabilitation, prolonged hospitalization and death. In Canada, the total cost of injury in 2010 was $26.8 billion with 59% calcu-

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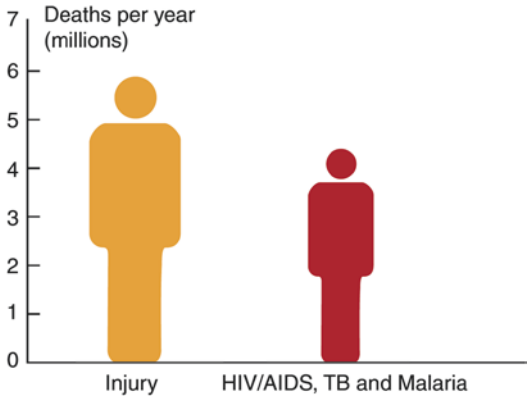


**Fig. 2.1** Mortality due to injury compared to other causes worldwide [3, 5]

lated to be due to direct costs [6]. However, as indirect costs may be harder to estimate, it is possible this value could be even higher in reality. If current epidemiological trends continue, the Public Health Agency of Canada estimates that total costs related to trauma will rise by 180% in 2035 [6].

The distribution of direct costs to patients and the medical system vary from country to country due to public and private funding of medical care. Initial presentation to hospital usually activates a trauma team involving various physicians, nurses, social workers and coordinating staff. Often, medical or surgical interventions such as radiographic imaging, blood transfusions and utilization of operative and intensive care suites are required during the hospitalization period which include additional costs. Post hospitalization, costs of rehabilitation, prosthetics/aids, home care and medical prescriptions may also be endured. Data from the National Study on the Costs and Outcomes of Trauma of over 5000 moderate to severely injured patients who were treated and discharged from United States (US) hospitals was used to estimate overall treatment costs [7]. It was determined that the mean 1-year cost of trauma care per patient was $75,210 USD and about 58% of that cost was accrued during the initial hospitalization period [7]. Meanwhile, the estimated total direct annual treatment costs of US adult trauma was approximately $27 billion USD in 2005 [7]. These direct costs represent a significant financial burden to the healthcare system, the patient or private insurance depending on the method of funding.

Indirect costs of trauma care are much more difficult to quantify as they have variable and expansive effects for each individual. A nation's economy can be severely affected when patients are unable to return to their pre-injury societal productivity. Studies have shown that only 60–66% of moderate to severely injured patients return to their full-time work duties [8, 9]. In the United States, an estimated $326 billion in loss of productivity costs occur annually due to trauma leading to missed work days [10]. Furthermore, costs incurred by patients with disabilities are severely underestimated in the literature as the loss of quality of life is a difficult intangible cost to quantify [11].

## 2.3 Implications of Economic Prosperity

Typically, economic improvements tend to lead to improvements of health indices within certain populations [12, 13]. Nonetheless, some studies have demonstrated an inverse relationship between injury rates and economic prosperity [12–14]. However, as road traffic trauma is one of the leading causes of injury, this may explain this effect. Despite conflicting literature, studies of developed countries indicate that sustained economic prosperity is associated with increased road traffic trauma, as more of the population would be able to afford to own and operate a motor vehicle [12, 13]. With regard to road traffic trauma, there has also been conflicting evidence regarding the association of increasing gasoline prices and rates of motor vehicle/motorcycle trauma [15, 16]. A Canadian study assessed the association of long-term economic prosperity and the resulting effect on trauma. Over a 16 year period of increasing mean annual gross domestic product (GDP), there was an increased risk of hospital admission due to trauma but no association was found with trauma mortality [14].

## 2.4 Prevention

Trauma can be divided into intentional and non-intentional injuries. Intentional injuries include those of self-inflicted harm, acts of violence towards self or others as well as combat related injuries. Non-intentional injuries such as falls, accidental fires, road traffic collisions and weather-related incidents tend to be more susceptible to preventative actions. Since trauma has significant costs to a country's economy and expenses, many governments have placed substantial efforts in developing and implementing preventative measures to reduce incidence and resulting costs of trauma (i.e. United States has founded the United States National Center for Injury Prevention and Control). As countries look to cut costs on the medical expenses related to triaging and treating trauma, it has been suggested that resources would be better allocated with injury prevention as more than half of fatalities may have been prevented with better preventative measures prior to the injuries [17]. This is especially true in higher income countries where there are only marginal improvements in medical care systems compared to low to middle income countries [17]. The Children's Safety Network, which is funded by the US Department of Health and Human Services, outlined a number of preventative measures (Table 2.1) and their associated societal cost savings in preventing trauma [18].

**Table 2.1** Preventative measures and associated overall societal cost savings [18]

| For each USD spent on: | Societal savings (USD) |
|---|---|
| Childproof cigarette lighter | $80 |
| Booster seat | $71 |
| Bicycle helmet for ages 3–14 years | $45 |
| Child safety seat | $42 |
| Zero alcohol tolerance for drivers under 21 | $25 |
| Smoke alarm | $18 |

### 2.4.1 Road Traffic Injuries

Along with over 5 million deaths, the WHO estimates over 20 million non-fatal injuries occur worldwide on annual basis due to road traffic injuries [3]. Furthermore, despite having only approximately 60% of the world's motor vehicles, low and middle income countries account for 93% of road traffic fatalities [19]. Interestingly, even within countries of high income, those of lower socioeconomic status are more likely to be involved in road traffic trauma [3, 19]. These road traffic collisions can cost nations up to 3% of their GDP on an annual basis [19]. In 2017, the WHO created a report outlining worldwide recommendations of preventative actions against road traffic collisions that lead to trauma [20]. Their assessments focussed on improving speed regulation, infrastructure status and safety regulations.

Although the world's fleet of motor vehicles is projected to double to over 2 billion by 2030, safety regulations across the world vary significantly and are non-existent in certain countries [21]. The United Nations (UN) World Forum for Harmonization of Vehicle Regulations is the group with the goal of unifying safety standards for all countries that include regulations on seat belts, frontal/side impact, child restraint anchorage points and pedestrian protection. A recent report indicated that over 40,000 fatalities, 400,000 severe injuries and $143 billion USD could be saved by 2030 in four Latin American countries if these regulations are abided by [22]. Furthermore, over 50% of roads assessed in 60 countries lacked basic infrastructure required for safe mobilization of pedestrians, cyclists and vehicle/motorcycle occupants. It was determined that merely improving the 10% highest risk roads in each of the 60 countries over the next 20 years would have the potential of preventing 3.6 million fatalities and over 40 million severe injuries [23].

### 2.4.2 Osteoporosis

Worldwide, one in three women and one in five men endure an osteoporotic fracture within their lifetime [24]. Hip fractures account for over half of osteoporotic fracture related costs as they are associated with a four-fold likelihood of requiring a long-term care facility post-treatment [25, 26]. This results in an expected annual direct cost of $25.3 billion USD by 2025 for the treatment of osteoporotic fractures in the US [27]. Overall, osteoporotic fractures result in direct medical costs as well as quality adjusted life years costs due to subsequent impairments. These include impairments to mobility, social wellbeing, physical function and quality of life [25].

In response to the increasing prevalence and economic burden of trauma with underlying osteoporosis, the American Society of Bone and Mineral Research and International Osteoporosis Foundation (IOC) have developed Fracture Liaison Services (FLS). These services are based on multidisciplinary care models that provide treatment and secondary prevention of osteoporotic injuries. They provide long-term monitoring, risk evaluation and fall prevention initiatives among many best practice guidelines developed [28]. These services have been extensively studied worldwide to assess their cost effectiveness across many settings. A recent systematic review demonstrated that FLS was cost effective in all countries studied (Australia, Canada, Japan, Sweden, Taiwan, United Kingdom and the United States of America) in comparison to standard of care or no treatment [29]. These programs also yielded cost savings in certain populations such as patients with prior hip fractures in the US. These savings were estimated to be $66,879 USD per lifetime/10,000 patients [25, 29]. Therefore, these economically and medically favourable services have demonstrated encouraging results and the IOC plans to further expand their implementation internationally.

## 2.5 Economical Impact of Osteosynthesis in Trauma Care

Prior to the visionary foundation of the Association of Osteosynthesis (AO) in 1958, the majority of fractures were treated conservatively in splints, casts and traction that resulted in significant immobilization for patients [30]. These Swiss founders established and popularized osteosynthesis for the treatment of long bone fractures to reduce hospital stay and time required until patients are able to return to work. It was only recently that studies evaluated the true economic impact of medical innovations in osteosynthesis. Eichler et al., performed a health economic evaluation of femur, tibia and radius fractures over a 60 year period (since the inception of AO) to estimate the health economic impact of innovations in osteosynthesis [31]. Within 17 high income countries, their modelling demonstrated total direct cost savings (Swiss Fracs) of $507 billion with tibia fractures, $272 billion with femur fractures, $69 billion with proximal femur fractures and $77 billion with radius fractures [31]. Furthermore, over 77.6 million years of life gained is estimated through the introduction of fracture osteosynthesis since its inception in 1958 to 2017 [31]. Despite limitations in the modelling design of the study, the impact of the AO founders' innovation has not only yielded substantial improvements to the medical management of fracture care, but also staggering economic relief to nations worldwide. The example of osteosynthesis exemplifies the impact of medical innovation in reducing the economic burden due to trauma, and provides potential evidence that initially costly interventions may be more cost effective in the long term.

## 2.6 Conclusion

In conclusion, trauma and injuries are an immense economic burden on nations, healthcare providers and patients. This is due to healthcare expenditure and reduction in economic productivity of patients due to prolonged hospitalization, rehabilitation, disability and death. Numerous political and health organizations have set out initiatives to decrease this economic burden through innovation of healthcare delivery and products as well as preventative measures lowering the incidence of trauma.

**Key Concepts and Take-Home Points**

- The total economic burden placed on society by trauma can be divided into direct and indirect costs. Direct costs include health care expenses to the individual and health care system due to the traumatic events. Indirect costs include expenses related to the decline of productivity due to disability, rehabilitation, prolonged hospitalization and death.
- Road traffic collisions can cost nations up to 3% of their GDP on an annual basis.
- Road traffic collisions are a major economic burden on all nations regardless of their economic prosperity and average socioeconomic status. Further improvements in road safety and regulations are needed to reduce these burdens.
- Fracture Liaison Services are based on multidisciplinary care models that provide treatment and secondary prevention of osteoporotic injuries to decrease the potential economic burden of trauma.
- The development and innovation of osteosynthesis over the past 60 years have substantially reduced the economic burden of trauma in terms of costs as well as mortality.

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# Evidence-Based Trauma Care

3

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**Learning Objectives/Learning Goals**

- To review the history of evidence-based medicine and the development of the best available in orthopedic trauma
- To understand the hierarchy of evidence, and to give a framework for critically evaluating the quality of literature
- To work through a case example and apply the best available evidence in managing the care of an orthopedic trauma patient

**PANEL 1: Case Scenarios**

**CASE 1**

A 75-year-old female is involved in a low speed motor vehicle accident. She complains of right wrist pain to her family physician two days after her injury. Her X-rays demonstrate a minimally displaced distal radius fracture.

**CASE 2**

A 22-year-old male patient fall off a ladder at work, on to his outstretched right hand. He presents to the emergency room complaining of severe right wrist pain. Initial radiographs show a displaced distal radius fracture.

How can you utilize evidence-based decision in the management of each of these traumatic injuries?

Dr. Guyatt first termed "evidence-based medicine" (EBM) in 1991 to describe a group of related principles initially developed by the epidemiology and biostatistics department, led by Dr. David Sackett, at McMaster University [1]. Dr. Sackett describes evidence-based medicine as "integrating individual clinical expertise with the best available external clinical evidence from systematic research" [2]. The process of gathering the best available evidence requires one to first developing a clinically important research question by identifying a specific population, intervention, comparator, and outcome to review. Next, a systematic review of the available literature and a critical assessment of the relevance and

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quality of literature should be undertaken to formally evaluate the evidence [3].

When compared to other fields of medicine, there are unique challenges applying EBM to surgical disciplines like orthopedics, including the difficulty of objectively assessing surgical interventions and limitations to performing appropriately blinded procedures [4]. The first foray into evidence-based medicine in the orthopedic literature was in 2000, less than five years after the seminal paper by Dr. Sackett, when the Journal of Bone & Joint Surgery first published the term "evidenced-based orthopaedics" [5]. Ultimately, the era of evidence-based orthopedics did not truly take hold until large, multicenter randomized controlled trials were routinely performed in late 2000s and early 2010s [6–14].

Distal radius fractures represent common acute traumatic injuries to both the young and elderly and have become a recent focus of evidence-based orthopedics. A search of MEDLINE from 1996 onwards for "distal radius" and "fracture" yielded over 5000 publications, more than 400 of which are randomized controlled trials (RCTs). This overwhelming amount of literature is challenging for a trauma surgeon to evaluate and critique and can lead to oversimplification of the results in summative reviews. However, not all RCTs are performed with rigorous methodology and as such would yield lower confidence in their results. Moreover, use of "real world" evidence, such as database or registry studies, can help inform the evidence in areas where randomized trials are not feasible or unethical. It is vital for surgeons to understand not only the basic principles of EBM, but also the hierarchy of evidence, study design and quality, and the presentation of results.

## 3.1 Principles of Evidence-Based Management

The well described *Evidence Pathway* [15] organizes the principles of evidence-based care into a simple algorithm:

1. *Assess:* Identify, and understand the importance of, a clinical issue affecting patients and outcomes.
2. *Ask:* Formulate a specific research question, directly related to the issue at hand, to be the foundation for a structured literature review. According to the PICO framework, a well-built clinical question identifies the patient population, intervention or exposure, comparator, and outcomes of interest [16].
3. *Acquire:* Perform an objective, systematic search of databases other sources to obtain relevant evidence. Other sources may include gray literature, such as bibliographies, research conference abstracts, or through interviewing content experts.
4. *Appraise:* Critically evaluate acquired evidence based on the hierarchy of evidence and the validity of results with respect to methodological quality and clinical relevance.
5. *Apply:* In conjunction with patient values and clinician expertise, apply the collected, evaluated evidence.

Application of this framework allows surgeons to make evidence-based decisions. This is particularly relevant when surgeons are asked to evaluate the ever-expanding literature in orthopedic trauma care.

## 3.2 Quality of Evidence and the Hierarchy of Evidence

For busy trauma surgeons, it would be nearly impossible to appraise what seems to be a never-ending mountain of articles, and then interpret results to land on a single decision for the patient requiring care [17]. Fortunately, this process can be accelerated by grouping studies by similarities in methodology. To understand the hierarchy of evidence is to understand the merits and demerits (i.e., sources of bias) associated with each study design, thereby providing an initial measure of quality [18]. As RCTs are not always feasible in

surgical research, assessment of methodology rigor is a secondary tool allowing for appraisal of high-quality studies beyond the accepted hierarchy of evidence [19]. The results of methodologically rigorous observational studies can provide high-quality evidence and support clinical decision-making in the absence of proper randomized controlled trials. Evidence-based medicine categorized study designs according to their methodological rigor, with RCTs providing the highest and most reliable evidence, followed by controlled observational studies, uncontrolled case series, and lastly, expert opinion [20]. This broad grading system, introduced by Dr. Sackett, has been widely adopted across specialties and journals [21]. Various versions of the evidence pyramid have been described, with the newly controversial addition of systematic reviews and meta-analyses at the top of this pyramid. Like clinical and observational studies, all systematic reviews and meta-analysis are not of equal quality and therefore rigorous methodological evaluation is warranted before considering the clinical value of findings [22].

By randomly allocating patients to either an intervention (new treatment) or control arm (standard or no treatment), RCTs are able to evenly balance both known and unknown patient variables across each treatment group, which is unique and not possible with any other study design [23]. However, randomization alone does not ensure that the remainder of the study is performed with the highest rigor. Any RCT that is compromised by issues with randomization, allocation concealment, blinding, expertise bias, failing to adhere to an intention to trail protocol, or trial attrition (lost to follow-up) may be demoted from Level 1 to Level II quality evidence. Given the varied quality of randomized trials and a thorough understanding of the principles of methodology and evidence appraisal are crucial for a surgeon to offer the highest most evidence-based treatment options to its patients [19].

**Allocation Concealment**—the investigators enrolling patients are unable to determine which treatment arm the next patient will be assigned to. Acceptable methods include central (internet or telephone based) allocation, or the use of sequentially numbered, sealed, opaque envelopes. Methods susceptible to bias include the use of chart numbers, odd/even dates, or unsealed envelopes.

**Blinding**—the participants of interest are unaware of which treatment arm the patient has been allocated to. Groups that can be blinded include patients, clinicians, outcome collectors, outcome adjudicators, data analysts, and manuscript writers. The more groups that are blinded, the less likelihood there is of performance or detection bias due to knowledge of treatment allocation.

**Expertise Bias**—the differential ability of a clinician to apply the intervention or procedure, due to skill or prior beliefs. This may occur when a surgeon is asked to perform a procedure that they either are not proficiently trained in or think is not effective, compared to the alternative treatment arm.

**Attrition**—loss of patients to follow-up to the point where the final cohort may no longer represent the original cohort. Traditional thresholds have required at least 80% of patients to be included at final follow-up. Bias may occur if those who drop out of a trial systematically differ from those who remain.

**Intention to Treat Principle**—the analysis of patient outcomes by the treatment group to which they were allocated to, regardless of whether this was the treatment which they actually received. This form of analysis preserves the power imparted by randomization to balance the distribution of known and unknown factors among the treatment groups.

Despite RCTs being considered the gold standard, they may not be feasible or appropriate for the assessment of particular interventions [19]. Specifically, within the field of orthopedic surgery, rare events or those that develop over a long period of time, such as development of acetabular erosion following hip hemiarthroplasty, are not easily investigated using an RCT. In other instances, an RCT may not be possible based on ethical or logistical grounds, for example, those requiring an unusually large number of patients due to small differences in effect sizes between treatments. Unique difficulties faced by surgeon scientists also include practice-and technique variation among surgeons within the same center, difficulty in implementing effective research protocol within surgical departments, logistics of patient enrollment, and the lower number of available participants (particularly when exploring infrequent injuries). Therefore, surgical specialties must often rely on other study designs to provide grounds and rational for clinical decision-making [19].

A surgeon must be proficient not only in the evaluation of RCTs, but in critical appraisal of observational literature, particularly when answering clinical questions unamenable to RCTs. Cohort studies involve the comparison of patients who are exposed to a risk factor (or treatment) to unexposed patients, who are then followed to determine the rate of occurrence of an outcome of interest [24]. Cohort studies may be prospective in nature, constituting higher level evidence relative to retrospective studies. Of the observational study designs available, prospective cohort studies are considered the most reliable study design to support potential intervention to outcome relationships [19]. A prospective design facilitates more rigorous data collection and patient follow-up. Similar to RCTs, feasibility challenges arise when attempting to follow large numbers of patients over long time intervals [24]. Retrospective cohort studies present data collected after the intervention has already been initiated, previously reported outcomes are then gathered, typically through review of patient charts or databases, and analyzed. Retrospective cohort studies are considerably less time consuming and resource intensive but are prone to additional sources of bias, inability to choose specific outcomes, inadequate follow-up, and changes in standard treatment practices over time [24]. Prospective designs allow investigators to study any outcome of interest while answers provided by retrospective studies are limited to research questions that can be addressed with information that has already been collected.

Prospective trial designs begin at a specified point when patients are either exposed or unexposed. These patients are then followed forward in time, to evaluate the impact of the exposure(s) on the outcomes of interest. Retrospective trial designs involve looking backwards from the present, into past records to identify patient outcomes and exposures.

Case-control studies are essential for the study of rare diseases or rare outcomes, in which prospective data collection would be excessively difficult and unreasonable. Data is collected retrospectively over a long period of time to ensure an adequate number of the event of interest. A group of patients with the outcome of interest is identified (cases) and then matched to a similar group of patients who did not develop the outcome of interest (controls). However, the retrospective nature of case-control studies in surgical research leads to limitations and bias faced by any retrospective study design, in particular that a temporal relationship between exposure and outcome is only weakly supported.

Recall bias is the differential likelihood of patients or providers to report an exposure in the setting of an adverse event or poor outcome

Case reports and case series are descriptive studies that involve detailed profiles of one or several patients. Without a control (i.e., unexposed) group for comparison, conclusions on causal associations between exposure and outcome cannot be made. Additionally, case series and case reports tend to describe the experience of a single surgeon or center, and therefore may suffer from personal bias and have limited generalizability to other practice settings or populations. However, case studies remain valuable for reporting rare events or new techniques (as a proof of concept), generating hypotheses or describing new entity or disease progression. While classified as low-quality evidence, they provide highly valuable information for other centers treating similar, often uncommon, patient presentations, and prior to the pursuit of higher-quality study designs (e.g., an RCT).

Generalizability refers to the ability to apply the findings of a study to a larger group of similar individuals.

Finally, systematic reviews and meta-analysis are summary studies that employ an organized, reproducible, and objective approach to the collection and synthesis of data from multiple primary studies. A systematic review, if conducted with rigorous methodology, is a crucial step in establishing recommendations. The strength of a recommendation relies mostly, though not entirely, on the quality of evidence included in the review. Systematic reviews are valuable reports describing all available and relevant evidence surrounding an important concept.

After completion of a systematic review, a meta-analysis may be performed if a sufficient number of studies report similar patient populations and outcome measurements. Meta-analyses synthesize results across relevant studies to increase the effective sample size and provide a single pooled estimate of treatment effect. The quality of a meta-analysis is contingent upon both methodological quality of included studies and variation in outcomes between studies. For example, using the concept of heterogeneity, one can quantify differences between included studies and determine if study populations are comparable (and thus, appropriate for pooling) [25]. There are many other ways to evaluate the quality of a meta-analysis, however complete evaluation of meta-analyses is beyond scope of this chapter. Meta-analyses of small but well performed studies can prove crucial for future study planning and evidence-based decision-making. In turn, rigorously conducted meta-analyses of Level I RCTs represent the pinnacle of the hierarchy and are infrequently published in surgical fields, largely because of the paucity of high-quality RCTs.

The conventional pairwise meta-analyses include two interventions with head-to-head (direct) comparisons, it does not consider all the other multiple treatment options that often exist (e.g., volar plate, percutaneous K-wires, external fixation for distal radius fractures). Network-meta-analyses address this discrepancy by using both direct and indirect comparisons to quantify the relative effectiveness of more than two treatment options simultaneously. Unlike standard pairwise meta-analyses that produce either odds ratios or relative risks with associated

confidence intervals and p values, network meta-analyses generate ranking outputs which suggest which treatment is most likely the best intervention for a given condition.

## 3.3 Presentation of Research Findings

Before presentation of research findings, all relevant studies have been gathered and assessed for both appropriateness of study design and likelihood of bias. It is now necessary to interpret the study findings as they relate to the clinical question. Authors may choose to describe their findings using a variety of different outcome measures, the choice of which depends on the type of data being reported (e.g., continuous versus dichotomous). Dichotomous outcomes are typically reported using relative risk (RR) or odds ratio (OR); alternatively, functional scores and radiographic outcomes are commonly reported as continuous variables using mean differences (MD). It is important to consider that point values are simply estimates of the effect direction and magnitude. In order to consider the uncertainty associated with a point estimate, confidence interval (CI) or standard deviation (SD) should also always be reported.

Mean difference, which describes the absolute difference in means between treatment groups, is a common way to express differences between treatment groups, particularly in meta-analyses. This is possible when outcome measurements are the same across studies. Alternatively, standardized mean difference (SMD) may be used in meta-analyses to express the effect size in each study relative to the outcome variability (i.e., standard deviation) in that study. Standardized mean difference is useful when the effect scale differs between studies; however, clinical interpretation of SMD is more difficult as the units are standard deviations [26].

As an example, we can review a meta-analysis performed comparing volar locking plates to percutaneous k wires for fixation of distal radius fractures. In this meta-analysis (Chaundry), functional status was reported using the MD for Disabilities of the Arm, Shoulder, and Hand (DASH) scores at 6 and 12 months after post-operation [27]. The authors reported that patients treated with volar plating scored 3.78 points lower (i.e., less disability). The 95% CI of 1.23–6.32 indicates that the mean difference will fall within that range 95% of the time. As in this case where the 95% CI of MD does not cross zero (i.e., no effect), it is likely that the treatment has an effect; accordingly, this finding is statistically significant according to the *a priori* threshold described by the authors. While these results are considered statistically significant, they do not provide any information on their clinical importance. In other words, are do these results translate in clinical practice and, more specifically, are they important enough to lead to a meaningful change from the patient's perspective.

This example illustrates another important consideration—the difference between statistically significant and clinically significant (i.e., relevant). The minimally important difference (MID) or minimal clinically important difference (MCID) is the required minimum change needed to occur to be meaningful and important from the patient's perspective [28, 29]. In reference to our example, a previous study of DASH scores has found that patients are unable to perceive change less than approximately 10 points, thus suggesting an MID would be near 10 points (NB: there are multiple techniques to establish an MID, however this represents a simplified example) [30]. Returning to the data from Chaudhry et al. [31], even though the volar plating group yielded a clinical improvement of nearly 4 points rated by the DASH, this falls well below the MID of 10 points. Moreover, the upper limit of 95% CI does not approach the MID, thus suggesting that it would be very unlikely for the difference in treatment options to reach an MID.

Alternatively, authors may present dichotomous data, such as number of patients experiencing a complication, using odds ratios (OR), relative risk (RR), and absolute risk ratio. In the meta-analysis by Zong et al. [32], again comparing volar plating to percutaneous for K-wires, the authors reported total post-operative complications using an odds ratio. The absolute risk for

any post-operative complication was reported as 19.4% (85 events in 438 exposed patients) in the plating group and 50.8% in the pinning group (222 events in 437 patients). A simple way to interpret the difference in risk between these two groups is using relative risk (risk difference) or absolute risk ratio. In this example, the absolute risk difference was 31.4% but the relative risk difference was 2.6 times (or 260%). Although both of these are valid statistics, it may be more appropriate to report the absolute risk difference to help with interpretability. Moreover, the number needed to treat (NNT) is often used to facilitate interpretation. In this example, the NNT is 3.2 (1/0.314), implying that for every three patients treated with plating rather than pinning, one complication will be avoided.

For both relative risk and absolute risk, a value of one—or a 95% CI including one—indicates the effect of two treatments is the same. Risk ratio, the more easily interpreted relative measure, describes risk in the treatment group relative to risk in the control group. Alternatively, relative risk reduction (RRR) can be calculated as $(RR - 1) \times 100\%$.

Relative measures are often preferred in meta-analyses, partly because they are more generalizable across multiple groups with different baseline risk [33]. When interpreting absolute and relative measures in the context of clinical significance, it is important to consider the event frequency: a 2% absolute risk reduction in an event that occurs 50% of the time is likely insignificant. Conversely, a 2% absolute risk reduction when baseline risk is 4% represents a relative risk reduction of 50%. A relative difference of that magnitude may be meaningful depending on the severity of the event, such as malunion requiring reoperation.

Odds ratios are perhaps the most difficult relative measure for clinicians to interpret. Odds ratios are calculated by dividing the odds of an outcome occurring in the treatment group by the odds of the same outcome occurring in the control group. Risk ratio and OR are similar and equally valid in different contexts but are not identical. When an intervention increases event probability, particularly common events, OR will be larger than RR thereby overestimating treatment effect [34]. The inverse also holds true, where the OR in infrequent events estimates the relative risk.

As previously mentioned, if the CI of a continuous measure does not cross zero, the difference between groups is considered statistically significant; the same is true if the CI of a dichotomous measure does not cross one. It is important to recognize that CIs represent an estimate of the range of plausible truths made by sampling a subset of the population of interest. The size of confidence intervals is influenced by individual and pooled sample sizes, measurement variability (i.e., standard deviation for continuous outcomes), and event frequency (i.e., absolute risk for dichotomous outcomes). Narrower confidence intervals represent a more precise estimate of the true value. Due to the chance nature of sampling, the fragility of significant findings may be called into question. Fragility describes the minimum number of patients that would have to go from experiencing an event to not experiencing the event, or the inverse, for a finding to go from significant to insignificant [35]. Emphasizing the importance of this concept, several analyses of orthopedic literature have found that a change of just two events would make findings non-significant [36, 37].

This section on presentation of outcomes would be incomplete without an explanation of subgroup analysis. Authors often analyze subsets of participants (e.g., smokers versus non-smokers, simple versus comminuted fractures) in an effort to draw additional conclusions from RCTs. Subgroup analyses may be planned prospectively or decided upon retrospectively. All subgroup analyses are observational, non-randomized comparisons and should be regarded accordingly. Subgroup findings are more reliable when differences are quantitative—of same direction of effect but differing in magnitude [38]. Subgroup findings are also more likely to be trustworthy when the effect is consistent across subgroups of independent studies. Alternatively, subgroup differences that are qualitative—differing in direction of treatment effect—are unlikely and should prompt skepti-

cism [38]. Retrospective and/or the presence of multiple subgroups further degrade the quality of evidence. Subgroup analyses should be critically analyzed and will seldom be the deciding factor in clinical decision-making.

## 3.4 Making Recommendations

Recommending a treatment for the majority of patients is not always a difficult decision, particularly when numerous, high-quality (i.e., low risk of bias) RCTs demonstrate consistent benefit to patients with a highly favorable risk-benefit profile. However, many interventions, particularly in orthopedics, are only supported by observational data or RCTs with few patients at high risk of bias. In these instances, making a recommendation can be difficult and thus it is the job of the clinician to help patients weigh potential benefits of a treatment in the context of appreciable harms.

Many systems to structure and qualify treatment recommendations exist [39]. The Grading of Recommendations Assessment, Development and Evaluation (GRADE) classification has become the most widely used, endorsed by more than 100 organizations worldwide. Advantages of GRADE include clear implications of strong compared to weak recommendations, robust criteria for increasing or decreasing ratings of evidence quality, integration of patient values, and a transparent relationship between quality of evidence and associated recommendations [40]. This system describes both the strength of a recommendation and the quality of evidence supporting a recommendation. Evidence is graded as high, moderate, low, or very low quality.

Occupying the top of the evidence hierarchy, RCT evidence begins as "high quality evidence," while observational studies, begin as "low quality evidence." The quality assessment of a pool of evidence is subsequently increased or decreased based on study methodological quality, sample size, effect size, precision, and other factors described previously in this chapter. After weighing the quality of evidence, the balance of wanted and unwanted effects (e.g., complications), patient values and preferences, and resource utilization, a strong or weak recommendation is made [40]. Strong recommendations indicate the advantages of a treatment clearly outweigh any undesirable effects, or the opposite, when harm is more probable than benefit. Weak recommendations indicate either a lack of evidence or an uncertain risk-benefit profile. In the case of a weak recommendation, patient values and provider expertise are often more influential in decision-making.

The GRADE approach provides a pragmatic approach to evidence-based decision-making. When used by surgeons, evidence grade and recommendation strength—both of which are brief, transparent summaries—can effectively streamline evidence-based decision-making. This is particularly true when navigating the expansive literature informing treatment of traumatic orthopedic injuries, as will be seen throughout the following chapters.

## 3.5 Conclusion

Nearly 30 years since the development of evidence-based medicine, the practice shift has faced numerous challenges. Critics draw attention to the emphasis on statistical benefits over clinically meaningful benefits, or to guidelines that ignore patient factors, and to an overall unmanageable quantity of evidence [39]. Throughout this introductory section, readers were presented with an objective, straightforward approach to apply evidence-based methodology. With an understanding of the hierarchy of evidence, clinicians will appreciate the value of observational data, particularly when randomized data are impractical to obtain. Further, with knowledge of the sources of bias and the benefits and drawbacks of various effect measures, it becomes clear that formation of recommendations is more patient-focused rather than less. The remainder of this text breaks the large evidence base into thorough yet manageable lessons that will leave readers with a practical approach to the evidence-based management of orthopedic trauma.

**Take Home Messages/Take Home Points**

- The application of evidence-based medicine to management of trauma patients requires a practical understanding of the hierarchy of evidence and a strong grasp of the available literature
- Clinicians should evaluate if a given intervention yields clinically important value to patients, in addition to a statistical difference.
- Recommendations for management of trauma patients should be based on the best available evidence used in conjunction with patient needs and goals.

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# Part II

# Acute Period (1–3 h)/Prehospital Phase and Trauma Bay

# 4 Trauma System and Rescue Strategies

Beat Schnüriger and Wolf E. Hautz

**Learning Objectives**

- To know the definition of a trauma system
- To understand and discuss the impact of a trauma system on a society
- To name the components of a trauma system
- To explain the importance of an accurate prehospital triage score
- To name the subgroup of patients at risk for an "undertriage"
- To debate the "scoop and run" versus "stay and play" field tactic

## 4.1 Trauma Systems

### 4.1.1 Definition of Trauma System

A trauma system is a prearranged approach to trauma patients in a defined geographical area that provides full and optimal care. It is integrating the local or regional Emergency Medical Service (EMS) system. Regionalization is an important aspect of trauma as a system because it enables the efficient use of health care facilities within a defined geographical area. The major goal of a trauma system is to improve patients' outcomes after trauma. When comparing states with and without a regional trauma system, a significant reduction in mortality was found when a regional trauma system was present [1].

### 4.1.2 Trauma System Components

The key elements of a trauma system are access to care, centralized call and triage center, integrated prehospital care, trauma center certification based on need, and rehabilitation. Additional components of a trauma system are prevention, education, research, disaster medical planning, and rational financial planning.

The preclinical components of a trauma system may encompass un-trained first responders, more advanced responders, specially trained staff such as emergency medical technicians (EMTs), physicians deployed to prehospital trauma scenes or even airborne medical services. The preclinical components are discussed in larger detail below.

The administrative components of a trauma system include system oversight and legal regulation, education, monitoring, and quality manage-

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ment as core functions. System oversight and regulation often rest with authorities of the interior or government bodies attending to public health, but other governmental agencies such as the department of defense may also assume those functions. An essential component of a trauma system is to certify traumas based on patient needs. In the US, for example, where this trauma center designation based primarily on financial interest there are too many trauma centers in large urban regions and too few in remote rural regions. In more developed systems, another—and quite effective—function of the administrative component is trauma prevention. When designed well, prevention measures directly result from data collected within a trauma system and should lead to improvements measurable though the systems monitoring and quality management components. Preventive measures may include safety regulations for hazardous industries, adaption of traffic infrastructure or simple speed limits for motor vehicles. A systematic review of the published evidence regarding the effectiveness of trauma systems in North America estimated the magnitude of benefit from implementation of a trauma system was approximately 15–20% reduction in risk of death among seriously injured trauma patients [2]. This number however likely is a lower bound estimate, because it only accounts for the benefits that result from the treatment of people already injured. It neglects the effect that systematic data collection within trauma systems has informing the preventive practice within the larger society. Often overlooked is the potential for regional trauma care research, including conducting randomized multicenter studies.

### 4.1.3 Implementing, Monitoring, and Improving Trauma Systems

#### 4.1.3.1 Education and Training

Training providers within a trauma system can only be as good as the adaption of the training to local needs and circumstances. Training should be adapted to the amount of time providers can dedicate to it and be specific for local circumstances. For example, where avalanches are an issue, advanced providers should be proficient in self-protection, temperature management, and know differences between wet snow and powder avalanches and its mechanisms of injury; where gunshot or stab wounds are frequent, advanced providers should receive training on specific algorithms, such as resuscitative balloon occlusion of the aorta.

Any training however should aim to strike a balance between theoretical concepts and practical application, giving priority to improving practice. For example, it is insufficient to know the debated indications and contraindications of cervical spine immobilization, if the majority of collars put on patients do not result in sufficient restrictions of cervical spine motion [3].

Whenever possible, trainers should have both prehospital trauma care experience and experience with the local health care system. Furthermore, trainers should have received didactic training by means of a faculty development or "train the trainer" course, simply because being a good trauma care provider does not suffice to become a good teacher of trauma care.

#### 4.1.3.2 System Evaluation and Quality Management

Trauma care systems are most effective when they incorporate routine system evaluation and quality management. Both measures can affect the system directly as well as inform preventive measures occurring outside the system. Data sources can be routine provider documentation in trauma registries, direct field observations, critical incident reporting, simply listening in on current provider communication or outcome studies. Other data sources include peer review of system components, benchmarking against similar systems, death certificate statistics, and hospital claims data. The trauma system should have the authority to validate the data source, including access to the patient's medical records.

The WHO (www.who.int) provides many useful tools to assess and manage trauma system quality, including a resource matrix for prehospital trauma care systems, a trauma system maturity index, and a trauma care checklist, similar to

the team checklist used in many operating rooms around the world.

#### 4.1.3.3 Hospital Resources

For optimizing hospital resources, external peer review is used to verify specific hospital's capabilities to deliver appropriate level of care. Trauma centers with full capabilities and resources are defined as Level I trauma centers. It serves as a regional resource for the provision of the most advanced trauma care through immediate 24-h availability of full surgical, interventional, anesthesiological, and intensive care service.

It has been shown that triaging severely injured patients to hospitals that are incapable of providing definitive care is associated with increased mortality [4]. It is of paramount importance to accurately select, at a very early stage of the chain of rescue, which trauma victim will benefit the most from the resources of a Level I trauma center. For this objective, field triage scores to identify major trauma patients are required (Table 4.1).

**Table 4.1** Trauma center categorization according to the Committee on trauma of the American College of Surgeons [5]

| | Definition | Elements |
|---|---|---|
| Level I | Comprehensive regional resource center that is a tertiary care facility central to the trauma system. Capable of providing total care for every aspect of injury—from prevention through rehabilitation. | – 24-h in-house coverage of attending trauma surgeon, and prompt availability of care in all surgical specialties, anesthesiology, emergency medicine, radiology, internal medicine, pediatric and critical care.<br>– Referral resource for communities in nearby regions<br>– Leadership in prevention, public education to surrounding communities.<br>– Continuing education of the trauma team members<br>– Comprehensive quality assessment program<br>– Research<br>– At least 1200 trauma patients yearly or 240 admissions with an Injury Severity Score of more than 15 |
| Level II | Able to initiate definitive care for all injured patients | – 24-h immediate coverage by attending trauma surgeon, as well as coverage by the specialties of orthopedic surgery, neurosurgery, anesthesiology, emergency medicine, radiology, and critical care<br>– Tertiary care needs such as cardiac surgery, hemodialysis and microvascular surgery may be referred to a Level I Trauma Center<br>– Provides trauma prevention and continuing education programs for staff<br>– Comprehensive quality assessment program |
| Level III | Able to provide prompt assessment, resuscitation, surgery, intensive care, and stabilization of injured patients and emergency operations. | – 24-h immediate coverage by emergency medicine physicians and the prompt availability of trauma surgeons and anesthesiologists.<br>– Comprehensive quality assessment program.<br>– Developed transfer agreements for patients requiring more comprehensive care at a Level I or Level II Trauma center.<br>– Back-up care for rural and community hospitals.<br>– Continued education of the nursing and allied health personnel or the trauma team.<br>– Involvement in prevention efforts and active outreach program for its referring communities. |
| Level IV | Able to provide advanced trauma life support (ATLS) prior to transfer of patients to a higher level trauma center. It provides evaluation, stabilization, and diagnostic capabilities for injured patients. | – Basic emergency department facilities to implement ATLS protocols<br>– 24-h laboratory coverage<br>– Available trauma nurse(s) and physicians available upon patient arrival<br>– May provide surgery and critical-care services if available.<br>– Developed transfer agreements for patients requiring more comprehensive care at a Level I or Level II Trauma center.<br>– Comprehensive quality assessment program<br>– Involved with prevention efforts and active outreach program for its referring communities. |

**Table 4.2** Criteria for consideration of transfer from Level III centers to Level I or II centers [5]

| | |
|---|---|
| 1. | Carotid or vertebral arterial injury. |
| 2. | Torn thoracic aorta or great vessel. |
| 3. | Cardiac rupture. |
| 4. | Bilateral pulmonary contusion with Pao2:Flo2 ratio less than 200. |
| 5. | Major abdominal vascular injury. |
| 6. | Grade IV or V liver injuries requiring transfusion of more than 6 U of red blood cells in 6 h. |
| 7. | Unstable pelvic fracture requiring transfusion of more than 6 U of red blood cells in 6 h. |
| 8. | Fracture or dislocation with loss of distal pulses. |
| 9. | Penetrating injuries or open fracture of the skull. |
| 10. | Glasgow Coma Scale score of less than 14 or lateralizing. |
| 11. | Spinal fracture or spinal cord deficit. |
| 12. | Complex pelvis/acetabulum fractures. |
| 13. | More than two unilateral rib fractures or bilateral rib fractures with pulmonary contusion (if no critical-care consultation is available). |
| 14. | Significant torso injury with advanced comorbid disease (such as coronary artery disease, chronic obstructive pulmonary). |

#### 4.1.3.4 Interhospital Transfer

The Committee on trauma of the American College of Surgeons have worked out and give recommendations on criteria for consideration of transfer trauma patients from Level III centers to Level I or II centers (Table 4.2) [5]. Close collaboration among all the hospitals in a regional trauma system is a prerequisite to the optimal interhospital transfer of patients. The development of mutually agreed upon written guidelines for the transfer of trauma patients between institutions is an essential part of a trauma system. These agreements should define which patients should be transferred and the process for doing so. Elucidating each hospital's treatment capabilities, as well as regional transportation options, is the first step. This information is then used to develop guidelines for rapid resuscitation, identification of injured patients who require a higher level of care, transportation options, and two-way communication of performance improvement and patient safety (PIPS) issues between hospitals [5].

## 4.2 Rescue Strategies

The delivery of high quality prehospital care is initiating the chain of rescue and therefore critical to the survival of the severely traumatized patient. Following, three different levels of prehospital trauma care are described.

### 4.2.1 First Tier: First Responders

The first tier of a trauma system can be established by teaching basic trauma principles to members of the public. First responders should be qualified to recognize an emergency as such call for help and provide life-saving treatment until more formally qualified staff is available.

Many developed countries train large parts of the population in half-day courses by making participation in such courses mandatory when applying for a driver's license or other regulated activities. Training typically includes a structured diagnostic approach to patients, for example, an ABC mnemonic, where A stands for assess and airway, B for breathing, and C for circulation [6]. Interventions trained often include safe positioning of unconscious but breathing victims, movements to open obstructed airways, provision of mouth-to-mouth/nose ventilation, and chest compressions. Also, techniques to stop bleedings can be included into basic training [7]. First responders typically do not carry any medical equipment and rely on public communication networks such as mobile phone coverage to communicate with other system components.

Although first responder training is short and equipment minimal to none, educating strategically selected groups of the public can have large effects for the injured. For example, between 1998 and 2000, 335 drivers of commercial vehicles such as taxis, busses, or trucks in Ghana participated in a first-aid course [8]. Before the course, most injured people arriving in hospitals were brought there by such commercial drivers, because they volunteered to transport victims of

traffic accidents they drove by, or because relatives of victims paid them. A year after the course, investigators conducted follow-up interviews with the trained drivers and with hospitals [9]. Two-thirds of the drivers indicated that they had provided first aid since taking the course, and the type of aid dramatically improved. For example, 42% of the drivers indicated they had attempted bleeding control (versus 4% before the course) and 35% had used airway management techniques (opposed to 2% before). Nurses scored the first aid of trained drivers much higher than those of an un-trained control group (7 out of 10 points versus 3 out of 10). The actual cost of the course was US$ 4 per driver trained, indicating that building in existing, although informal structures can substantially and efficiently improve trauma systems in the developing world.

### 4.2.2 Second Tier: Basic Prehospital Trauma Care

The second level of prehospital trauma care is typically established either at the community level or on the level of larger factories or organizations. Providers are most often volunteers but have more extensive formal training than first responders. Training typically includes basic life support (BLS) including bag-mask ventilation and the use of automated external defibrillators, or advanced bandage and splinting techniques. Providers are further trained in basic scene management, field triage, and basic documentation requirements. The amount and sophistication of material available within the second tier are highly variable and can range from a small first-aid bag to dedicated vehicles. In many areas of the world, this level of prehospital trauma care is integrated with other regionally relevant services, such as mountain rescue, park rangers, or costal lifeguards.

### 4.2.3 Third Tier: Advanced Prehospital Trauma Care

The third tier is composed of highly trained staff, mostly working under a paid employment contract. Providers, called emergency medical technicians (EMT) or paramedics in many parts of the world, typically have received hundreds or more hours of both, formal education and supervised training on the job. In most countries of the developed world, providers at this level of trauma care are members of a regulated profession with legislation that sets their freedom of action and defines expectations towards them and the system component. For example, German legislation regulating professional preclinical trauma care sets a timeframe for system responses (for e.g., 10 min from reception of a call for help until arrival on scene of the first qualified staff.)

Entities of the third tier are often equipped with a dedicated communication system that connects them among each other, to a central coordination unit and/ or to hospitals in the proximity. Furthermore, the third tier typically uses dedicated and extensively equipped transportation units, such as ambulances or helicopters. Beyond these basic similarities—extensively trained professionals with dedicated and often extensive equipment—the design and work of third tier components are highly variable across the world. While many European systems widely employ prehospital physicians, most of the Anglo-Saxon parts of the world give priority to the use of EMTs and restrict the use of physicians outside hospitals to very special situations (such as, e.g., remote area coverage provided by the flying doctor service in Australia).

Two systems rather different with respect to the availability of prehospital physicians are the Netherlands and Germany. While Germany is known for its physician based prehospital approach to any emergency patient, with a dense network of hundreds of physician staffed ground vehicles and helicopters, in the Netherlands, prehospital care is a domain of EMTs who can call upon one of just four physician staffed mobile medical teams. A retrospective registry study compared the effect of national prehospital rescue strategies between the two countries on the status of severely injured patients at the time of admission to a trauma center [10]. Of the 12,168 patients included in the study, around 58% in the Netherlands arrived at the hospital in company of

a physician, a stark contrast to the 98% observed in Germany. Patient injuries and demographics were largely comparable between the two countries, and the study found no difference in 24 h mortality. However, the mean prehospital time for patients in Germany was 15 min longer than in the Netherlands (68.7 min vs. 53.8 min) despite comparable treatment free intervals (and thus likely distance of the third tier to the scene of injury) and German patients received twice as much prehospital volume (1103 mL vs. 541 mL). The study did not assess system effectiveness, but its results raise the question whether the extensive use of prehospital physicians is indeed efficient. The expense of providing routine physician presence in the field is also a consideration, and in the US there is virtually no physicians directly involved in prehospital care.

### 4.2.4 "Scoop and Run" Versus "Stay and play"

As mentioned above, a victim may be initially assessed by a provider able to provide basic life support (BLS) or perhaps advanced life support (ALS). While BLS programs provide solely non-invasive maneuvers such as maintenance of spinal precautions, fracture splinting, extremity hemorrhage control, and assisted ventilation with the aid of a bag-valve-mask system, ALS programs have the capacity to provide definitive airway control with endotracheal intubation and venous access in the prehospital setting. Moreover, depending on the local circumstances, prehospital ALS interventions can be provided by EMS personnel with or without a physician. With a physician, an even much larger scope of resuscitative interventions is within the armamentarium of the preclinical team including needle chest decompression or even cricothyrotomy [11]. ALS interventions to the injured patient in the field have largely replaced programs offering BLS alone. Of note, ALS was provided to 79% of severely injured patients in the US [12].

While prehospital ALS has theoretical advantages, the evidence supporting its effectiveness and justification for widespread implementation for trauma is limited [13]. A major concern and a matter of debate are the delay to definitive care due to the administration of ALS interventions in the field—also known as the "Stay and Play" approach. This stands in contrast with the BLS principles, which is representing the "Scoop and Run" tactic. Several studies directly comparing outcomes among patients receiving ALS or BLS prehospital care have demonstrated the absence of benefit, or even the presence of harm, with ALS care, although a number of studies showed no increase in the prehospital time with field ALS interventions [14–18]. However, it is important to note that the majority of studies examining care in the prehospital environment are based on data from established regional systems, in which the decision for a field ALS or BLS response is protocolized. As a result, more critically injured patients receive ALS—which makes it difficult to assess whether the higher rates of adverse outcomes are due to ALS or occur in spite of ALS care. As a result, it may be more informative to focus on studies of individual interventions or specific injury pattern.

### 4.2.5 Prehospital Endotracheal Intubation

Several studies comparing bag-valve-mask ventilation with more advanced airway management found no benefit associated with prehospital intubation. In fact, a number of studies have demonstrated higher rates of mortality, with the group most likely to be affected being those patients with traumatic brain injury [19–21]. These data are particularly concerning, given the theoretical benefit of airway control in this population. Prehospital endotracheal intubation is challenging [22] and potential benefits have to be outweighed with endotracheal intubation-related complications, including multiple intubation attempts [23], improper tube placement [24, 25], prolonged scene time [26], transient desaturation [27], hyperventilation [28, 29], hypotension [30], hypertensive response to laryngoscopy and endotracheal intubation [31] which may lead to increased intracranial pressure [32], and endotra-

cheal intubation/laryngoscopy-induced increased intracranial pressure [33].

Although the previously cited studies appear to support scoop and run, a number of methodological issues should be highlighted. More severely injured patients are more likely to undergo intubation attempts. The question is further complicated by the heterogeneity of patients and providers included in available studies. For example, many studies of prehospital intubation include patients with both blunt and penetrating injuries [20, 34], while others have focused on patients with head injuries [35, 36]. Providers include physicians and paramedics with variable training, and the frequency of intubation attempts and successful intubations clearly depend on each individual prehospital system. This has been shown by Klemen and Grmec who demonstrated decreased early mortality in patients with traumatic brain injury intubated in the field compared with those patients without definitive airway control [35]. The findings of that study, however, were confounded by the differences in training between the field physician providers, who cared for virtually all of the intubated subjects in the study, and the paramedic providers, who cared for all of the nonintubated subjects. Finally, the geographical situation needs to be taken into account. In circumstances of very long transport times, e.g., in rural environments, interventions prior to transportation to hospital might provide some advantage. For example, in the US when transport times exceed 45 min, helicopter flight nurses routinely preform ALS procedures. In an urban environment with relatively short transport times, however, there is no strong evidence supporting field endotracheal intubation [13].

### 4.2.6 Prehospital Fluids

For hypotensive patients with penetrating torso injuries, delay of aggressive fluid resuscitation until operative intervention has been shown to improve the outcome although the benefit was primarily in those with penetrating cardiac wound [37]. This well conducted study has stimulated many similar studies and the concept of planned hypotensive or damage control or hemostatic resuscitation has been promulgated. Nevertheless, there are still preclinical protocols that call for the provision of intravenous (IV) access with two large bore IVs followed by the rapid administration of saline or Ringers lactate if the blood pressure is below 90 mmHg systolic. However, obtaining an IV in poor conditions is difficult and is resulting in a delay to definitive treatment. In addition, running fluid into a patient without hemorrhage control is itself controversial and has the potential to harm by worsening of trauma-induced coagulopathy and hypothermia [38]. However, this controversy is further complicated by the availability of whole blood and blood products in prehospital systems, particularly in air medical transport with longer transport times. Recent studies in the US demonstrated improved outcome with plasma in air transport [39] but no benefit with ground transport [40]. Currently, studies on the impact of the administration of blood products in the prehospital setting on outcomes after trauma are ongoing. However, it is vital that the prehospital trauma care providers always consider the delay to definitive care against the potential benefit from the field treatment.

### 4.2.7 Field Triage Scores

Adequate prehospital trauma triage of injured patients is essential for optimal trauma care. In an inclusive trauma system, it is critical to transport patients with severe injuries to a Level I trauma center and patients without severe injuries to lower-level hospitals. Management of care of the injured trauma patient on the scene of injury remains challenging, and situations can be chaotic. After a rapid trauma assessment of clinical and physiological parameters, EMS professionals must identify patients at risk for severe injury and select the proper destination. Therefore, prehospital triage scores with a high accuracy to predict severe injury are required.

The prehospital triage scores are mainly based on physiologic and non-time-dependent factors (Table 4.3). However, even in a very advanced pre-

**Table 4.3** Selection of indications for immediate transport to a trauma center

| |
|---|
| Physiologic parameters: |
| • Glasgow Coma Scale (GCS) ≤13 |
| • Systolic blood pressure <90 mmHg |
| • Respiratory rate <10 or >29 breaths/min (or in age <1 year, respirations<20 breaths/min) |
| • Requiring ventilatory support |
| Non-time dependent factors |
| • Penetrating injury to head, neck, torso, or proximal extremity (above knee or above elbow) |
| • Two or more proximal long bone fractures |
| • Crushed, degloved, mangled, or pulseless extremity |
| • Extremity amputation proximal to the wrist or ankle |
| • Pelvic fracture |
| • Open or depressed skull fracture |
| • Paralysis |

hospital setting, 20% of the patients with severe injuries are not transported to a Level I trauma center [41]. This is significantly higher than the benchmark level of 5%, as set by the ACS-COT [42]. This underlines the difficulties and real world challenges of prehospital evaluation of trauma victims. Of note, these undertriaged patients are at increased risk for preventable morbidity and mortality [43]. Especially elderly patients with more co-morbidities or patients with traumatic brain injury who require operative intervention are susceptible for an undertriage [44, 45]. Currently, no single field triage score has been accepted as the gold standard and there is need for improvement of the prehospital triage protocol.

Since 1986, the Centers for Disease Control and Prevention (CDC) in the US collaborated with the American College of Surgeons Committee on Trauma (ACS-COT) to provide guidance for the field triage process though its "Field Triage Decision Scheme." In 2011, the CDC reconvened the Panel to review the 2006 Guidelines and recommend any needed changes. Figure 4.1 is showing the 2011 Guidelines for field triage of injured patients [46]. Triaging a single trauma patient is guided according to the defined triage criteria for that particular regionalized trauma system. If the patient meets the criteria of a major trauma victim, her or she is transported to the nearest designated trauma center.

## 4.3 Conclusion

A trauma system will improve the care of polytraumatized patients on different outcome levels. Triaging polytraumatized patients to Level I trauma centers will improve outcome. No single field triage score has been accepted as the gold standard and there is need for improvement of the prehospital triage protocol because undertriaging is an ongoing problem. Reducing the delay to definitive treatment of trauma victim is the primary goal of the rescue. The benefit of prehospital treatment efforts needs careful scientific assessment, as advanced life support not necessarily results in better outcomes than basic life support.

**Key Concepts**

- Have a trauma system in place and support centralization of polytraumatized patients
- Triage polytraumatized patients to Level I trauma centers
- Be aware of undertriage of polytraumatized patients
- Have a prehospital triage protocol in place with ongoing quality control of accuracy
- Reduce the delay to definitive treatment of trauma victims
- Carefully consider and assess prehospital treatment efforts, as advanced life support may not necessarily result in better outcomes than basic life support

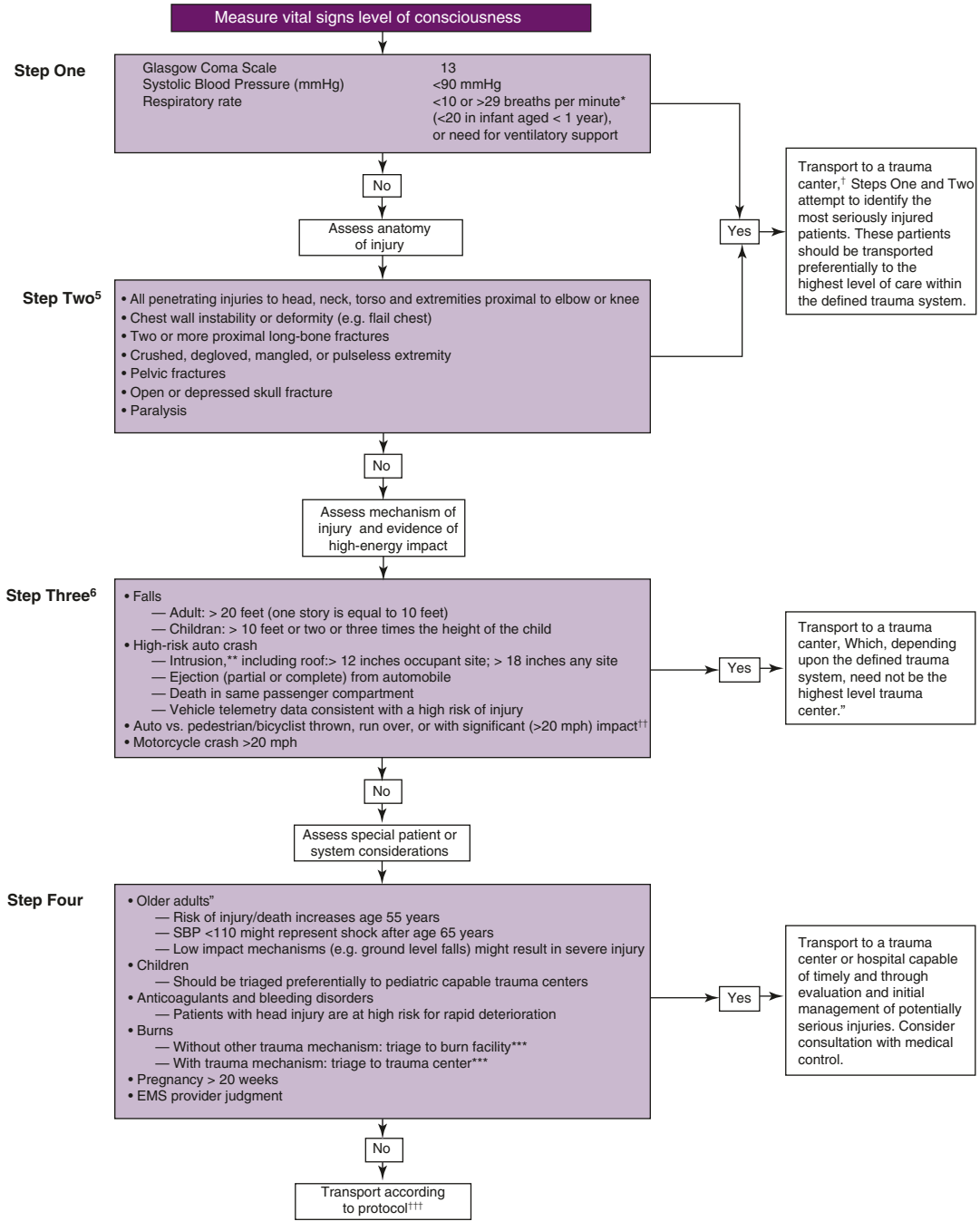


**Fig. 4.1** Guideline for field triage of injured patients [46]

**Take Home Messages**

- A trauma system is a prearranged approach to trauma patients in a defined geographical area that provides full and optimal care.
- A significant reduction in mortality is found when a regional trauma system is present.
- The key elements of a trauma system are access to care, prehospital and hospital care, and rehabilitation.
- Undertriaged trauma patients are at increased risk for preventable morbidity and mortality.
- Elderly patients with more co-morbidities or patients with traumatic brain injury are susceptible for an undertriage.
- Prehospital trauma care providers should always consider the delay to definitive care against the potential benefit from their field treatment.

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# Preclinical Management/Rescue

5

Gerhard Achatz, Björn Hossfeld,
and Benedikt Friemert

**Learning Objectives**

The aim and focus of this chapter are as follows:

- to give an overview of the basic contents of preclinical care of polytrauma patients.
- to present not only the basic concept but also specifics for the individual body regions.
- furthermore, to discuss special features regarding tactical and strategic aspects and special situations.

## 5.1 Introduction

Basically, the care of polytrauma patients is based on the principles of the Pre-Hospital Trauma Life Support (PHTLS®) as well as Advanced Trauma Life Support (ATLS®).

ATLS® was established at the end of the 1970s by the trauma surgeon Dr. James Styner after the loss of his wife and the experienced care for himself and the rest of his family after an airplane crash, following the Advanced Cardiac Life Support program of the American Heart Association. His impression of the care for his own person as well as his children after this accident made him decide that the care for injured persons should and had to be better and more structured. Thus, he finally founded ATLS® [1].

Based on this, Dr. Norman McSwain developed a prehospital concept in the following years as the first chairman of ATLS® and thus established the course format of PHTLS® in 1983. In the meantime, PHTLS® has become the most widely used prehospital concept for the care of trauma patients [2].

The essential advantage of this therapy concept is now the common language with ATLS®, which leads to a mutual understanding and, above all, to a common and goal-oriented approach within the framework of the handover of the patient in the hospital. The understanding of important core elements of a priority-associated patient treatment is a key element. Both systems focus on a rapid and

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priority-associated assessment of the patient's condition and, above all, on the prioritization of appropriate therapeutic measures ("treat first what kills first") [1, 2]. However, the existing framework conditions, the diagnostic tools, and the therapeutic options differ considerably.

The goal in the prehospital setting must therefore be to stabilize the patient with less information and in a shorter time under sometimes significantly more difficult conditions, so that the patient can then be brought quickly and stabilized to the correct target hospital.

This chapter is intended to precisely illustrate the special features and requirements for this important and first stage in the trauma chain of survival.

Depending on the literature, different concepts of care for the prehospital phase have alternated in recent years, or these are partly predetermined for the respective individual situation by external circumstances and the condition of the patient. As essential and basically contrary concepts are to be mentioned: [3].

- "Stay and Play": on site an almost full care takes place, which tries to address all aspects of injury and almost already corresponds to a kind of "intensive medical" treatment still at the accident site.
- "Scoop and run": this concept, which is widespread in Anglo-American rescue systems, focuses only on the most urgent measures on site and then on the transport to a hospital as quickly as possible.

Both concepts as contrasting examples are used regionally very differently, the approach to the care of the trauma patient is thus divergent. This is then also reflected, for example, in the equipment of rescue vehicles, both materially and in terms of personnel [4].

The authors have experience with the emergency medical services (EMS) in Central Europe, especially in Germany. Here, prehospital care is usually provided by the cooperation of experienced paramedics and an EMS-physician on scene. This means that a high level of emergency medical expertise can be brought to bear directly on patient care from the outset. From this conception and on the basis of corresponding scientific work, a mixture of both extreme therapy concepts in the sense of a "treat and go" or "work and go" approach appears to be the most sensible for the patient with regard to the later outcome [5]. It is important to focus on essential clarification and treatment steps, to strive for the subsequent transport to a suitable destination hospital and not to delay it significantly.

The polytraumatized patient offers simultaneous injuries of several body regions or organ systems. Even a single one of these injuries or the combination of several is life-threatening for the affected person [6–8].

Typical causes are serious traffic accidents and falls from great heights, accidents at work, recreational accidents, or violent crimes.

After the arrival of the rescue forces and, if necessary, an EMS-physician at the scene of an accident, self-protection must never be forgotten, and so it may be necessary that access to the patient must first be made possible by the deployment of appropriate auxiliary forces. If a more complex rescue is necessary, however, initial measures such as securing the airway may have to be initiated in parallel. Depending on the patient's condition, rescue and recovery may be so urgent that further damage (e.g., to a trapped limb) must be accepted to ensure the patient's survival (crash rescue).

If access to the patient is then freely possible, the next step is to proceed according to the familiar principles of the A > B > C > D > E algorithm so that individual medical treatment can usually begin.

## 5.2 The Basic Concept

The polytraumatized patient is further clarified and assessed according to priority within the framework of the so-called primary survey.

According to the above-mentioned principle "Treat first what kills first!", diagnosis and therapy are carried out according to absolute urgency in relation to the existing vital threat.

Figure 5.1 clearly shows the corresponding steps of A > B > C > D > E, which should make

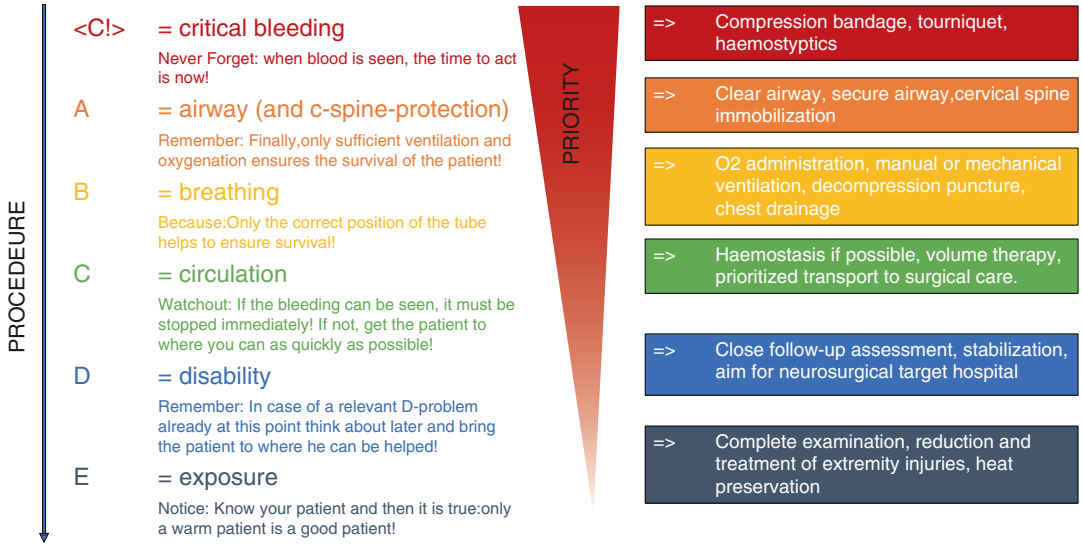


**Fig. 5.1** Summary of the essential aspects of the principles of care and provides an overview of the essential components that must be considered in relation to priorities

it possible to ensure the vital functions and thus make the patient fit for transport.

The "A":

Assessment of the airway is the first step. Mechanical disturbances and obstructions of the airway are eliminated. Furthermore, if the airway is not safe or there is a corresponding decrease in vigilance (GCS < 9), further airway protection is indicated. This requires knowledge of various methods of airway management, even if endotracheal intubation may be considered the only safe airway. This measure must be mastered and, in many situations, can be the initial and essential building block for the targeted further treatment of the patient. However, since even this very common method can lead to a can-not-intubate, can-not-oxygenate situation, surgical airway protection measures must also be mastered as a last resort! [9].

Remember: Finally, only sufficient ventilation and oxygenation ensure the survival of the patient!

Airway protection is supplemented from the outset by in-line stabilization of the cervical spine, which is then further ensured by rapid application of a rigid collar [9].

The "B":

Once the airway is secured, gas exchange must now be accomplished at the alveolar level, as inadequate ventilation of the lungs with consequent decreased oxygenation would lead to hypoxia and consequent lasting damage to the patient. In the prehospital setting, inspection, palpation, and auscultation of the thorax may further indicate the presence of chest trauma [9].

Relevant and rapidly threatening sequelae of injury may include: laryngotracheal injury, tension pneumothorax, open pneumothorax, unstable thorax, and extensive pulmonary contusion, marked haemothorax, or pericardial tamponade [10].

Quickly these diagnoses must be recognized, which is not always easy in the prehospital setting. A possible ultrasound, which can also be performed out-of-hospital, can support here if necessary and facilitate the clarification.

In accordance with the principle of parallel diagnosis and therapy, the above-mentioned consequences of injury must also be treated immediately, and so, in addition to the above-mentioned securing of the airway, relief puncture, the insertion of a chest drain, or relief puncture of the pericardium are also quickly applied prehospitally. In addition, appropriate monitoring of oxygen saturation is quickly initiated, and this helps to assess the success of the measures initiated. After intubation, capnography is the gold standard for monitoring and helps to avoid the false

sense of security that oxygen saturation alone can give in the worst case [11, 12].

Because: Only the correct position of the tube helps to ensure survival!

The "C":

If enough oxygen is present in the alveolar system and good gas exchange is still possible, the patient will only benefit if there is also subsequently a good circulation that ensures oxygen supply to the corresponding organ systems.

A compromised circulatory situation in the trauma patient is very often based on shock symptoms caused by haemorrhage. The latter must be recognized urgently and quickly, only then can the necessary therapy begin immediately [13–15].

A good inspectorial assessment with focus on skin coloration and recapitulation time are first steps to assess the patient. Furthermore, the pulse rate, the pulse strength, and also the blood pressure allow a quick and good assessment of the situation.

If the suspicion of a bleeding situation is confirmed, the next step is to quickly determine the cause of the blood loss. Here the saying "Blood at the floor and four more" can be helpful and targets the 4 four relevant areas with thorax, abdomen, pelvis with thigh, and in addition a relevant external bleeding that causes blood accumulation "at the floor." [10].

It is obvious that relevant haemorrhages in the body cavities can only be addressed to a limited extent in the prehospital setting and thus can only be treated symptomatically, but not causally. Appropriate fluid therapy, the possible administration of tranexamic acid, and the use of vasopressors are the correct treatment steps here. The prehospital administration of whole blood, red blood cell concentrates, plasma, fibrinogen, and PPSB is much discussed internationally [16]. In the end, the main focus is on rapid and targeted transport to a hospital.

If the cause is a pelvic injury, a pelvic sling can bring about appropriate stabilization and compression of the pelvis and thus cause the bleeding to stop or at least slow down. Injuries to the extremities, especially in the thigh area, benefit from axial reduction and splinting or stabilization in this regard. In the case of external bleeding, a pressure dressing should be applied quickly, and the application of a tourniquet may be necessary prehospitally for transport to the hospital. If such an obvious external bleeding exists, it may be necessary to deviate from the usual priority-associated algorithm already at the first approach to the patient [17]. In this case, in the spirit of $a < C! \gg A > B > C > D > E$, the obvious bleeding should be stopped immediately and then return to the usual sequence [18].

Watch out: If the bleeding can be seen, it must be stopped immediately! If not, get the patient to where you can as quickly as possible!

The "D":

The next step in the evaluation and treatment of the polytrauma patient is the "D" with recording of the Glasgow Coma Scale and assessment of pupil appearance and function. In addition to this central assessment, the neurological status of the extremities is cursorily assessed so that relevant spinal injuries can be detected in addition to a possible craniocerebral trauma [9, 10].

This step is important because it is prognostic regarding the long-term outcome of the patient, furthermore because it essentially determines the necessity of a possible induction of anaesthesia and finally because it is important for the selection of an appropriate target hospital. If a craniocerebral trauma/brain injury is suspected, the patient will benefit from a direct transfer to a trauma centre with neurosurgical expertise, even if the initial transport route and time are longer.

Remember: In case of a relevant D-problem already at this point think about later and bring the patient to where he can be helped!

The "E":

Now that all potentially immediately life-threatening aspects have been addressed, the patient is finally examined "from curl to sock." This helps to prevent relevant injuries from being overlooked. Here, above all, if possible, the patient is also turned with a log roll in the sense of "check the back" so that the rear side can also be assessed [9, 10]. Furthermore, an appropriate heat preservation is then considered immediately

afterwards, since cooling down is extremely relevant in many respects, but especially with regard to the topic of the so-called lethal triad [19]. Together with acidosis and coagulopathy, possible hypothermia has a significant influence on the patient's prognosis and, above all, these three essential aspects are mutually dependent in the sense of a vitious circle [20].

Notice: Know your patient and then it is true: only a warm patient is a good patient!

## 5.3 Special Features of Individual Body Regions

After the basic overview of priority-associated care as listed above, the following section will once again present essential special features of the care of individual body regions and examine these in more detail. The focus will once again be on what needs to be paid attention to in terms of targeted treatment. This is done with the aim of considering the patient's outcome at this point. The core statements of the S3 - Guideline on treatment of polytrauma/severe injuries of the German Trauma Society, which summarizes the current literature on the respective topics in an excellent way, will be included at this point [21].

### 5.3.1 Skull and Brain Trauma

Traumatic injuries to the head always present a major challenge in the prehospital phase; conversely, more extensive options for the care of the patient with a craniocerebral trauma in the setting of care at the accident site as well as on the transport route are significantly limited for this aspect.

The limited level of consciousness that is usually present must be evaluated regularly, and the Glasgow Coma Scale has become established as an essential working tool. Furthermore, the pupils are also evaluated as an expression of possible cerebral damage [22, 23]. If there is an urgent suspicion of a more serious injury, a normotension with an arterial blood pressure of not less than 90 mmHg should be aimed for in the adult patient. In children, this pressure may need to be adjusted for age. And it is the objective to have the arterial oxygen saturation over 90% [22].

Signs of significant central damage with suspected significantly elevated intracerebral pressure may include the following clinical signs:

- pupil dilation
- stretch synergisms
- extensor response to painful stimuli
- progressive clouding of consciousness with increasingly decreased GCS

In these cases, it is recommended to counteract further brain damage with hyperventilation, hypertonic saline solution, or the administration of mannitol, if necessary, whereby glucocorticoids should no longer be used [24, 25]. If the injury has its origin in a perforating cause, the object that may still be stuck should be left in place if possible.

Subsequently, if the patient's condition is then otherwise stabilized, rapid transport to a suitable destination hospital with appropriate diagnostic (computed tomography) and interventional (radiology) or surgical (neurosurgery) options is paramount and must be sought quickly and prioritized [22].

### 5.3.2 Thoracic Injuries

As part of the initial assessment of the patient, a clinical evaluation is always performed, in particular with an examination of stability and to exclude possible crepitations, auscultation, and thus overall respiratory function. The respiratory rate is also recorded and completes the overall clinical picture. In addition to the clinical measures, it is very helpful to determine the oxygen saturation by pulse oximetry and, in the case of patients who may then need to be intubated, to monitor the ventilation pressure and, if necessary, to perform capnography [10, 26, 27].

After this initial clinical assessment, which is in some cases supported by equipment (for example, ultrasound), a suspected diagnosis of

pneumothorax or haemothorax can be made if there is a unilateral or absent breath sound. If the patient shows a normal breathing and auscultation is unremarkable, it can be assumed that a major pneumothorax is not present [28, 29]. However, it must always be considered that smaller pneumothorax findings may also be progressive in the course. However, a tension pneumothorax must always be considered if a unilateral attenuated breath sound is present and accompanied by respiratory or significant cardiocirculatory disturbances as well as typical symptoms such as upper influence congestion. Tension pneumothorax is the most common reversible cause of trauma-induced cardiovascular arrest and must be relieved immediately, especially in the prehospital setting [9, 10, 30]. Initial needle decompression and subsequent placement of a chest drain are the main therapeutic steps. The placement of the chest tube is always recommended via a mini thoracotomy with good manual assessment of the local findings and without a trocar.

### 5.3.3 Abdominal Injuries

Abdominal injuries are often accompanied by internal bleeding and are not infrequently the reason for the need for appropriate volume therapy. Prehospital ultrasound examination can help to diagnose this relevant injuries [31]. Since initially the injury itself cannot be treated causally, symptomatic therapy must be initiated quickly; this then very often concerns a reduced volume status [10]. For this reason, some key aspects on this topic may be highlighted at this point:

Volume therapy should be initiated in severely injured patients, and venous accesses should be established in the trauma patient for this purpose. In cases of uncontrollable bleeding, such as abdominal haemorrhage, volume therapy should be reduced in order to keep the circulation at a low stable level [32–34]. Crystalloid solutions should be used for volume therapy; isotonic whole-electrolyte solutions are preferable here. Partially balanced infusion solutions with acetate, malate, and instead of lactate may also be considered [35, 36]. If a penetrating injury is present, hypertonic solutions may also be used, as well as they can also be recommend in the case of traumatic brain injury [37–39].

A final and causal therapy is then only possible in the clinic by appropriate surgical measures. Rapid transport with subsequent short and targeted clarification in the hospital is essential.

### 5.3.4 Spinal and Pelvic Injuries

In general, a physical examination of the spine combined with an appropriate clinical assessment of the pelvis should be performed in every patient, especially if there is a corresponding history of trauma with a fall from a great height or similar [40]. If the patient is unconscious, a spinal injury must always be assumed until proven otherwise [41]. The cervical spine should be mentioned as a particular predilection site, which should be immobilized except in exceptional situations, such as a so-called crash rescue, e.g. in the event of fire or explosion [9, 10]. A good indicator for a gentle and adapted transport is the transport under freedom from pain. With regard to the destination hospital, patients with already diagnosed neurological deficits and thus suspected spinal injury should primarily be transported to or flown to a suitable trauma centre with appropriate surgical expertise [42, 43].

### 5.3.5 Extremity Injuries

Relevant and heavily bleeding—especially arterial—injuries of the extremities, which directly affect the vital functions, should be treated with a higher priority. Here, the basic algorithm of the PHTLS should be applied in an extended manner: <C! ≫ A > B > C > D > E [9, 18]. For bleeding control, manual compression can be recommended as part of a step-by-step scheme, followed by a possible compression bandage in the next step, and finally, as ultima ratio, the

application of a tourniquet. Immediate reasons for this may include:

- Life-threatening bleeding or multiple sources of bleeding on an extremity
- inaccessibility of the actual injury
- Multiple casualties with bleeding
- Severe bleeding of the extremities with simultaneous critical A, B, or C problem
- Impossibility of haemostasis by other measures
- Severe bleeding of the extremities with additionally present time pressure under dangerous situations [44, 45]

If all the above measures do not result in significant bleeding control, the use of chemical haemostyptics is possible.

It is essential that the care of extremity injuries should avoid further damage and especially should not significantly prolong the total rescue time. To elicit appropriate extremity injuries, an orienting examination should be performed prehospital. If a corresponding injury is suspected, the corresponding extremity should be immobilized so that transport is possible with as little pain as possible and without restrictions. It is important to perform a preclinical reduction in case of gross dislocation of fractures or if dislocation is present—especially if neuromuscular restrictions are present. Open injuries should be cleaned of gross contamination, followed by the application of a sterile dressing [46].

### 5.3.6 Soft Tissue Injuries and Burns

Severe soft tissue injuries are usually the result of a large force impact such as high impact trauma, falls from great heights, or crush injuries. However, they can also result because of penetrating mechanisms, such as gunshot or blast injuries [47, 48].

Prehospital, attention should be paid to severe soft tissue injuries in the sense of the well-known priority-associated algorithm, especially if these also lead to a relevant C-problem, as shown above. In this case, the focus is primarily on the stop of the bleeding, followed by coarse cleaning as already indicated and finally sterile draping [49]. However, for all injuries that are still not life-threatening, the subsequent outcome must be considered at this point, at least to the extent that such injuries lead to secondary and persistent damage if, for example, the soft tissue is clearly compromised due to malposition of the extremities or similar. Thus, the soft tissue must already be relieved prehospitally by appropriate reduction measures, if the patient is not in extremis and an appropriate measure can be given a short time [50].

Regarding burns and thermomechanical combination injuries, it is important prehospitally to identify the severely burned patient on the one hand and, on the other hand, to identify the existing combination injuries with B problems. The assessment of the extent of the burn on the one hand and the presence of pulmonary involvement on the other hand require special attention, since preclinical measures must be initiated, and the extent of the burn injury has a significant influence on the selection of an appropriate target hospital [51, 52]. Corresponding to the neuro traumatological case constellations, it is also the situation here that, if necessary, a longer transport route to a suitable destination hospital can be accepted for the benefit of the patient.

## 5.4 Other Special Features

### 5.4.1 Strategic Aspects

In the sense of the "treat and go" concept mentioned above, the primary aim should be to keep the prehospital rescue time short, and the measures carried out here should be targeted at further stabilization of the patient, to achieve safe and good transportability of the patient [5]. Thus, tactical aspects and the time factor must be taken into account, so that for most severely injured patients, air rescue is very often primarily recommended [53, 54]. If the rescue routes to the nearest suitable hospital are short enough,

ground-based transport can also be used if necessary. In this context, it is important to ensure that the most suitable target hospital is selected in accordance with the injury pattern. An important example of this is the traumatic brain injury, which should be transported directly to a hospital with neurosurgical expertise [53]. If possible, the patient should be registered in advance; a targeted and structured handover or transfer guarantees that there is as little loss of information as possible and that the patient receives the best possible treatment and diagnostics from the outset in the hospital following prehospital rescue [55].

### 5.4.2 Mass Casualty Incident

Mass casualty incidents with a large number of polytraumatized patients can occur after major incidents. This usually involves relevant accidents or natural disasters, and in the recent past may also involve events associated with violence, such as terrorist attacks involving the use of firearms or explosive devices [56, 57].

This will initially lead to a prehospitally phase in which the available treatment resources are not initially sufficient to cope with the damaging event. The situation will arise that the usual and best possible individual medical treatment for the individual injured person cannot be offered in this way [57].

This is conditioned, as that by appropriate infrastructural measures primarily the primary care must be ensured locally, it must take place an appropriate production of the transportability with consideration of the transport urgency. The goal must then be to distribute the at least provisionally stabilized patients in the set to different hospitals in the sense of an appropriate patient allocation, so that the individual hospital is not overloaded. If this can still be implemented for normal large-scale incidents and the patients can be transported in a well-distributed manner with at least emergency care, it has recently become clear that this is not possible for events with a terror-associated background due to the lack of security on site for the security and rescue forces. It will be necessary to change from a recommended "treat and go" strategy to a significantly reduced strategy. This on the one hand as already indicated because of the pure number of injured per se, in addition, because partly existing basic conditions at the place of the incident do not permit a safe supply also for the rescue forces.

This will result in the necessity to significantly reduce prehospital measures (such as only the possible makeshift securing of the airway with, for example, oro- or nasopharyngeal tube or to address a relevant extremity bleeding by a makeshift ligation or the application of a tourniquet. Patients, regardless of the severity of their injuries, will therefore arrive at the hospitals with significantly less pre-care and, as a rule, it will be necessary for patients who are then often significantly more unstable to undergo measures that are already normally carried out prehospitally.

### 5.4.3 Principles for Drug Therapy in the Out-of-Hospital Phase

Sedation, analgesia, and emergency anaesthesia are key elements of prehospital emergency medical care. These measures pose a significant challenge to the whole emergency team. Pain may be eased through supportive measures (e.g. reduction of fractures, immobilization) and verbal emotional support. In many cases however, patients will only be pain free once potent analgesics have been administered [58].

The therapy of existing pain symptoms is also a central component in the treatment of trauma patients. Beyond the above-mentioned information on the therapy and elimination of existing disorders and problems, it is a justified obligation to provide the patient with a sufficient pain therapy [59]. In this context, the extent of pain relief is a key criterion for patients' perceived quality of care. However, study results show that only less than 50% of trauma patients received adequate analgesic care prehospital [60, 61]. Today, however, adequate analgesia must be required as a basic measure in rescue and emergency medical as well as in prehospital

trauma care. Sufficient analgesia is an important component of qualified emergency medical therapy and essential to avert further vital threat and complications [59].

For patients with analgesia then performed, close monitoring must be called for. This is because with the drugs typically used, adverse effects can also occur rapidly after sufficient analgesia, and thus the relevant vital functions may be compromised (e.g. loss of consciousness, respiratory and circulatory depression). This aspect must be addressed by close monitoring of the patient, especially with standard monitoring, prophylactic oxygen application, and titrated drug administration. The necessity of a possible emergency induction of anaesthesia must be taken into account at any time [59].

For the treatment of existing pain symptoms in a polytraumatized patient, the following drugs are available or recommended by the authors:

- the NMDA antagonist (es)ketamine
- the opioids morphine and fentanyl.

In analgesic dosage, (es)ketamine has a rapid and potent onset of action without significantly impairing spontaneous breathing or corresponding protective reflexes (dissociative anaesthesia). It should be noted, however, that in frequently occurring nightmare-like states, the administration of a sedative such as midazolam is usually recommended in addition to ketamine administration. The enantiomer esketamine (S-ketamine) has a higher analgesic and anaesthetic potency. Corresponding side effects as mentioned before usually become less prominent. And since an increase in heart rate and blood pressure can also be observed via central sympathetic stimulation, these are welcome side effects, especially in trauma patients [58].

As mentioned, morphine and fentanyl can also be used in the prehospital setting, with varying degrees of analgesic, sedative, and antitussive effects. Furthermore, a possible respiratory depression and, regarding the trauma patient, an increase in heart rate and blood pressure are important, so that a possible positive effect may be expected here.

In addition to appropriate pain therapy, the patient's condition or the general conditions may make it necessary to introduce appropriate sedation. Benzodiazepines such as midazolam or lorazepam are well suited for this purpose, as they have a very good anxiolytic and amnestic effect. With titrating administration, the side effect of possible respiratory depression can also be well assessed and controlled.

The low-dose administration of propofol is also possible, but here special attention must be paid to further undesirable limitations such as respiratory depression or regurgitation, and a constant readiness for emergency intubation must be given [58].

An indication for emergency anaesthesia in the trauma patient is given in the case of acute or threatening oxygenation or ventilation disorders. In addition to situations of acute respiratory insufficiency, persistent vigilance disturbance (GCS <9) with risk of aspiration, such as in the presence of craniocerebral trauma or hemodynamic instability, may also be present. To indicate an appropriate emergency anaesthesia in a traumatized patient, certain requirements should be met after thorough evaluation of the patient and orienting examination, the indication must be critically reviewed. The patient's condition must be optimized to the maximum and an established and standardized procedure is required regarding preparations and sequence. It is quite essential that possible complications, such as the need to create a surgical airway, can be also managed by the acting personnel. In this regard, propofol, midazolam, or etomidate are used as induction hypnotics. Appropriate muscle relaxation in these situations is readily performed with succinylcholine or rocuronium. Appropriate muscle relaxation is particularly useful and recommended in the prehospital setting, as it is the only way to create optimal intubation conditions in what are usually already difficult general conditions. The anaesthesia should usually be continued and

maintained with midazolam in titrating administration with good controllability. Fentanyl can also be used accordingly.

Table 5.1 summarizes the most common drugs for pain therapy, sedation, and induction and maintenance of anaesthesia [62].

**Table 5.1** Overview of essential and important emergency drugs that can be used in prehospital trauma care for pain therapy, sedation, and induction of anaesthesia (according to Michael et al. [62]

| | Dosage | Effect mechanism | Side effects | Special characteristics |
|---|---|---|---|---|
| *Analgetic* | | | | |
| Ketamine / Esketamine | Ketamine for analgesia: 0.5–1 mg/kg bw i. v. for preservation of protective reflexes Onset of action (i. v.): 30 s Duration of action (i.v.): 5–15 min Esketamine for analgesia: 0.25–0.5 mg/kg bw i. v. during preservation of protective reflexes Onset of action (i. v.): 30 s Duration of action (i. v.): 5–15 min | Non-competitive antagonism at NMDA receptor, agonistic at opiate receptors, inhibition of peripheral reuptake of catecholamines, influence on central and peripheral monoaminergic and cholinergic transmission, leads to dissociative anaesthesia. | Sympathomimetic: Increase in heart rate and blood pressure, respiratory depression to apnoea, increased defensive reflexes in the pharyngeal and laryngeal area (CAVE: laryngospasm during suctioning suction/intubation), anxiety, hallucinations. | Ketamine does not increase ICP and can be used in traumatic brain injury trauma, cautious use in severe, use in severe cardiac failure, bronchodilator effect in asthma. Storage: not below 0°C due to risk of breakage of the container. Esketamine does not increase ICP and can be used in traumatic brain injury, cautious use in severe cardiac failure. Storage: not below 0°C because of danger of breakage of the container |
| Morphine | Fractionated administration, e.g. 2.5 mg boli i.v. | Pure agonist at opiate receptors with high affinity to the μ-receptor and low affinity to the κ-receptor. Decrease in pulmonary vascular resistance. Hydrophilic substance, therefore delayed onset of action (5–15 min), duration of action 3–5 h. | Respiratory depression, muscle rigidity, hypotension especially with hypovolemia, vomiting, nausea, bradycardia, pruritus, bronchospasm, sedation. | Antidote: Naloxone Histamine releases active metabolites morphine-6-glucuronide and morphine-3-glucuronide with risk of of accumulation in renal insufficiency. |
| Fentanyl | Analgesia: Bolus doses of 0.05–0.1 mg. Titrate i.v. Onset of action: <30 s. Duration of action (mean): 0.3–0.5 h. | Pure agonist at opiate receptors with high affinity to the μ-receptor and low affinity to the κ-receptor. | Respiratory depression, muscle rigidity, hypotension especially with hypovolemia, bradycardia. | Antidote: Naloxone Storage: protect from light. Thoracic rigidity possible. |
| *Sedatives* | | | | |

**Table 5.1** (continued)

| | Dosage | Effect mechanism | Side effects | Special characteristics |
|---|---|---|---|---|
| Midazolam | Anaesthesia induction: 0.15–0.2 mg/kg bw i.v. Maintenance of anaesthesia: 0.03–0.2 mg/kg bw i.v. Onset of action: 60–90 s. Duration of action: 1–4 h. | Binding to α-subunit of the GABA receptor causes a prolonged opening of chloride channels and thus an increased effect of the inhibitory CNS transmitter GABA. | Paradoxical excitation. CAVE: Combination with alcohol (increased alcohol effects), respiratory insufficiency in combination with opioids. | CAVE: Incorrect dosing in case of confusion if different concentrations charged 5 mg/5 mL (=1 mg/mL) ampoule or 15 mg/3 mL (=5 mg/mL) ampoule. |
| Propofol | Anaesthesia induction: (1–) 1.5–2.5 mg/kg bw i.v. Maintenance of anaesthesia: 3 (4)–6 (−12) mg/kg bw/h i.v. or bolus application 0.25–0.5 mg/kg bw i.v. Onset of action: 15–45 s. Duration of action: 5–10 min. | Agonist at the GABA receptor. | Respiratory depression to apnoea, drop in blood pressure (negative-inotrope, decreased peripheral vascular resistance) especially in hypovolemia, excitation phenomena, local injection pain, Histamine release. | Low bronchodilator effect, beneficial in craniocerebral trauma and increased ICP. |
| *Narcotics* | | | | |
| Propofol | see above | | | |
| Midazolam | see above | | | |

(continued)

**Table 5.1** (continued)

| | Dosage | Effect mechanism | Side effects | Special characteristics |
|---|---|---|---|---|
| Ketamine/ Esketamine | Ketamine for anaesthesia induction: 1–2 mg/kg bw i.v. or 4–10 mg/kg im. Onset of action (i.v.): 30 s. Duration of action (i.v.): 5–15 min. Esketamine for anaesthesia induction: 0.5–1 mg/kg bw i.v. or 1.5–5 mg/kg im. Onset of action (i.v.): 30 s. Duration of action (i.v.): 5–15 min. | see above | | |
| Etomidate | Anaesthesia induction: 0.15–0.3 mg/kg bw i.v. Onset of action: 15–45 s. Duration of action (HWZ): 3–12 min. | Not completely clarified, hypnotic effect partly via a GABA-mechanism. | Nausea and vomiting, mild respiratory depression, local injection pain, Myoclonus. | Reduction of cortisol synthesis (11β-hydroxylase) even with single-bolus administration with particular risk in sepsis and trauma for complications such as ARDS, multiple organ failure, longer length of hospital stay, more ventilation days, longer intensive care stay, higher lethality. |
| Fentanyl | Anaesthesia induction: initial 2 µg/kg bw i.v. Maintenance of anaesthesia: 1–3 µg/kg i.v. Onset of action: <30 s. Duration of action (mean): 0.3–0.5 h. | see above | | |
| *Muscle relaxants* | | | | |

**Table 5.1** (continued)

| | Dosage | Effect mechanism | Side effects | Special characteristics |
|---|---|---|---|---|
| Succinylcholine | Single dose:<br>In all age groups 1.0–1.5 mg/kg bw i.v.<br>Onset of action: 60–90 s.<br>Duration of action: 3–6 min. | Only depolarizing muscle relaxant, action at the nicotinic acetylcholine (ACH) receptor at the motor end plate. | Arrhythmias, tachycardia, bradycardia, potassium liberation up to asystole, blood pressure disorders. Muscle pain after fasciculations. Allergic reactions. Increase of intraocular pressure (CAVE: penetrating injuries). Increase of intragastric pressure. Increased salivation. Increased jaw pressure (up to 60 s). Malignant hyperthermia. | Increased sensitivity in neuromuscular diseases (dose reduction if necessary). Precurarization with non-depolarizing muscle relaxants attenuate side effects, more noticeable rigor of the masseter muscle is considered as a warning sign for rhabdomyolysis or or malignant hyperthermia, with activity reduction of cholinesterase. Prolongation of duration of action. |
| Rocuronium | For RSI:<br>1.0–1.2 mg/kg bw i.v.<br>For geriatric patients 0.6 mg/kg bw i.v. (duration of action possibly prolonged).<br>Onset of action: 60–120 s<br>Duration of action:<br>30–67 min | Medium-acting, non-depolarizing neuromuscular blockade. Competitive effect to the at the motor end plate located ACH receptor. | Tachycardia, injection pain, allergic reaction. | Reversible by Sugammadex.<br>Physically incompatible with:<br>Dexamethasone, Diazepam, Furosemide, Hydrocortisone sodium succinate, Insulin, Intralipid, Methylprednisolone,Prednisolone-sodium succinate, Thiopental. |

## 5.5 Case Report

We would like to summarize the essential contents of this chapter by means of a case report:

In German-speaking countries the emergency medical service (EMS) system relies on a team of well-trained paramedics and special trained EMS-physicians qualified for on-scene resuscitation not only in cardiac arrest, but also in prehospital trauma care. EMS-physicians are mobile by car and can join any ambulance in a so-called rendezvous-system. In addition, a helicopter emergency medicals service (HEMS) system covers the whole country with an operational radius of approximately 70 km. Every HEMS is staffed by a special trained team existing of a HEMS-physician and a flight paramedic [63].

When a dilapidated rectory in a rural village is being demolished, a wall collapses suddenly. One worker is buried under bricks, beams, and dust. His colleagues alert the dispatching centre, which sends the local fire brigade, an ambulance, and the nearest HEMS to the accident site.

When the rescue team arrives, the colleagues were already able to dig up the patient largely from under the stones, so that the fire brigade is quickly able to rescue the patient to a safe area under spinal immobilization using a rigid collar and a spine board. The patient is unconscious and suffers from soft tissue injuries on the head and in the face.

The primary assessment according to the <C>ABCED algorithm shows:

- <C>: no critical bleeding
- A: cervical spine in manual in-line stabilization, upper airway free.
- B: $SpO_2$ without supplemental oxygen 90%, and a respiratory rate of 20/min, which either may be regarded as a sign of chest trauma or expression of pain, as well as a combination of both.
- C: HR 145/min, BP 110/60 mmHg in the sense of a haemorrhagic shock.
- D: unconsciousness, Glasgow Coma Score 3.
- E: risk of hypothermia on a clear spring day.

The patient's pupils are dilated at this point but are sensitive to light. In addition to the suspected traumatic brain injury, the body check reveals the suspicion of a thoracic trauma with fractured ribs on the left side leading to a flail chest. The auscultation, however, results in weak breath sounds on the injured side, so that a pneumothorax is assumed.

The HEMS crew establishes two venous accesses, starts volume therapy, and performs rapid sequence induction using a combination of thiopental and succinylcholine with subsequent intubation on the accident site. Laryngoscopy and endotracheal intubation are performed with first pass success using a video laryngoscope [64]. To maintain anaesthesia a repetitive combination of fentanyl, midazolam, and rocuronium is applied.

After connection to the ventilator the HEMS-physician performs point of care ultrasound (extended focused abdominal sonography for trauma–eFAST) without findings of free fluids in the abdomen but confirming the suspicion of pneumothoracs on the left side [65]. A thoracotomy and chest tubing are performed immediately. As oxygenation improves while circulatory parameters remain unstable, small-volume resuscitation is [66] initiated using 200 mL of saline 10%, followed by 1000 mL Ringer's acetate and 1 g tranexamic acid, assuming a haemorrhagic shock.

With respect to the trauma kinematic a pelvic binder is applied, the patient is immobilized in a vacuum mattress and covered in a rescue bag to maintain warmth.

After an on-scene-time of 28 min and radio notification of the admitting level-1 trauma centre, the patient gets transported by HEMS and arrives in the trauma resuscitation room cardiocirculatory stable and sufficiently ventilated 63 min after the initial alert (Fig. 5.2).

## 5.6 Take-Home-Message and Conclusion

Prehospital care of polytraumatized and thus severely injured patients must be carried out in an orderly and structured manner. The aim is to stabilize the patient and provide initial care in such a way that the patient is not further harmed and prompt and rapid transport to a suitable hospital is possible.

The <C ≫ A > B > C > D > E algorithm is a valuable tool and guiding structure to implement this orderly patient care. Derived from the PHTLS®, it can help to increase the efficiency of prehospital trauma care and thus improve the prognosis for the patient [67].

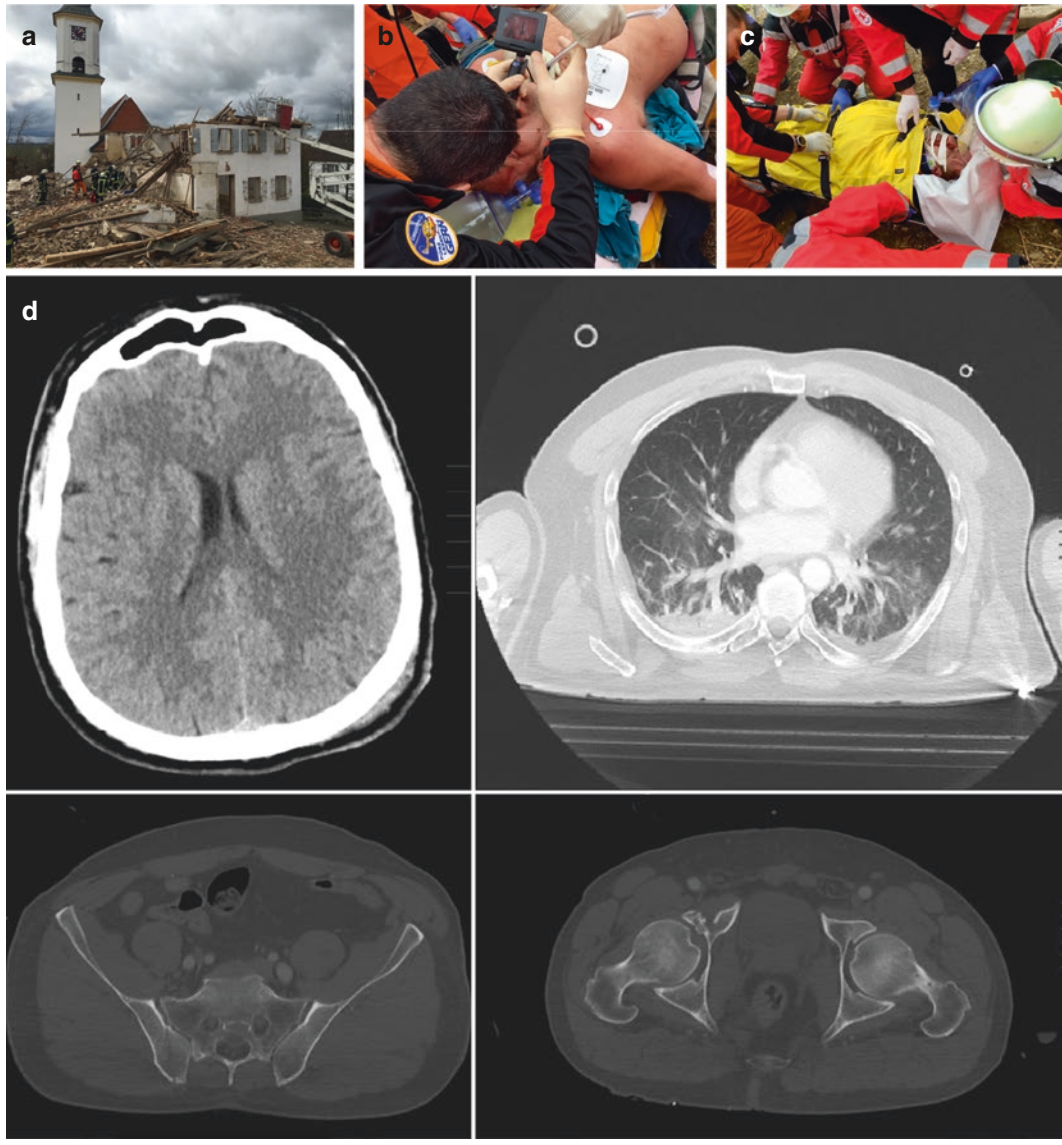


**Fig. 5.2** (**a**) Accident scene with collapse of a house wall during demolition work on the house. (**b**) Video laryngoscopy assisted endotracheal intubation. (**c**) Readiness of the patient for air transport to the nearest level 1 trauma centre. (**d**) Illustration of relevant diagnoses

- top left: craniocerebral trauma with generalized brain swelling in hypoxic brain damage
- top right: severe chest trauma with significant lung contusions on both sides and rib series fracture C3–6 and C8–9 with pneumothorax on the left
- bottom: unstable pelvic ring fracture (AO: 61-C1)
- further diagnoses: longitudinal petrous bone fracture left, zygomatic arch fracture right, various head lacerations, spinal trauma with spinous process fractures C5 to T1, transverse process fractures C7 to T1 right and L1 to L3left, scapula fracture left

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# Initial Assessment and Diagnostics

6

Philip F. Stahel and Adrian W. Olson

**Learning Objectives**

- Identify the correct sequence of diagnostic priorities for trauma patients per ATLS® criteria.
- Understand the A-B-C-D-E algorithm of the primary survey as it relates to identifying injuries with the highest likelihood of postinjury death.
- Establish the concepts of the primary, secondary, and tertiary survey as part of the diagnostic workup of the polytrauma patient.
- Explain the specific adjuncts to primary and secondary survey.
- Recognize patients who need early consideration for transfer to another facility with appropriate resources and capabilities.

## 6.1 Introduction

The primary goal of the initial assessment and management of polytrauma patients is survival [1]. Hereby, the term "polytrauma" entails more than simply the sum of all individual injuries sustained by a trauma patient [2]. In these patients, the recognition and early restoration of the "lethal triad" of persistent metabolic acidosis, hypothermia, and coagulopathy is paramount for post-injury survival (Fig. 6.1). The complex underlying pathophysiology renders multiply injured patients vulnerable to preventable complications resulting from an uncoordinated initial diagnostic workup [3, 4]. More than 100 years ago, the "Father of Modern Medicine," Sir William Osler (1849–1919), stated that *"Specialism has fragmented the specialties themselves in a way that makes the outlook hazardous."* This notion is directly applicable to polytrauma where the widely disseminated paradigm of "fragmentation of care" by involving multiple individual specialists to assess and manage the critically injured patient has shown to result in suboptimal outcomes. The "European model" has historically considered trauma as a singular disease, and therefore designated the trauma team as the single "specialist" responsible for the care of the polytrauma patient [5]. The term "polytrauma" is more widely used in European trauma centers, in analogy to the "multiply injured patient" in the United States [6]. Multiple polytrauma definitions have been suggested since the 1970s (Table 6.1). The "Berlin definition" originates form an interna-

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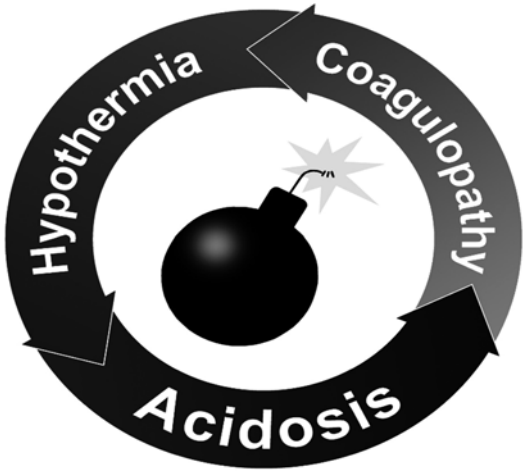


**Fig. 6.1** The lethal triad of polytrauma

tional consensus conference and combines anatomic injuries with physiological parameters [7]. The utility and predictive value of the "Berlin definition" has been validated in multiple recent studies [8–10].

Until the 1980s, the delivery of trauma care in the United States was highly inconsistent. The implementation of standardized checklists, such as the "Advanced Trauma Life Support" (ATLS®) protocol, has reduced the variation in diagnostic workup strategies and the delivery of standardized appropriate care, and thereby improved patient outcomes and trauma survival rates [11]. The ATLS® program remains the "key pillar" towards a standardized diagnostic approach in the initial assessment of the and management of the trauma patient [12]. Of note, per ATLS® protocol, identified injuries are managed simultaneously to the initial diagnostic workup [13]. The present chapter was designed to outline the initial assessment and diagnostic work-up of the polytrauma patient, as templated on the ATLS® algorithm that stratifies the initial assessment into a primary and a secondary survey, with selected "adjuncts" available to support the initial assessment and simultaneous management of identified injuries (Table 6.2)

The specific management strategies for individual injuries are described elsewhere in this textbook.

**Table 6.1** Historic polytrauma definitions

| | |
|---|---|
| John Border (1975) | "More than 2 significant injuries in ≥2 body regions" |
| Harald Tscherne (1984) | "Two or more injuries, among which at least one, or the sum of all injuries, is life-threatening." |
| Otmar Trentz (2000) | "A syndrome of multiple injuries exceeding a defined injury severity (ISS > 17) with consecutive systemic trauma reactions which may lead to dysfunction or failure of remote—Primarily not injured—Organs and vital systems." |
| Hans-Christoph Pape (2006) | "Injuries of at least two long bone fractures, or one life-threatening injury and at least one additional injury, or severe head trauma and at least one additional injury." |
| Butcher and Balogh (2012) | "AIS ≥3 in at least two body regions." |
| Berlin Consensus Conference (2014) | "AIS ≥3 in at least two body regions, and one or more additional variables from 5 selected physiologic parameters." |

**Table 6.2** Adjuncts to the initial assessment of the trauma patient

| | | |
|---|---|---|
| **Adjuncts to the primary survey** | A | Pulse oximetry<br>Capnography<br>Chest X-ray |
| | B | Pulse oximetry<br>ABGA<br>eFast<br>Chest X-ray |
| | C | EKG<br>Foley catheter<br>Gastric catheter<br>eFast<br>AP chest X-ray<br>AP pelvic X-ray |
| **Adjuncts to the secondary survey** | A | Repeat chest X-rays |
| | B | Contrast CT chest |
| | C | Contrast CT abdomen pelvis<br>Inlet/outlet pelvic X-rays<br>X-rays of long bones<br>Contrast urography<br>Angiography<br>Endoscopy<br>TTE/TEE |
| | D | Non-contrast CT head<br>CT spine with 2-D recons<br>MRI spine/brain |
| | E | Additional extremity radiographs |

## 6.2 The Primary Survey

The initial assessment of the trauma patient occurs in two staged phases in the emergency room: the primary and the secondary survey [12]. The tertiary survey is performed in a delayed fashion subsequent to patient admission to the hospital (typically on postinjury day 1), with the intent of reducing the risk of missed injuries that were not immediately life- or limb-threatening at the time of patient arrival [14]. During the primary survey, the injured patient is rapidly assessed by the standardized algorithm of the ATLS® protocol, based on the "A-B-C-D-E" mnemonic:

- **A**irway maintenance, with cervical spine protection
- **B**reathing and ventilation
- **C**irculation and hemorrhage control
- **D**isability: brief neurologic evaluation
- **E**xposure with environmental control (protection from hypothermia)

Hereby, life-threatening conditions are identified and managed simultaneously, and are stratified by a prioritized sequence (ABCDE) based on the effects that specific injuries may have on a patient's physiological response, since it is not possible to define all anatomic injuries during the early phase of the diagnostic workup [12].

### 6.2.1 A—Airway

The ATLS® protocol mandates that the prioritized sequence of assessment and management is predicated by the extent of the risk of dying. Thus, the injury with the greatest threat to life is managed first. If a trauma patient is able to communicate verbally, the airway is not immediately compromised. However, patients are at risk of losing their airway fast, particularly in presence of high risk associated injuries, such as maxillofacial fractures or smoke inhalation injury. Regardless of the specific injury causing acute airway compromise, e.g., direct physical trauma vs. secondary to traumatic brain injury, the first priority is assurance of a patent airway. If indicated, this implies rapid-sequence endotracheal intubation to provide a safe definitive airway. In rare emergent cases, when intubation is contraindicated or cannot be safely accomplished, a surgical cricothyroidotomy may be required to establish an early definitive airway. Correct positioning of the endotracheal tube is confirmed by auscultation, end-tidal $CO_2$ monitoring, and a chest X-ray. Every trauma patient receives supplemental oxygen, independent if intubated or not. The bleeding trauma patient's oxygen requirement is illustrated by the historic Nunn & Freeman formula from 1964:

$$O_{2av} = CO \times SaO_2 \times Hb \times 1.34.$$

This formula specifies that the oxygen available in the tissue ($O_{2av}$) is equal to the product of cardiac output (CO in mL/min), arterial $O_2$ saturation ($SaO_2$ in %), and hemoglobin concentration (Hb in g%), whereby 1.34 represents the O2-binding capacity of hemoglobin (in mL/g) [15]. While the oxygen demand is satisfied under physiological conditions, the underlying variables are significantly compromised in the polytrauma patient due to acute blood loss (Hb), pulmonary contusions ($SaO_2$), myocardial contusion or pericardial tamponade (CO), and therefore result in a severe deficit of oxygen supply for the trauma patient [2].

Of importance, per ATLS® criteria, the cervical spine must be protected from excessive motion during maneuvers to retain the upper airway or perform endotracheal intubation. The protocol mandates cervical spine protection in a C-collar, and by manual in-line traction when the C-collar is opened for acute airway management.

### 6.2.2 B—Breathing

Airway maintenance alone does not ensure adequate ventilation. Therefore, in second priority to establishing a safe airway, injuries that significantly impair ventilation must be identified and mitigated acutely. These include tension pneumothorax, massive hemothorax, open pneumo-

thorax, and tracheobronchial injuries [16, 17]. Most commonly, a tension pneumothorax acutely compromises ventilation and hemodynamics, and must therefore be excluded due to the imminent threat to life. The clinical symptoms of a tension pneumothorax include acute dyspnea, ipsilaterally decreased respiratory sounds with hypersonoric percussion sound, and congested jugular veins. As a pitfall, congested jugular veins may be absent in patients with hemorrhagic-traumatic shock due to hypovolemia and circulatory centralization. A tracheal deviation to the contralateral side represents a late sign and is rarely detected by clinical inspection of the neck. If a tension pneumothorax is suspected by clinical findings alone, chest decompression must be obtained by puncture of the second intercostal space in the midclavicular line with a large-bore needle. This life-saving maneuver converts the tension aspect into a simple pneumothorax and must be subsequently finalized by the placement of a chest tube. The most frequent cause of tension pneumothorax is mechanical positive pressure ventilation in a patient with chest trauma and an occult visceral pleura injury. When in doubt, a chest tube should be placed in critically injured patients with rib fractures due to the risk of developing a tension pneumothorax after intubation and positive end-expiratory pressure ventilation. Additional critical thoracic injuries other than a tension pneumothorax include flail chest with pulmonary contusions, massive hemothorax, and open pneumothorax, also designated as a "sucking chest wound." Patients with a flail chest may be candidates for early intubation and mechanical ventilation due to the risk of terminal respiratory failure. A massive hemothorax is managed by chest tube placement. However a massive hemothorax with ongoing hemorrhage may require early surgical management by a resuscitative thoracotomy.

### 6.2.3 C—Circulation

Circulatory compromise in the trauma patient is most frequently due to bleeding and traumatic-hemorrhagic shock [18]. Until proven otherwise, the polytrauma patient is by definition in a state of shock, which must be diagnostic and managed in a timely fashion to prevent early postinjury mortality. Once a tension pneumothorax is ruled out as a cause of shock under the "B" problems, hypovolemia from traumatic hemorrhage remains the main working hypothesis in the initial assessment of the trauma patient. Internal and external sources of hemorrhage must be recognized in a very timely fashion, and the bleeding must be stopped, if necessary, by surgical measures. The immediately available clinical "windows into the microcirculation" include the assessment of pulse (tachycardia), skin perfusion (hypovolemia), and level of consciousness (cerebral hypoperfusion). The additional window into the microcirculation relates to renal perfusion, which can be assessed by quantifying urinary output after placement of a Foley catheter.

In order to estimate the approximate extent of traumatic hemorrhage, the compensatory mechanisms to hypovolemia have to be taken into consideration. For example, the acute blood loss of up to 30% of the circulating volume, which is equivalent to 1500 cc in a patient of 70 kg body weight, does not lead to hypotension due to the increase in peripheral resistance, which masks the true "state of shock" (Table 6.3). However, the cardiac output is reduced to up to half the normal value in this situation, which leads to organ hypoperfusion and metabolic acidosis due to anaerobic metabolism. Therefore, the key question—*"Is the patient in shock?"*—must be addressed early during the primary survey is to determine presence or absence of significant traumatic hemorrhage [13]. This includes a streamlined and standardized approach towards recognizing and controlling external and internal bleeding sources.

#### 6.2.3.1 "Is the Patient in Shock?"—Clinical Assessment

The clinical symptoms of shock are traditionally represented by the "three windows to the microcirculation":

1. Skin perfusion: Patients with a pink skin in the face and extremities are likely not at risk

**Table 6.3** Classification of traumatic-hemorrhagic shock[a]

| | Class 1 | Class 2 | Class 3 | Class 4 |
|---|---|---|---|---|
| Blood loss | <750 cc | 750–1500 cc | 1500–2000 cc | >2000 cc |
| Blood loss (% volume) | <15% | 15%–40% | 30%–50% | >40% |
| Heart rate | <100/min | >100/min | >130/min | >140/min |
| Blood pressure | Normal | Normal | Decreased | Decreased |
| Pulse pressure | Normal | Decreased | Decreased | Decreased |
| Respiratory rate | 14–20/min | 20–30/min | 30–40/min | >35/min |
| Urine output | >30 mL/h | 20–30/mL/h | 5–15/ml/h | Negligible |
| Mental status | Normal | Anxious | Confused | Lethargic |

[a](per ATLS® criteria [12])

of significant hypovolemia. In contrast, the presence of cold and clammy skin, with ashen-gray facial skin, pale extremities, and delayed capillary refill in conjunction with tachycardia are strong clinical indicators of traumatic-hemorrhagic shock.

2. Cerebral perfusion: When the circulating volume is critically reduced due to hypovolemia, patients may present with an altered level of consciousness due to cerebral hypoperfusion. However, this may represent a late sign of significant hemorrhage due to the physiological autoregulation which retains cerebral blood flow in presence of systemic hypotension. Agitation, confusion, somnolence, or lethargy may represent indirect signs of critical cerebral hypoperfusion in bleeding trauma patients.
3. Renal perfusion: The placement of a Foley catheter allows to monitor the extent of urine production as a surrogate marker of renal perfusion. Patients with severe hypovolemia will present with oliguria (defined as <0.5 mL/Kg BW/h) or anuria. The Foley catheter furthermore allows to detect macrohematuria secondary to renal trauma or urogenital injuries.

These clinical findings help provide a rough estimate of whether a trauma patient is "hemodynamically normal" or just transiently "hemodynamically stable." One of the key aspects of the initial assessment per the ATLS® protocol is to initiate resuscitative measures in parallel to the diagnostic workup, and to monitor the patient's response to resuscitation by continuous clinical re-evaluation [12]. Based on the response to resuscitative measures, patients are stratified into "responders," "non-responders," and "transient responders." The latter cohort of patients are frequently under-triaged due to occult hemorrhagic shock, with a high risk of acute deterioration and fatal outcomes [13].

A persistent base deficit or elevated lactate suggests ongoing resuscitation requirements. The patient's physiological state and response to resuscitation have to be determined early on in order to initiate appropriate timely treatment. For this purpose, trauma patients have been traditionally stratified into the following 4 physiological categories: [19]

### Stable

These trauma patients respond to initial therapy and are hemodynamically stable throughout their initial clinical pathway, without clinical or laboratory signs of occult hemorrhage and "hidden shock."

### Borderline ("At Risk")

These trauma patients usually typically present with a combination of injury patterns that renders them at risk of poor outcomes. The patients may be under-triaged due to initial response to resuscitation ("transient responders") and rapid subsequent deterioration.

Criteria for identifying these patients include:

- Hypothermia (<36 °C)
- Acidosis (lactate, BD)
- Coagulopathy (INR, aPTT, TEG/ROTEM)
- Severe traumatic brain injury (GCS ≤8).
- Bilateral femur shaft fractures
- Radiographic evidence of pulmonary contusions
- Multiple injuries in association with thoracic trauma or head injury
- Multiple injuries in association with severe abdominal or pelvic trauma

#### Unstable

Patients in traumatic-hemorrhagic shock at presentation (systolic BP <90 mmHg) will require a fast-tracked abbreviated assessment by the ATLS® algorithm. Non-responders and transient responders will undergo immediate life-saving surgery, as indicated, and timely transfer to ICU for restoration of the "endpoints of resuscitation" (see below).

#### In Extremis

These patients present in a state of uncontrollable exsanguinating hemorrhage and have a high predicted mortality. These patients are non-responders by definition, and require immediate activation of a mass transfusion protocol (MTP) in conjunction with "damage control" procedures at the bedside, including ED thoracotomy and "crash" laparotomy [20]. Once the life-saving procedures are carried out, patients are transferred directly to ICU for invasive monitoring and ongoing resuscitation.

### 6.2.3.2 "Is the Patient in Shock?"—Laboratory Tests

A complete blood count (CBC) represents a part of the baseline diagnostic workup for trauma patients. However, the diagnostic value of hemoglobin or hematocrit for occult hemorrhage in trauma patients remains a topic of debate [21]. One major drawback of isolated hemoglobin or hematocrit values is due to the confounding influence of dilution by administration of crystalloids. Recent studies have unequivocally determined that neither isolated nor serial repeat assessment of hemoglobin or hematocrit represents sensitive tests to predict the necessity for emergent surgical intervention in blunt trauma patients with occult hemorrhage [22–24].

In contrast to the poor predictive value of the CBC, both base deficit and serum lactate have been shown to significantly predict the presence of "hidden shock" in trauma patients and to monitor the response to resuscitation [21]. The extent of shock by base deficit is stratified into three categories: mild (−3 to −5 mEq/L), moderate (−6 to −9 mEq/L), and severe (<−10 mEq/L). This stratification provides a significant correlation between the admission base deficit and transfusion requirements within the first 24 h and the risk of postinjury complications and death [25]. It is also important to note that the base deficit is a better prognostic marker of death than the pH, by arterial blood gas analysis [26]. The base deficit has been stablished as a highly sensitive marker for the extent of post-traumatic shock and mortality, both in adult and pediatric patients [26, 27]. In essence, a base deficit below −5 mEq/L by arterial blood gas analysis is associated with a significantly increased rate of postinjury complications and transfusion requirements, whereas a level less than −10 mEq/L is associated with a very high predicted mortality [25, 26]. In contrast, a normal base deficit (or base excess) with values around +2 to −2 mEq/L is associated with a low postinjury mortality around 6% [25, 26].

Historic landmark studies have shown that the serum lactate level on admission represents a "key" predictor for the presence of traumatic-hemorrhagic shock on admission. Abramson and colleagues performed a prospective observational study in patients with multiple trauma to evaluate the correlation between lactate clearance and survival [28]. All patients in whom lactate levels returned to the normal range (≤2 mmol/L) within 24 h survived. Survival decreased to 77.8% if normalization occurred within 48 h and to 13.6% in those patients in whom lactate levels were elevated above 2 mmol/L for more than 48 h [28]. These findings were confirmed in a study by Manikis and colleagues who showed that the initial lactate levels were higher in non-survivors after major trauma, and that the prolonged time for normalization of lactate levels of more than

24 h was associated with the development of post-traumatic organ failure [29].

Although both the base deficit and serum lactate levels are well correlated with the extent of traumatic-hemorrhagic shock and response to resuscitation, these two parameters do not strictly correlate. Therefore, the independent assessment of both parameters is recommended for the initial evaluation of the bleeding trauma patient.

#### 6.2.3.3 Postinjury Coagulopathy

Uncontrolled hemorrhage accounts for nearly 40% of all trauma deaths, and around one-third of all bleeding trauma patients present with a coagulopathy on admission [30]. This subset of trauma patients has a significantly increased risk of adverse outcomes and death compared to non-coagulopathic patients with similar injury severity. The diagnostic workup for postinjury coagulopathy includes conventional laboratory tests, such as the international normalized ratio (INR), activated partial thromboplastin time (aPTT), fibrinogen levels, and platelet count [21]. In general, the diagnosis of coagulopathy using conventional assays is determined by the following thresholds:

- Prothrombin time (PT) >18 s
- Activated partial thromboplastin time (aPTT) >60 s
- PT/aPTT >1.5× control values
- INR >1.5 (PT)
- Quick value <70% (PT)
- Platelet count <100 × 10 [9]/L

However, most of the conventional coagulation tests were developed to monitor anticoagulant therapy, and therefore reflect a crude and artificial in vitro assessment of coagulation. The pure reliance on in vitro coagulation tests (which are performed at a normal pH and a temperature of 37 °C) does not reflect the "true" in vivo coagulopathy in hypothermic and acidotic trauma patients [31]. In addition, the testing by conventional coagulation parameters is associated with a significant delay of around 20–30 min until results are available, and the patient's state of coagulopathy will have changed by the time results are available, due to ongoing resuscitation efforts.

These significant limitations of conventional laboratory tests are mitigated by modern "point of care" coagulation assays, using thromboelastography (TEG) or rotational thromboelastometry (ROTEM) [32]. These modalities are performed quickly at the bedside, and thus represent a "real-time" assessment of coagulation in the bleeding trauma patient.

*For further information on this selected topic, the reader is referred to a separate dedicated chapter in the book (see* Chap. 10, *"Trauma-induced coagulopathy").*

#### 6.2.3.4 Imaging Studies

Historically, the classic "triad" of plain radiographs obtained in the ED per protocol included a portable X-ray of the chest, a.p. pelvis, and a lateral cervical spine view. The lateral cervical spine X-ray was removed from the latest tenth edition of the ATLS® manual (a) due to the traditional difficulty of obtaining an appropriate lateral view at the bedside, and (b) due to the advent of the multi-slice CT scan technology, which largely replaced conventional spine radiographs in the diagnostic trauma workup [12].

The a.p. chest X-ray allows to detect a pneumothorax, hemothorax, widened mediastinum, displaced rib fractures, and severe pulmonary contusions. In additional, if the clinical diagnosis of a tension pneumothorax is missed, the X-ray may additionally demonstrate a tracheal deviation and mediastinal shift [16]. The a.p. pelvic X-ray is obtained to rule out pelvic fractures or pelvic ring disruptions as a major cause of retroperitoneal bleeding [33].

The rapid ultrasound assessment using a "focused assessment with sonography in trauma" (FAST) protocol has been an established adjunct to the primary survey since the 1990s, as a rapid bedside modality for detection of intra-abdominal free fluid in trauma patients. Over time, the FAST exam largely replaced the historic role of a diagnostic peritoneal lavage (DPL) [34]. The FAST exam has a high specificity (up to 0.99), but low sensitivity (around 0.7), for diagnosis significant intra-abdominal injuries [34]. In the twenty-first

century, the FAST paradigm was expanded to the eFAST protocol ("extended focused assessment with sonography in trauma") to include the assessment of intrathoracic injuries, such as pneumothorax, hemothorax, and cardiac tamponade [35]. The eFAST ultrasound technique relies on the following five diagnostic windows:

1. Right upper quadrant view for detection of free fluid in the right pleural space and between the liver and the right kidney (hepatorenal recess or "Morison pouch").
2. Left upper quadrant view for detection of free fluid in the left pleural space and between the spleen and the left kidney (splenorenal recess or "Koller pouch").
3. Anterior thoracic view for detection of missing pleural sliding on the right and left side of the chest.
4. Subcostal/subxiphoidal 4-chamber view for detection of fluid inside the pericardial sac.
5. Pelvic view for detection of free fluid in the rectovesical cavity between the rectum and the bladder ("Proust pouch") in males, or in the rectouterine cavity between the rectum and the posterior wall of the uterus ("Douglas pouch") in female trauma patients.

The role of computerized tomography (CT) scanning of acute trauma patients has significantly increased since the introduction of multislice CT (MSCT) scanners [36]. The integration of modern MSCT scanners in the emergency room area allows the timely assessment of trauma victims with high sensitivity for detecting occult injuries [37]. While the conventional diagnostic approach per ATLS® protocol in the 1990s was shown to require around 45 min to establish a working diagnosis, the implementation of modern MSCT scanners in the twenty-first century decreased the time to definitive diagnosis to around 12 min, with a higher sensitivity and specificity [38]. A faster and more accurate diagnosis is associated with shorter times spent in the ED and improved timeliness for achieving definitive bleeding control. Furthermore, contrast medium-enhance MSCT imaging has largely replaced the historic "gold standard" aortogram for assessment of aortic injuries, and allows for detection of occult vascular injuries and bleeding sources with high sensitivity [12].

If a MSCT is not available in the emergency room, the diagnostic workup by CT scanning implies transportation of the patient to the radiology suite, which implies a risk of transportation. Transfer times for diagnostic imaging must be carefully balanced against the risk of prolonged transportation times, particularly in hemodynamically unstable trauma patients. Therefore, stringent institutional protocols must be in place to streamline critical patients to the operating room in absence of CT scanning, if indicated. Of critical importance, the initial assessment and diagnostic workup of traumatic bleeding are paralleled by the simultaneous management of internal and external bleeding sources as those are recognized, in conjunction with appropriate fluid resuscitation and blood product replacement.

*Since the management strategies for specific injuries are beyond the scope of this chapter, the reader is referred to the respective dedicated chapters in this book* (see Chaps. 7–10 and 16–19).

#### 6.2.3.5 Monitoring Resuscitation

Subsequent to the diagnostic workup and simultaneous management of acutely life-threatening injuries, the critically injured patient is transferred to the ICU as soon as possible, with the intent of restoring the defined "endpoints of resuscitation": [39]

- Stable hemodynamics, without the need for vasoactive or inotropic stimulation
- No hypoxemia or hypercapnia
- Serum lactate <2.5 mmol/L
- Normal coagulation (INR, TEG/ROTEM)
- Normothermia (>36 °C/96.8 °F)
- Normal urinary output (>1 mL/Kg BW/h)

### 6.2.4 D—Disability

The fourth priority during the primary survey consists of a brief neurologic evaluation, including quantifying the Glasgow Coma Scale (GCS) score, assessing pupillary size and reaction, and

**Table 6.4** Glasgow coma scale

| Original scale | Revised scale | GCS score |
|---|---|---|
| *Eye opening (E)*[a] | | |
| Spontaneous | Spontaneous | 4 |
| To speech | To sound | 3 |
| To pain | To pressure | 2 |
| None | None | 1 |
| | Non-testable | NT |
| *Verbal response (V)*[a] | | |
| Oriented | Oriented | 5 |
| Confused conversation | Confused | 4 |
| Inappropriate words | Words | 3 |
| Incomprehensible sounds | Sounds | 2 |
| None | None | 1 |
| | Non-testable | NT |
| *Best motor response (M)*[a] | | |
| Obeys commands | Obeys commands | 6 |
| Localizes pain | Localizing | 5 |
| Flexion withdrawal to pain | Normal flexion | 4 |
| Abnormal flexion (decorticate) | Abnormal flexion | 3 |
| Extension (decerebrate) | Extension | 2 |
| None (flaccid) | None | 1 |
| | Non-testable | NT |

Best possible score: 15. Worst possible score: 3
[a]The GCS score is calculated as E + V + M

determining presence and level of spinal cord injury. The GCS is a historically established, rapid, simple, and objective methods for quantifying the level of consciousness (Table 6.4). A decrease in a trauma patient's level of consciousness may indicate decreased cerebral perfusion and oxygenation, as a surrogate marker of traumatic-hemorrhagic shock, or presence of traumatic brain injury (TBI). The severity of TBI is classified by the GCS as minor (GCS 13–15), moderate [9–12], or severe (GCS 3–8). A patient with a GCS of 8 or less is comatose by definition, which requires endotracheal intubation for airway protection (unless this already occurred as part of "A" in the primary survey). Hypoxia and hypotension must be avoided by all means in patients with TBI, due to the risk of inducing secondary brain insults which are associated with poor long-term outcomes [40]. Patients with severe TBI (GCS ≤8) must be transferred to a trauma center with appropriate resources to manage these critically injured patients, as soon as the patients are considered stable for transfer [41]. A neurosurgical consultation is mandatory for patients with head injuries or spinal cord injuries.

*The reader is referred to the respective designated chapters in this textbook* (Chaps. 14 and 21).

### 6.2.5 E—Exposure

The final step in the primary survey consists of a complete exposure of the trauma patient, including a log-roll maneuver to assess the patient's back side, including palpation of the thoracic and lumbar spine, and inspection for presence of soft tissue wounds, lacerations, penetrating injuries, or hematomas (unless this step already occurred under "C" as part of the assessment for bleeding sources) [12]. Since most trauma patients are hypothermic, which increases the risk of exacerbating postinjury coagulopathy, the patient's undressing and exposure are performed with maintenance of environmental control by applying warm blankets, heating lamps, and transfusion of IV crystalloids that are prewarmed to 39 °C (102.2 °F) by the use of high-flow fluid warmers.

## 6.3 Secondary and Tertiary Survey

The secondary survey does not begin until the primary survey with the A-B-C-D-E algorithm is completed and simultaneous management of identified life-threatening injuries has been accomplished, with improvement of the patient's physiologic response to resuscitation by continuing re-evaluation [12]. In essence, the secondary survey represents a "head-to-toe" evaluation of the trauma patient, including a complete history (as available) and a formal physical exam. The reassessment of vital signs and response to resuscitation continue during the secondary survey. Due to the potential of missing minor injuries during the initial assessment, a standardized tertiary survey is performed on postinjury day 1 and repeated as needed until the patient is fully awake and cooperative with a formal physical examination. Missed

injuries are found in up to 39% of all polytrauma patients and mainly relate to fractures around the hand/wrist and foot/ankle [42, 43]. Implementation of a protocolized approach to the tertiary survey allows to close the gap and reduce the ratio of missed injuries closer to zero [14].

## 6.4 Conclusion

Polytrauma patients are at high risk of postinjury complications and death. The fast-tracked initial assessment and diagnostic workup by the ATLS® protocol allows to identify and manage potentially life-threatening injuries in a prioritized sequence, using a standardized and internationally validated checklist.

**Key Concepts**

- After securing a patient airway and assuring adequate breathing and ventilation, the next key question *"Is the patient in shock?"* must be addressed by clinical assessment, laboratory parameters, and imaging studies.
- Trauma patients with postinjury coagulopathy have a high predicted mortality. The established "endpoints of resuscitation" must be addressed by ongoing resuscitative measures during the initial assessment.
- The diagnostic workup must allow to determine whether a trauma patient's needs exceed the resources of a facility, with a consideration for early patient transfer to a trauma center with appropriate resources and capabilities.

**Take Home Message**

- Strict adherence to the priorities of the initial assessment by the ATLS® protocol reduces the risk of preventable postinjury complications and improves trauma survival.

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# Volume and Blood Management

7

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**Learning Objectives**

- Volume therapy during the initial trauma resuscitation
- Transfusion and coagulation management including an example of a coagulation and transfusion algorithm
- Proper management of anticoagulated trauma patients
- Laboratory screening for oral anticoagulants in trauma patients
- Reversal and treatment of residual anticoagulant effects in case of an ongoing bleeding

## 7.1 Introduction

Traumatic injuries are one of the leading causes of death worldwide. Uncontrollable bleeding is thereby still the main preventable cause of death in severely injured patients [1]. A key element of *the European guideline on management of major bleeding and coagulopathy following trauma* is therefore to identify and stop the bleeding as fast as possible [2]. Beside surgical care for the cause of bleeding, trauma resuscitation also means detecting and treating systemic coagulation disorders quickly in order to stabilize the patient. Systemic coagulation disorders in the context of trauma are multifactorial in nature: Bleeding causes a loss of coagulation factors and requires fluid therapy to maintain circulation which leads to a further dilution of the remaining coagulation factors [3, 4]. Acidosis and hypothermia additionally impair the enzymatic activity of the coagulation factors, while protein C is simultaneously activated to prevent excessive, uncontrolled clot formation. Subsequently, the activated protein C forms a complex with protein S, which inactivates the coagulation factors Va and VIIIa by proteolysis with corresponding anticoagulatory effect. Inhibition of the "thrombin-activated fibrinolysis inhibitor" additionally leads to an increase in fibrinolysis. The pathological coagulation activation and, at the same time, excessive clot dissolution (hyperfibrinolysis) leads to further consumption and loss of coagulation factors. This process can quickly become aggravated and self-sustaining, causing so-called trauma-induced coagulopathy [3]. Trauma-induced coagulopathy is now established as an independent clinical pathology leading to an increased morbidity and mortality [5]. To tackle this issue, focused trauma management should already start in pre-hospital care, e.g., by administration of tranexamic acid [6]. Trauma patients are then admitted to a trauma center depending on their injury pattern. In the case of multiple injuries, primarily specialized

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trauma centers should be contacted to provide the best possible care. Parallel to surgical care, initial anesthesiologic care is also provided including stabilization of airway, ventilation, circulation, coagulation, and consciousness. Regarding transfusion and coagulation management a multimodal Patient Blood Management program should be an inherent part of modern, evidence-based trauma care [7, 8]. This chapter will focus on distinct Patient Blood Management strategies that may be implemented in the specific setting of trauma care.

## 7.2 Volume Therapy

Traumatic hemorrhage leads to a mismatch of oxygen supply and tissue demand due to reduced perfusion [9]. The impaired microcirculation is a main factor for secondary damage after a hemorrhagic shock. Volume therapy therefore aims to improve macro and especially microcirculation and thus organ perfusion [10]. In severely injured patients a venous access should be placed as soon as possible followed by a goal-directed volume resuscitation in order to keep the circulation at a low-stable level and thus without increasing the bleeding [2, 11]. The optimal fluid for volume therapy is still discussed. Colloid solutions were not able to show advantages over crystalloid solutions for volume resuscitation [12–14], but are afflicted with more side effects, especially hydroxyethyl starch [10, 15, 16]. Therefore, colloids are not recommended for volume therapy of trauma patients in first line [2]. In patients not responding to crystalloid solutions, a bolus of gelatin may however be considered as an alternative [2, 16, 17]. Albumin solutions should not be used, as they increased mortality in patients with concomitant traumatic brain injury [18]. Regarding hypertonic solutions, no empiric recommendations are made in guidelines [2]. Hypertonic crystalloids are proven to be safe but failed to show any improvement in survival or neurological outcome after traumatic brain injury. As they have no advantages over balanced crystalloid solutions, they should not be used in first line, but may be considered in special circumstances as an alternative (e.g., severe traumatic brain injury with increased intracranial pressure). Most common crystalloid solutions in clinical routine are balanced full electrolyte solutions (e.g., Ringer's acetate malate or Ringer's lactate) or physiological saline 0.9% solution. Normal saline is still the most commonly administered crystalloid, although its use has long been associated with hyperchloremia, metabolic acidosis, potassium increase, kidney damage up to dialysis, and increased mortality [19]. Based on physiological considerations and the results of initial reviews, a more favorable side effect profile was postulated for balanced electrolyte solutions. Recently, it was shown that balanced electrolyte solutions reduced the incidence of persistent renal dysfunction, new renal replacement therapy, and mortality compared to saline 0.9% [20, 21]. In conclusion, a restrictive, goal-directed volume resuscitation using balanced crystalloid solutions to maintain the circulation at a low-stable level is recommended [2].

## 7.3 Transfusion Management

The body tolerates acute anemia by increasing cardiac output. Primarily the stroke volume of the heart is increased, secondarily its beat frequency. A critical hemoglobin value is reached when the oxygen supply (as the product of cardiac output and the oxygen content of the blood, of which the hemoglobin concentration is a relevant part) falls below the body's oxygen requirement. Below this, the body's oxygen debt reaches a critical level, which is always fatal if left untreated (at least in animal models) [22]. However, in individual cases, very low hemoglobin levels of up to 1.4 g/dL can be survived without erythrocyte transfusion if cardiac output is increased significantly, a relevant perfusion pressure is maintained and the body's oxygen requirement is reduced [23]. Only few prospective, randomized trials investigated the optimal hemoglobin levels as transfusion triggers in trauma patients. The largest studies have been conducted in patients in intensive care, cardiac surgery, and orthopedics. Mentioned studies aimed, but failed

to prove that a liberal transfusion strategy is superior to a restrictive strategy [24]. Different clinical outcomes were analyzed, including mortality and morbidity consisting of cardiogenic shock, acute renal and pulmonary failure, ability to walk (in orthopedics), rebleeding, and long-term survival. Even in high-risk populations, there was no evidence of improved outcome with liberal transfusion triggers [24]. Also in patients with craniocerebral trauma, a liberal transfusion regime was not associated with an improved neurological outcome [25]. Moreover, a restrictive transfusion strategy was associated with a lower risk of severe or life-threatening bleeding [26]. Based on this data, a transfusion trigger of 7 g/dL is recommended as "the new normal" in all critically ill patients, especially in trauma patients [27]. However, in patients with a concomitant acute coronary syndrome a transfusion trigger of 8 g/dL may be considered. Traumatic blood loss, especially in body cavities in thoracic and abdominal trauma, is often not contaminated and can therefore be re-transfused, especially after preparation in the cell saver. This procedure should be considered early on during trauma care, especially if an emergency insertion of thoracic drainage or an emergency laparotomy is performed.

## 7.4 Coagulation Management

Coagulation management in trauma patients can be done in two different approaches. It can be based on the transfusion of fresh frozen plasma, packed red blood cells, and platelet concentrates in a fixed ratio [28], or on a goal-directed substitution of coagulation factors [17, 29, 30]. The second approach requires repetitive point-of-care measurements prior and after a targeted factor substitution according to a predefined coagulation algorithm and has been shown to be superior [31–33].

When a trauma patient is admitted to the resuscitation area, coagulation management starts by taking patients medical history, if possible. Physicians should especially focus on preexistent coagulation disorders or anticoagulant medication. In addition to patient's history, blood samples are taken for point-of-care and laboratory measurements to assess blood coagulation at admission and to confirm an eventual, residual anticoagulant effect. Platelet function tests (e.g., Multiplate®, ROTEM platelet®, or TEG® platelet mapping) may be performed if platelet aggregation inhibition is suspected. These tests allow to detect platelet inhibitors and enable to counteract the inhibition of the cyclooxygenase pathway (e.g., acetylsalicylic acid) with desmopressin, or a targeted platelet transfusion depending on the present aggregation inhibitor [34].

One of the most important point-of-care diagnostics are the viscoelastic coagulation tests such as rotational thromboelastometry (ROTEM®) [35]. Four channels investigate and determine coagulation disorders from different pathways: EXTEM (activated by tissue thromboplastin) reflects the extrinsic pathway of the coagulation system, INTEM (surface activation) reflects the extrinsic pathway of the coagulation system, FIBTEM (inhibition of platelets by cytochalasin D) determines functional fibrinogen levels, and APTEM (addition of aprotinin or tranexamic acid) inhibits an ongoing hyperfibrinolysis [35]. In summary, these four channels provide all information to detect low fibrinogen levels, trauma-induced hyperfibrinolysis, low platelet counts, and delayed clotting initiation within a few minutes. This allows a targeted substitution of fibrinogen, tranexamic acid, and other coagulation factors. A factor-based ROTEM® guided coagulation management reduced the exposure of trauma patients to allogeneic blood products and increased survival without in increasing risk for thromboembolic events [17, 30, 36, 37]. Apart from point-of-care testing, standard laboratory coagulation tests are also essential to obtain additional information of the coagulation system. Mandatory are the parameters platelet count, prothrombin time, diluted thrombin time, anti-Xa activity, factor V activity, factor XIII activity, and fibrinogen levels–if no viscoelastic test is available.

Blood coagulation needs an acceptable physiological basis in order to work properly. If this basis is deranged from the beginning on, further

hemostatic therapy will be less effective. Therefore, it is crucial that the following parameters should be controlled initially as follows: Normothermia (>35 degrees Celsius), normocalcemia (free $Ca^{++}$ >1.15 mmol/L), normal acid-base status (pH >7.2), hematocrit 0.21–0.24 (or hemoglobin value 7.0–8.0 g/dL), and permissive hypotension until bleeding control (MAP 55–60 mmHg or 80–90 mmHg in case of a concomitant traumatic brain injury).

The fibrinolysis inhibitor tranexamic acid improves survival of bleeding trauma patients with or without concomitant brain injury [38, 39]. It is crucial to administer tranexamic acid as soon as possible—necessarily within 3 h of injury—to obtain mentioned survival benefit [40]. Therefore, tranexamic acid (Bolus of 15 mg/kg or 1 g i.v.) should already be administered empirically in the pre-hospital setting and the dose should be repeated at hospital admission [2, 6, 41]. Fibrinogen is the first coagulation factor dropping to a critical low level in case of a major bleeding. Therefore, fibrinogen concentrate (2–4 g i.v.) needs to be substituted if ROTEM® findings present a FIBTEM ≤7 mm. Factor XIII concentrate (15 U/kg i.v.) may be given empirically after 6 g of fibrinogen or at if the factor XIII activity in the laboratory results drops below 60%. Platelet concentrate transfusion (1 Unit) is indicated in case of confirmed thrombocytopenia (<50 G/l or <100 G/L in case of a traumatic brain injury) or an EXTEM/INTEM "maximum clot firmness" <40 mm. Platelet count should be reassessed before transfusion of each additional concentrate. Fresh frozen plasma (4 Units) should be administered if the factor V activity drops below 20%. Once fibrinogen, platelets, factor V and XIII are corrected and the prothrombin time is still prolonged (expressed as quick value <30%, INR >2.3 or extended EXTEM clotting time) 4-factor prothrombin complex concentrate (1000–2000 IE) is indicated and may be given as a slow continuous infusion. Protamine should be administered to antagonize residual heparin activity (dose 1:1). This is however uncommon in trauma patients primarily admitted by the emergency medical service. If bleeding still persists despite mentioned anesthesiologic and surgical care, a hematology expert should be consulted. Further therapy options such as administration of von Willebrand concentrates may be indicated only according to expert's advice (Fig. 7.1).

## 7.5 Management of Anticoagulated Trauma Patients

The expanding use of oral anticoagulants is challenging trauma treatment nowadays. Physicians are increasingly encountering patients taking oral anticoagulants in a wide variety of situations. This underlines the growing importance of this topic. Substances used for oral anticoagulation are vitamin K antagonists (VKA) such as phenprocoumon or acenocoumarol and the newer direct oral anticoagulants (DOAC). Currently available DOAC include the thrombin (factor IIa) antagonist dabigatran, and the factor Xa antagonists rivaroxaban, apixaban, and edoxaban. Betrixaban is another factor Xa antagonist, but currently not available in Europe. Main indications are the therapy and secondary prophylaxis of venous thromboembolism, the prevention of stroke and systemic embolism in non-valvular atrial fibrillation, and thromboprophylaxis after hip and knee replacement. These pathologies predominantly affect older patients in whom comorbidities with an impact on oral anticoagulants excretion and bleeding risk occur more frequently [42].

### 7.5.1 Screening for Oral Anticoagulants

In an emergency setting—e.g., following trauma—it is important to identify patients taking oral anticoagulants fast and reliable in order to control bleeding. Unconscious patients are particularly challenging, since no medical history can be taken, and physicians must therefore recognize an oral anticoagulant effect by other means. Laboratory analyses are an important and unavoidable diagnostic tool for this purpose. They are not only able to detect an existing oral anticoagulant effect, but depending on the test,

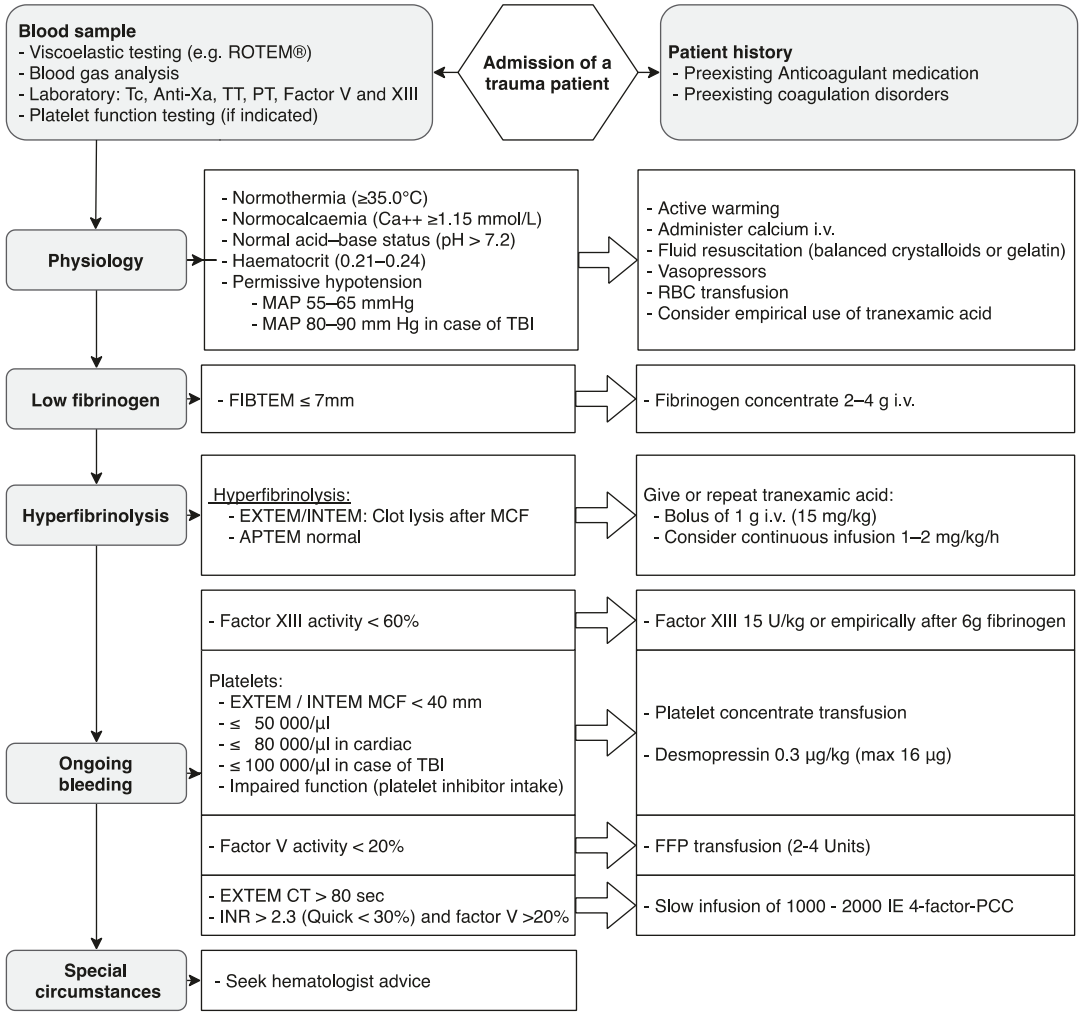


**Fig. 7.1** Graphic illustration of the coagulation and transfusion algorithm of the Institute of Anesthesiology at the University Hospital Zurich

also able to quantify the underlying plasma level. In laboratory analyses, a distinction is made between so-called standard coagulation tests (prothrombin time expressed as a quick or INR value, activated partial prothrombin time, and thrombin time) and special measuring methods such as liquid chromatography with mass spectrometry or measurement of the anti-factor Xa activity (anti-Xa). The latter is currently recommended for quantifying the DOAC activity. While standard coagulation tests are available around the clock in every hospital, this is not the case for special measurement procedures such as anti-Xa measurement, especially in smaller hospitals [43]. Not all oral anticoagulants can be measured and quantified by the same test: VKA affect primarily PT/Quick test and INR, which serve for their monitoring and have no effect on thrombin time and fibrinogen. Dabigatran significantly prolongs thrombin time and fibrinogen may be underestimated in the presence of a high dabigatran plasma level. Factor Xa antagonists (rivaroxaban, apixaban, edoxaban) are the only class of oral anticoagulants with an impact on anti-Xa activity assays and have no effect on thrombin time or fibrinogen (Table 7.1).

**Table 7.1** Overview of the impact of different OAC on coagulation assays

| | PT/INR | Thrombin time | Anti-Xa assay |
|---|---|---|---|
| VKA | +++ | – | – |
| Dabigatran | –/+ | +++ | – |
| Factor Xa antagonists | –/+ | – | +++ |

### 7.5.2 Reversal and Treatment of Oral Anticoagulants

In case of an ongoing major bleeding of anticoagulated patients the effect of the respective anticoagulant should be reversed as follows [2].

#### 7.5.2.1 Reversal of Vitamin K-Dependent Oral Anticoagulants

Patient's response to VKA is highly variable due to the interaction with the vitamin K cycle and hence interference with synthesis of vitamin K-dependent coagulation factors. Assessing the anticoagulant effect in a bleeding trauma patient with the international normalized ratio (INR) is essential because complications are closely related to the intensity of anticoagulation. After INR monitoring, emergency reversal of the anticoagulant effect of VKA should be done by the early use of both intravenous prothrombin complex concentrate (25–50 U/kg) and phytomenadione (5 mg) [2]. 4-factor prothrombin complex concentrate was proven to be more effective than fresh frozen plasma for VKA reversal without increasing complications and mortality. The risk of thromboembolic events is even lower if patients are treated with prothrombin complex concentrate compared to fresh frozen plasma [44].

#### 7.5.2.2 Reversal of Factor Xa Inhibitors

In case of major bleeding, plasma levels of oral anti-Xa agents such as rivaroxaban, apixaban, or edoxaban should be measured and quantified with recommended anti-Xa assays before reversal. In case of a life-threatening bleeding residual anti-Xa effect should be reversed with intravenous tranexamic acid 15 mg/kg (or 1 g) and prothrombin complex concentrate (25–50 U/kg), or a specific antidote if available [2]. Andexanet alfa is such a specific antidote for rivaroxaban and apixaban. It binds the agents and hinders them to block coagulation factor Xa. As a result, the anticoagulant induced bleeding can be reduced [45]. Andexanet alfa is approved by the FDA in the United States and by the EMA in Europe for the treatment of uncontrollable bleeding while on rivaroxaban or apixaban, but so far it is still not commonly available. Additionally, intravenous desmopressin (0.3mcg/kg) may be considered as recently was shown that anti-Xa agents also impair platelet function [46]. So far it is still not fully understood how anti-Xa agents impact platelet function. Not recommended for reversal of factor Xa inhibitors are vitamin K, protamine, or fresh frozen plasma as they are not effective for reversal.

#### 7.5.2.3 Reversal of Direct Thrombin Inhibitors

In case of major bleeding, dabigatran plasma levels should be measured by using diluted thrombin time (or thrombin time if not available) before reversal. The dabigatran effect should then be reversed in first line with its specific antidote idarucizumab (intravenous bolus of 5 g) [2, 47]. Additionally, intravenous tranexamic acid 15 mg/kg (or 1 g) may be administered. Dabigatran is known to impair platelet function to a much greater extent than anti-Xa agents. Therefore, intravenous desmopressin (0.3 mcg/kg) is considered at an early stage and platelet count should be maintained over 80.000/mcL in case of an ongoing major bleeding [2]. Not recommended for reversal of dabigatran are prothrombin complex concentrate, fresh frozen plasma, vitamin K, and protamine as they are not effective for reversal. Noteworthy, prothrombin complex concentrates immediately and completely reverses the effect of factor Xa inhibitors but has no influence on the anticoagulant action of dabigatran and should therefore not be used for reversal of direct thrombin inhibitors.

#### 7.5.2.4 Reversal of Platelet Inhibitors

So far, no specific antidote is available to reverse the effect of platelet inhibitors. As a first step intravenous desmopressin (0.3 mcg/kg) should be administered in patients treated with platelet-inhibiting drugs. If bleeding persists, platelet concentrate transfusion may be considered in case of a platelet count of <50 G/L or <100 G/L in patients with a concomitant traumatic brain injury. Platelet count should be reassessed before transfusion of each additional concentrate. An in vitro study demonstrated that clopidogrel had no effect and prasugrel only a mild effect on transfused donor platelet function, whereas ticagrelor completely abolished platelet donor activation. Depending on the present platelet inhibitor, transfusion of a platelet concentrate may have limited effect on hemostasis. There is also no evidence that platelet concentrate transfusion only due to a documented platelet dysfunction improves outcomes in patients undergoing emergent neurosurgery.

## 7.6 Conclusion

Traumatic bleeding is still the main preventable cause of death in severely injured patients. Trauma resuscitation aims to detect and treat systemic coagulation disorders as early as possible in order to counteract coagulopathy and stabilize the patient. The initial trauma treatment comprises a restrictive, goal-directed volume resuscitation using crystalloid solutions and vasopressors on demand to maintain the circulation at a low-stable level. A goal-directed factor-based coagulation management was shown to improve outcomes and lower mortality following major trauma and is therefore recommended in first line. This approach requires a predefined coagulation algorithm including repetitive point-of-care measurements as well as a restrictive transfusion management. The increasing use of oral anticoagulants is challenging trauma treatment. Residual effects of anticoagulants should be assessed and quantified quickly with suitable laboratory tests and reversed in case of an ongoing major bleeding.

**Take Home Messages**

- Trauma-induced coagulopathy is an independent clinical pathology leading to an increased morbidity and mortality.
- Coagulation management should already start during the pre-hospital care, e.g., by administration of tranexamic acid.
- A restrictive, goal-directed volume resuscitation using balanced crystalloid solutions to maintain the circulation at a low-stable level is recommended.
- A goal-directed substitution of coagulation factors together with a restrictive transfusion strategy is associated with improved outcomes in trauma patients.
- The expanding use of oral anticoagulants is challenging trauma treatment nowadays. Laboratory screening for anticoagulants is therefore essential at admission.
- In case of an ongoing major bleeding in anticoagulated patients the residual anticoagulant effect should be reversed.

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# 8 Resuscitative Endovascular Balloon Occlusion of the Aorta

Charles J. Fox and Ernest E. Moore

**Learning Objectives**

- Understand the role of endovascular strategies in managing hemorrhagic shock.
- Define REBOA and compare this alternative technique to resuscitative thoracotomy.
- List the steps of the REBOA procedure and recognize the proper scenario for clinical use.
- Recite potential complications of REBOA and tips to prevent problems.

## 8.1 Introduction

The emergence of endovascular strategies for managing vascular conditions has been steadily introduced into the management of acute traumatic injuries over the last two decades. Devices initially used for ruptured thoracic and abdominal aortic aneurysms established feasibility and have now harnessed widespread enthusiasm and support for use in stable trauma patients [1–4]. National trauma data bank studies have demonstrated a substantial increase in the use of simpler "endo" therapies with low morbidity to optimize hemorrhage control [5, 6].

Non-compressible torso hemorrhage (NCTH) has been the recent focus of an emerging technology referred to as resuscitative endovascular balloon occlusion of the aorta (REBOA) [1, 2]. REBOA is a technique originally described by Carl Hughes during the Korean war and was used later by Francis Robicsek in casualties who were rapidly bleeding to death from combat injuries or a ruptured thoracic aortic aneurysm (Table 8.1). A balloon placed via the femoral artery can be used to occlude the aorta and provide temporary hemorrhage control and raise the mean arterial pressure. Reducing blood flow beyond (distal to) the balloon reduces the torso bleeding. Often compared with open aortic clamping, this new technique may increase mean arterial blood pressure (cardiac and cerebral perfusion), control bleeding, and provide an alternative to EDT,

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**Table 8.1** Essential items: resuscitative endovascular balloon occlusion of the aorta (REBOA)

| Inventory | Example equipment options |
|---|---|
| Ultrasound probe, cover, and gel | 5.0–13 MHz linear array transducer |
| 7 Fr. Access system | Terumo pinnacle precision |
| Aortic occlusion balloon | Prytime ER-REBOA |
| Suture, Tegaderm, scalpel | 2.0 nylon, 11 blades |
| Non-diluted contrast agent | Isovue-300 or Omnipaque 240 |
| Injectable saline | 50 mL |
| Syringes | 20 cc |

including selective individuals with injury in the thoracic cavity [7].

Originally the technique, introduced in the 1950s, was abandoned due to its complications, but now has renewed enthusiasm with recent technologic advances such as smaller sheaths and wireless fluoroscopy free catheters. This has resulted in widespread use among some groups while others reluctantly adopt new endovascular skills. Translational research has produced several recent publications, and US level I trauma centers have now preferred to use REBOA in lieu of performing EDT in selected cases. This alternative has been highlighted during the COVID pandemic. The AAST Aortic Occlusion for Resuscitation in Trauma and Acute Care Surgery (AORTA) Registry established in 2013 has prospectively tracked these patients [8].

A systematic review of the use of resuscitative endovascular balloon occlusion of the aorta (REBOA) has also led to enthusiasm for changing paradigms outside of large academic trauma centers in the management of non-compressible torso hemorrhage (NCTH). The use of this technique, while originally intended for hospital-based practice, as an alternative to resuscitative thoracotomy has expanded to implementation of programs both within the military and in community trauma programs. In addition to London's Air Ambulance Service describing an original case that captured widespread media attention, the US military has enthusiastically adopted and studied the use in forward operating environments during recent conflicts and has documented rationale and indications in the form of a clinical management guideline published by the Institute of Surgical Research [9]. A Belgium Special Operations Surgical Team (SOST) described three successful cases in an austere prehospital military setting using REBOA citing no other equivalent manner to control torso hemorrhage. Members of a US Air Force SOST have also used REBOA in roughly 20 cases with handheld ultrasound to perform a focused abdominal sonogram while gaining ultrasound guided femoral arterial access using a 7-French sheath [10]. While evidence based practice is formulated, we discuss the approach associated with severe hemorrhagic shock related to abdominopelvic injury.

## 8.2 REBOA for Pelvic Fractures and Refractory Shock

The mortality for pelvic ring disruption continues to remain remarkably high [11]. Preperitoneal pelvic packing (PPP) augmented by REBOA is well described in Denver and may limit transfusion requirements. The need for angioembolization can be established in the OR via the femoral sheath while the REBOA catheter is inflated rather than taking the patient to radiology for additional diagnostic steps [12]. Transfer of patients to the interventional radiology suite for angioembolization is done selectively and only when it cannot be accomplished in a hybrid operating room or with portable fluoroscopy by the trauma team. REBOA can be deployed in the infrarenal abdominal aorta, referred to as Zone III (Fig. 8.1) for optimal control of patients with pelvic fractures while in severe refractory hemorrhagic shock [13]. Additionally, the arterial catheter can be used for hemodynamic monitoring while waiting on a radial line. A revised algorithm for the management of hemodynamically unstable patients with abdominopelvic hemorrhage is shown in Fig. 8.2.

Critically injured patients diagnosed with an unstable pelvic fracture are resuscitated in the usual manner to maintain a perfusing blood pressure. Patients in extremis with CPR in progress should undergo resuscitative thoracotomy as long as the duration of CPR does not exceed 10 min for blunt trauma [14]. Expeditious ultrasound

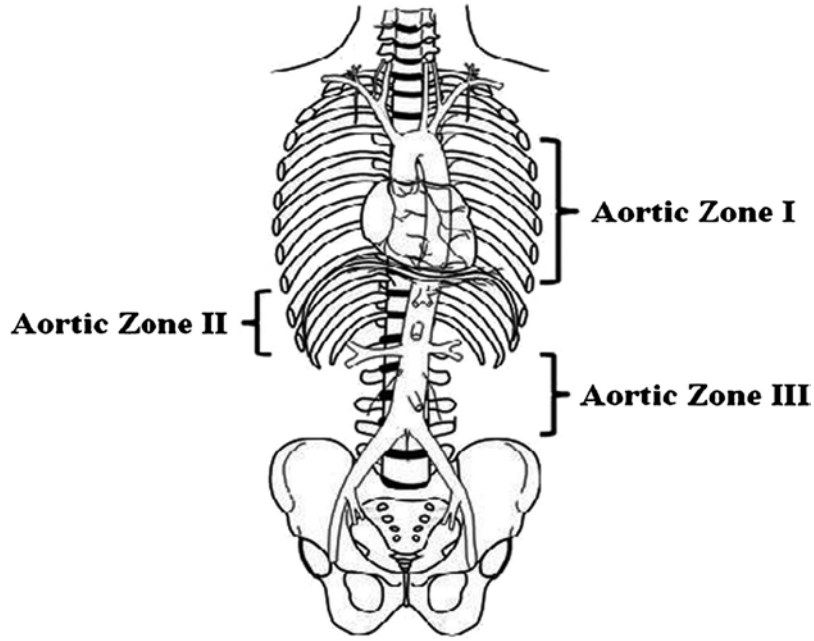


**Fig. 8.1** Aortic zones related to REBOA. Zone I extends from the origin of the left subclavian artery to the celiac artery and is a potential zone of occlusion. Zone II extends from the celiac artery to the lowest renal artery and is not an occlusion zone. Zone III is defined from the lowest renal artery to the aortic bifurcation. REBOA in this zone may be effective for pelvic and junctional femoral (contralateral) hemorrhage. Reproduced with permission from [1]

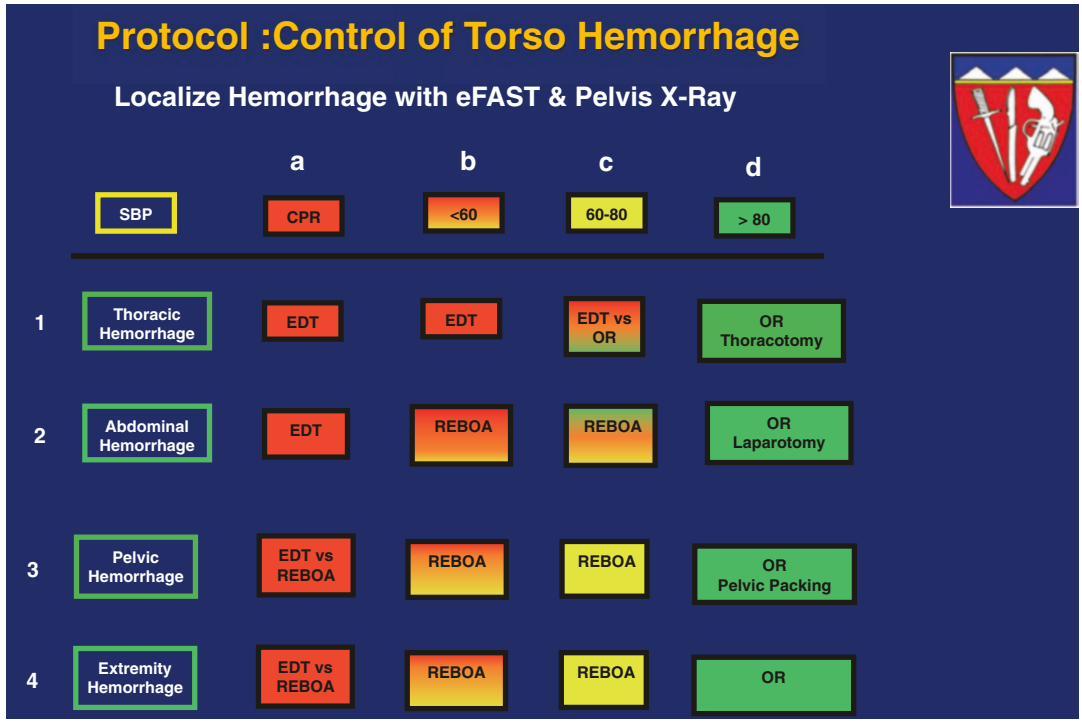


**Fig. 8.2** Protocol for the management of hemodynamically unstable patients with torso hemorrhage. *SBP* Systolic blood pressure, *eFAST* Extended focused abdominal sonographic examination for trauma, *ED* Emergency department, *REBOA* Resuscitative endovascular balloon occlusion of the aorta, *OR* operating room. Modified with permission from [17]

guided femoral arterial cannulation should be performed as early as possible on patients in severe shock. Depending on the situation the patient is either transferred to the CT scanner or directly to the OR for pelvic packing and external fixation [15]. The REBOA is ideally limited to less than 60 min of occlusion time. Pelvic arteriography can easily be performed by the trauma team with diluted contrast agents and additional consultants are called when necessary.

## 8.3 An FDA Approved Device for Trauma

The ER-REBOA™ Catheter (Prytime Medical, Inc., Arvada, CO) is approved by the Food and Drug Administration (FDA) for large vessel occlusion with a built-in central lumen for blood pressure monitoring (Fig. 8.3). The ER-REBOA™ Catheter contains a strong, flexible inner shaft that works in place of a guidewire (no guidewire is needed). The 65 cm working length (balloon tip to hub) catheter contains two lumens that traverse the length of the catheter and connect to extension tubing with stopcocks. The balloon lumen is used to inflate and deflate the balloon. The "arterial line" lumen is used to monitor blood pressure. The 32 mm diameter balloon is made of a compliant (takes the form of the vessel) polyurethane material and will inflate to the indicated size parameters when inflated to the proper volume (max <26 mL, range 4–22 mL for 10–30 mm) recommendations. Radiopaque marker bands are located on the catheter at the balloon to allow for identification of the balloon position. External length marks on the catheter shaft assist with positioning when fluoroscopy/X-ray is not available. The device has a unique atraumatic distal tip (P-tip™), to avoid branch cannulation. This proprietary atraumatic curved P-Tip™ enables a blind insertion and prevents branch vessel cannulation. Prevention of branch vessel cannulation is important because this can happen with blind guidewire advancement and can lead to branch vessel dissection or perforations.

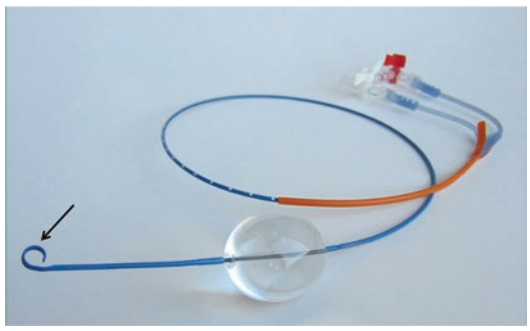

**Fig. 8.3** ER-REBOA™ Catheter with P-Tip™ (arrow) (Courtesy: Prytime Medical, Inc., Arvada, CO)

## 8.4 Procedural Steps

While the patient is being resuscitated with blood products the most suitable common femoral artery (CFA) should be accessed with ultrasound guidance and a 7 French (Fr) micro puncture system sheath. This is placed sterilely using the Seldinger technique. A variety of commercially available sheaths are suitable for this purpose, and our preference is the Pinnacle Precision Access System (Terumo Medical, Elkton, MD). Alternatively, a 4 or 5 Fr sheath can be used for arterial sampling and monitoring but if REBOA is desired, a 7 Fr sheath will be needed. We tend to go directly to a 7 Fr sheath to avoid any product confusion and eliminate the risk of losing access with a sheath exchange during REBOA placement. The access is obtained using the available ultrasound probe in the emergency department. Adjustments of the gain will aid in artery or vein identification. We recommend a right (right-handed surgeon) femoral line using a shorter 11 cm sheath. The insertion length of the ER-REBOA™ Catheter is based upon the bottom of balloon measured from the groin to umbilicus distance for a Zone III (Aortic bifurcation) occlusion or with the bottom of the balloon at the xiphoid for Zone 1.

All catheters and sheaths are flushed with heparinized saline (50 U/mL). The catheter should be prepared for insertion by flushing the catheter, removing air from the balloon, and connecting the device to the monitoring system. 5 mL of contrast and 15 mL of saline should be drawn up

together into a 20 mL syringe to use for balloon inflation. Have a pre-mix of saline and contrast readily available for balloon opacification with a technician standing by for confirmation of placement with a digital radiograph (Fig. 8.4a). Insert the peel away into the hemostatic valve of the sheath and advance the ER-REBOA™ but slide back and do not destroy the peel away in case the device is needed again later. The occlusion time, pre and post-inflation vital signs, and balloon position are noted. The lumbar vertebrae is a good reference point for Zone III REBOA's. The occlusion time can be noted on the patient using a surgical marking pen. A portable X-ray, C-arm, or fixed imaging should always confirm the position as the balloon can migrate with deflation or increased arterial pressures. Once in position be sure to draw back blood from the distal arterial monitoring port to remove any residual air and then flush with saline and connect to a pressure transducer. The femoral sheath is secured to the patient using transparent tape or a commercially available device. (Fig. 8.4b). Inflation of the balloon should not persist in an uninterrupted fashion for more than 30 min in Zone I, similar to open aortic clamping. Therefore, if the balloon has been inflated for an extended period, it should be deflated and then re-inflated to allow for reperfusion if the patient condition allows. The 7Fr sheath can be used to perform a pelvic angiogram or another can be placed to facilitate angioembolization (Fig. 8.5). After definitive hemorrhage control is obtained the balloon is deflated completely and the ER-REBOA™ Catheter is removed, noting the occlusion time. Once the patient's coagulopathy has been corrected and core temperature normalized the 7 Fr sheath can be removed, ideally within 24 h. The sheath can be removed at the bedside and manual pressure held on the access site for 30 min. Calcified atherosclerotic vessels may require careful monitoring for hematoma formation. Once the sheath is removed, our protocol is to perform a pulse exam, obtain an ankle brachial index and a unilateral duplex ultrasound to assess velocity and color flow of the femoral artery in order to assess for malperfusion or an occult injury such as an arteriovenous fistula or pseudoaneurysm. These

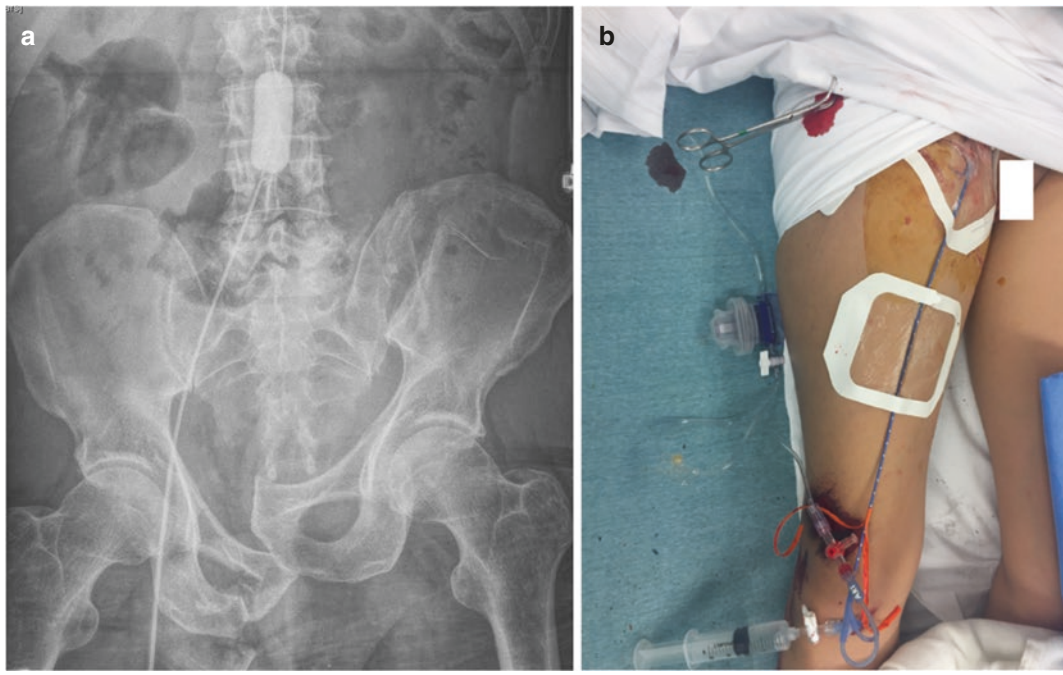


**Fig. 8.4** Plain X-ray in emergency department demonstrating REBOA balloon inflated in REBOA Zone III (**a**). Patient with pelvic sheeting and REBOA catheter in right common femoral artery (**b**). Reproduced with permission from [16]

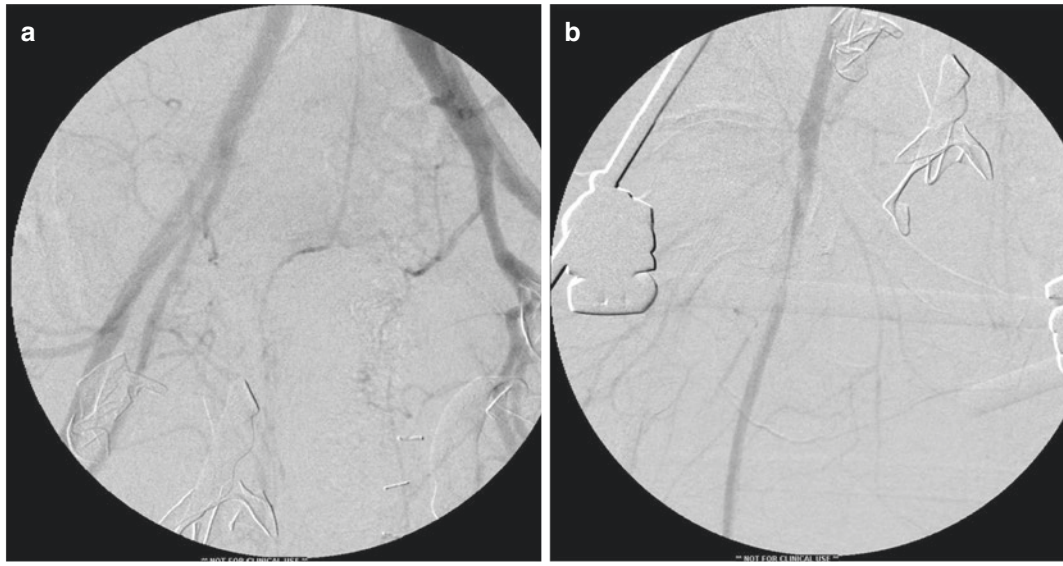


**Fig. 8.5** Pelvic arteriogram without pelvic arterial contrast extravasation (**a**) and right common femoral arteriogram with arterial dissection (**b**). Reproduced with permission from [17]

complications are important to detect early to avoid long-term sequalae and quality reporting for modification of the newer generation devices.

## 8.5 Treatment Algorithm

Our institutional algorithm incorporates clinical assessment, extended focused abdominal sonographic examination for trauma, and basic radiographic imaging obtained in the trauma bay to determine areas of primary hemorrhage and level of hemodynamic compromise in order to guide management. Patients arriving to the trauma bay while receiving cardiopulmonary resuscitation undergo EDT if within the time constraints for known benefit [18]. Exceptions are patients with isolated pelvic or extremity trauma undergoing short-term cardiopulmonary resuscitation where REBOA may be preferred. However, there is a risk of missed thoracic or abdominal injury with ongoing bleeding that must be acknowledged.

Patients presenting in hemorrhagic shock due to thoracic trauma should undergo thoracotomy, either emergently in the trauma bay or in the operating room. REBOA in these patients is controversial and theoretically may worsen their injury due to increased aortic pressure with accelerated blood loss and increased ventricular afterload. Therefore, if REBOA is employed with a thoracic injury, the SBP should be maintained at less than 100 mmHg to minimize this risk. This is critically important in those with a potential thoracic aortic injury. The desired pressure in the setting of a concomitant traumatic brain injury is poorly understood but SBP should probably also remain <100 mmHg.

With presumed abdominal hemorrhage, patients with a SBP of 80 mmHg or greater should be transferred to the operating room without delay to avoid further complications. A sheath should be inserted in responders with a SBP of 80–90 mm Hg so that a REBOA may be inserted quickly in the event of rapid deterioration. In patients with a SBP <80 mm Hg, REBOA in the emergency department (ED) may temporize major visceral bleeding and stabilize the patient for transport to the operating room (OR).

Patients in hemorrhagic shock secondary to pelvic trauma represent a unique scenario where we selectively place a Zone III REBOA with a SBP between 80 and 90 mmHg to permit a rapid total body CT scan prior to the OR. All patients

with a SBP <80 mmHg should undergo prompt REBOA placement. At our institution, control of pelvic bleeding is accomplished by preperitoneal pelvic packing in the OR [19], whereas other institutions may perform pelvic angioembolization. Alternatively, the REBOA catheter may be used to facilitate angiography via contralateral access, and endovascular treatment for pelvic hemorrhage accomplished in the operating room [20].

Finally, patients with significant lower extremity trauma resulting in shock may also benefit from Zone III REBOA. Our institutional algorithm utilizes REBOA in these patients for SBP <80 mmHg; once stabilized, they can be transferred either for additional imaging or the OR for treatment. Thus far, the only literature supporting REBOA for extremity trauma is to select case reports, but we have used it successfully in several patients with gunshot wounds. The impact of the ischemia incurred from zone 3 occlusion on injured extremities is unknown, but certainly periods >90 min are well-tolerated, and some have reported inflation for 120 min without problems [21].

## 8.6 Techniques to Reduce Ischemia

Partial REBOA (P-REBOA) is a recently described alternative to continuous REBOA or intermittent periods balloon occlusion [22]. Either a specially designed catheter with partial occlusion capability or graded volumetric releases has been described. In doing so, one can reduce the total ischemic time and extent of reperfusion injury while allowing for a longer occlusion time before definitive intervention with subsequent balloon removal. Similarly, development of an endovascular variable aortic control (EVAC) system to autoregulate aortic flow in a continuous manner as an alternative to P-REBOA with extension of occlusion times in animal models has been described [23]. Intermittent REBOA with planned intervals of deflation in between periods of inflation has been shown in swine models to extend the tolerance of zone 1 occlusion up to 120 min [24]. Lower extremity cooling can reduce ischemic muscle injury and compartment pressures following prolonged zone 3 occlusion in a swine hemorrhagic model [25]. These techniques may extend physiologically tolerable occlusion times when utilized in patients.

## 8.7 Potential Complications

Previous devices for REBOA required much larger sheaths, guidewires, and had many more steps to be used efficiently by those unfamiliar with endovascular techniques. We previously used the Coda™ balloon catheter (Cook Medical, Bloomington, ID), which required a minimum 12 Fr sheath with an outer diameter of ~5 mm, whereas the ER-REBOA™ requires only a 7 Fr sheath with an outer diameter of ~3 mm. This has considerably decreased access site complications and nearly eliminated the need for cut down and surgical repair of the arteriotomy site. The initial access may result in hematoma when ultrasound is not used. Adjusting the gain will help to distinguish the vein and artery from soft tissues. The thicker non-compressible arterial wall should be punctured at an oblique angle to avoid a back-wall injury. A traumatic needle puncture can produce occult injury that is often detected late as arteriovenous fistula or pseudoaneurysm. Once arterial blood return is noted, a wire is selected and passed carefully noting progress and resistance during the advancement. The micropuncture system comes with a less traumatic tapered 21 gauze needle but the 0.021 inch wire often lacks rail strength to navigate quickly and can bend easily in a trauma setting. This wire is can also navigate into the contralateral iliac artery, internal iliac artery, deep iliac circumflex artery, and even the inferior epigastric artery when inserted without the aid fluoroscopy. Any concerns should be immediately investigated before proceeding. For these reasons, we prefer the 0.035-inch wire but that will require an 18-gauge entry needle. To avoid balloon malposition and inadvertent coverage of renal and mesenteric branches it is advised to obtain a digital radio-

graph to confirm placement and use catheter markings and surface landmarks for guiding proper placement. The P tip and wireless features mitigate the likelihood of branch vessel cannulations. Once the balloon is in proper position, it inflates gently to avoid vessel injury or rupture using tactile feedback and the information for use (IFU) to avoid over-inflation. It is especially important with subsequent deflations and re-inflations to verify that the balloon has not migrated into the iliac vessels as this may result in dissection, or rupture when the balloon is overinflated relative to the vessel size. On the way to mitigate that situation is to always note the distance of insertion and has an assistant manually hold the catheter in that exact position until it is properly secured with a commercial device, tape, or sutures. The time of inflation should be marked on the patient's thigh with a surgical marking pen to closely monitor the ischemic time. Hemodynamic monitoring is especially important and supraphysiologic proximal pressures should be avoided during the active resuscitation. Similarly, consider that an undiagnosed proximal injury to the aorta may co-exist, particular in those with blunt trauma. During balloon deflation, rapid and unpredictable return of distal flow may result in hypotension or cardiovascular collapse. It is important that this step be well coordinated with resuscitation efforts, recognizing the potential for ischemic reperfusion injury. Hyperkalemia, hypocalcemia, and acidosis must be aggressively managed and may be a source of refractory shock. Additionally, clot disruption may occur with deflation and sudden changes in the lower extremity pulse exam should be anticipated. A Doppler device is especially useful as palpable pulses may not be immediately present during hemorrhagic shock. During sheath removal, an access site injury may be revealed and manifest by active bleeding or hematoma. Generally, this can be controlled with some steady and direct pressure for 30 min. When a pulse is absent after sheath removal and arteriogram is necessary to rule out dissection or thromboembolism. Flow limiting dissections are treated with balloon angioplasty and occasionally stented. Thrombus is best removed by an immediate open surgical approach or mechanical thrombectomy depending on the vessel location. A post REBOA evaluation of the access site is recommended to rule out arteriovenous fistula, pseudoaneurysm and verify flow using color flow duplex ultrasound. An Ankle Brachial Index is advised and when <0.9 further contrast enhanced imaging is recommended.

## 8.8 Future Directions

Applications for REBOA with associated injuries such as TBI remain unclear. For example, in a swine model with combined hemorrhagic shock and traumatic brain injury (TBI), REBOA was associated with poorer outcomes due to worsened shock, arguing against of REBOA in the setting of those with TBI [26]. Currently the subject of ongoing investigations in Denver, this detrimental effect may be due to the increase cerebral edema that occurs when cerebral autoregulation is compromised. REBOA has proven beneficial in other settings of massive hemorrhage such as among peripartum women with abnormal placentation [27] as well as mitigating major venous injuries when deployed in the IVC [28]. As such, the application of REBOA may expand to other clinical settings with hemorrhagic shock as a resuscitative measure until definitive treatment can be accomplished or in settings of medical cardiac arrest when increased coronary perfusion is necessary.

## 8.9 Conclusion

Prehospital hemorrhage control is essential to minimize preventable mortality. REBOA use has been shown to be safe and effective and may be

an alternative to emergency department thoracotomy in select cases. Complications appear limited but are occasionally reported. The REBOA catheter provides a less invasive option for controlling non-compressible torso hemorrhage particularly in the management of those in refractory shock with pelvic fractures. Its role in the prehospital setting remains undefined.

**Key Concepts**

- REBOA placement is based on the three zones of the aorta.
- Zone III (lowest renal artery to the aortic bifurcation) is ideal for pelvic management.
- Success is much lower when access is performed as a last-ditch effort.
- The initial access may result in complications when ultrasound is not used.
- Verify position with a digital radiograph and monitor time of occlusion.
- Deflation can have the same physiologic response as removing an aortic clamp.
- Remove sheath within 24 h and document peripheral vascular exam.

**Take Home Messages**

- REBOA is an endovascular adjunct designed to improve cerebral and coronary perfusion during shock from non-compressible torso hemorrhage.
- Early arterial access and deployment of the occlusion balloon are crucial for success.
- In cases of full cardiac arrest, emergency department thoracotomy may be preferable.
- Novel methods such as intermittent and partial REBOA are being explored to extend occlusion time and prevent ischemic complications.

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# Preperitoneal Pelvic Packing

9

Julia R. Coleman, Ernest E. Moore, and Clay Cothren Burlew

**Learning Objectives**

- Describe the morbidity and mortality associated with pelvic ring injuries and hemodynamic compromise.
- Outline the principles of initial management of patients with pelvic ring injuries, in particular those who present in hemorrhagic shock.
- Define indications and operative technique for preperitoneal pelvic packing (PPP).
- Describe scenarios in which angiography and angioembolization are indicated after external fixation and PPP.

## 9.1 Background

Pelvic ring injuries are responsible for significant morbidity and mortality in trauma patients. The majority of injuries are due to high energy blunt trauma including falls, motor vehicle collisions, and auto-pedestrian mechanisms, and can be life threatening, with mortality rates up over 30% in modern series [1–5]. Patients with pelvic ring injury who present with hemodynamic compromise have a significantly higher rate of mortality, nearly four-fold higher than those without hemodynamic instability [6]. In severely injured patients with pelvic fractures and hemodynamic compromise, the primary cause of early death is due to hemorrhage, whereas late mortality is driven by traumatic brain injury and multiorgan failure [7]. Factors predictive of mortality include hemodynamic instability, lactic acidosis, age >65 years, female sex, and injury severity, specifically concomitant chest and bowel injuries [8, 9]. Despite ongoing evolutions in trauma care, the mortality rate has remained high [10, 11], highlighting potential for improvement in the current approach to pelvic fracture management.

As noted in modern series, there is a significant variation in the diagnostic and therapeutic approach to patients with pelvic fractures and hemodynamic compromise. An option for primary hemorrhage control for pelvic fracture-related bleeding that has become more widely accepted in the past decade is preperitoneal pelvic packing (PPP). Rationale for PPP includes more rapid hemorrhage control compared to angioembolization by addressing the primary source of hemorrhage [12]. The objective of this book chapter is to describe the initial management of patients with complex pelvic ring injury, as well as the indications, operative technique, and outcomes of PPP.

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## 9.2 Initial Evaluation and Management of the Pelvic Fracture Patient

Initial evaluation and management of patients with pelvic fractures should be approached with attention to the primary survey and ATLS protocol [13]. In any patients with blunt mechanism and hypotension (systolic blood pressure [SBP] <90 mmHg), a pelvic binder or pelvic stabilization with a sheet should be placed at the level of the greater trochanters; pelvic binding in of itself can significantly reduce pelvic volume, prevent shifting of bony elements, and improve hemorrhage control [4, 14–16]. As part of the initial assessment, Focused Assessment with Sonography for Trauma (FAST) exam and chest radiograph (CXR) should be performed to rule out intraperitoneal or intrathoracic sources of hemorrhage. The FAST exam reliably identifies clinically significant hemoperitoneum in life-threatening pelvic fracture-related hemorrhage, with a false-negative rate as low as 2% [17].

In patients with hypotension unresponsive to resuscitation (persistent SBP <80 mmHg), insertion of a resuscitative endovascular balloon occlusion of the aorta (REBOA) catheter should be considered for Zone III (infra-renal) inflation [18]. REBOA ultimately allows for temporary and/or partial occlusion as a bridge to further resuscitation, imaging, and transport to the operating room; preliminary data of patients with concomitant REBOA and PPP suggest that this combination provides life-saving hemorrhage control in otherwise devastating injuries [19]. Notably, while Zone III REBOA has been shown to decrease pelvic hemorrhage, it does not generate as much pelvic pressure as preperitoneal packing, an essential factor of venous hemostasis [20]. Further, when comparing isolated REBOA to isolated PPP for pelvic hemorrhage control, patients who receive REBOA spend longer time in the emergency department with greater mortality rates than with PPP [21]. However, in conjunction, REBOA and PPP result in expeditious time to hemorrhage control [19, 22].

In conjunction initial ATLS-driven care, FAST, CXR, and REBOA, particular attention should be paid to concomitant injures, specifically chest wall, extremity, spine, and genitourinary injuries [23–28]. Over two-thirds of severely injured patients with pelvic fractures have concomitant injuries which merit surgical intervention at some point during their hospitalization, and nearly one-fourth have a concomitant injury identified on initial trauma work up that merits urgent intervention altering the initial acute operative plan [29]. Lastly, in the trauma bay, labs should be drawn, including lactate and base deficit, to assess degree of physiologic insult, and when available viscoelastic hemostatic assays should be acquired to guide precision transfusion [30]. Data suggests that trending serial lactate measurements in the early window after pelvic ring injury are a rapid and reliable estimation of true severity of hemorrhage rather than routinely used hematologic measurements [31]. Ultimately, if the patient remains hemodynamically unstable despite the aforementioned resuscitation measures and 2 units of packed red blood cells (PRBCs), the patient should be taken to the operating room emergently for external fixation and PPP.

## 9.3 Indications for Preperitoneal Pelvic Packing

Packing for retroperitoneal hemorrhage from pelvic fracture was first described in 1994 in Europe in the setting of complex pelvic fractures [32]. This technique was later modified to an anterior, preperitoneal approach [33]. In conjunction with external fixation, which closes down the pelvic space, PPP is an optimal strategy to address pelvic hemorrhage. PPP rapidly and effectively addresses venous (presacral and paravesical venous plexuses) and bony sources of pelvic hemorrhage by tamponade, while external fixation reduces the available volume of the retroperitoneal space in both open and closed ring pelvic fractures [34]. Indications for PPP are the same historical indications for angioembolization and are described in our institutional protocol (Fig. 9.1). Specifically, blunt trauma patients with hemodynamic instability in the ED despite

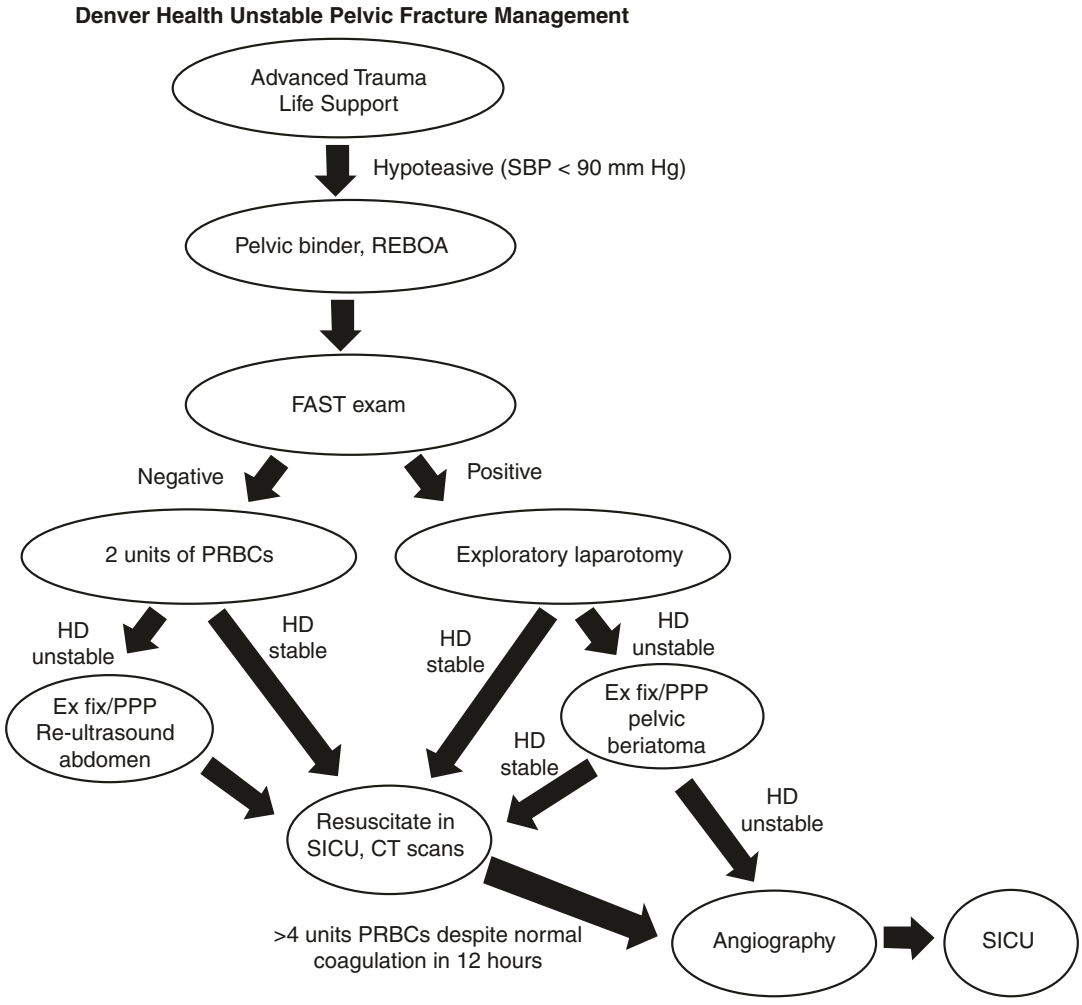


**Fig. 9.1** Algorithm for the evaluation and management of unstable pelvic fractures

REBOA should be employed in centers with expertise and is typically deployed in Zone III for patients with persistent hypotension despite red cell transfusion with SBP <80 mmHg

*SBP* Systolic blood pressure, *REBOA* Resuscitative endovascular balloon occlusion of the aorta, *FAST* Focused assessment with sonography in trauma, *PRBCs* Packed red blood cells, *PPP* Preperitoneal pelvic packing, *SICU* Surgical intensive care unit, *CT* Computed tomography, *HD* Hemodynamically

transfusion of 2 units of PRBCs with a known pelvic fracture. Alternatively, patients undergoing laparotomy for intraabdominal hemorrhage that have an associated pelvic hematoma may require PPP if they remain hemodynamically unstable despite control of intraabdominal bleeding. If a patient is being transferred to the operating room for hemorrhage in the chest or abdomen, PPP can be performed simultaneously if concomitant pelvic hemorrhage is suspected or discovered intraoperatively. While PPP has predominantly been described in adults, there are also reports of its use and effectiveness in pediatric trauma patients as well [35, 36].

## 9.4 Operative Approach

In anticipation of PPP, a multidisciplinary approach should be taken, with fastidious involvement of the orthopedic team for external fixation, as well as other specialty teams for rel-

evant concomitant injury repair such as urology in the setting of a genitourinary injury or neurosurgery in the setting of intracranial hemorrhage requiring craniotomy. A benefit of PPP is that it can be performed simultaneously in conjunction with other operative procedures. According to a review of 42,122 patients with pelvic fractures from the National Trauma Data Bank, 10% of pelvic fracture patients have a common or external iliac vascular injury, 26% have a concomitant bladder injury, and 17% have an intraperitoneal bowel injury [37], and as such, it is not surprising that nearly 90% of patients with severe pelvic fractures require more than one procedure (beyond external fixation/PPP) [38].

The technique for PPP has been previously described [39, 40] and in experienced hands, can be completed in less than 5–10 min [40]. The patient should be positioned supine on a table compatible with fluoroscopy and prepped in the standard fashion from neck to knees. PPP should be preceded by external fixation to stabilize the bony pelvis, create a smaller pelvic volume, and provide a stable counter-pressure for the pelvic packing. For unstable anterior-posterior compression and lateral compression injuries, anterior frames can be placed via the faster but potentially less stable iliac crest route or the more stable but fluoroscopy-dependent supra-acetabular approach; in contrast, vertical shear injuries are best stabilized with a posterior C-clamp [41]. It is important that the trauma team is present in the operating room for placement of the external fixation to ensure that the anterior fixation bar is positioned such that access for the suprapubic PPP incision is not obstructed.

After external fixation, a 6–8 cm vertical midline incision is sharply made from the pubic symphysis cephalad, sharply cutting the subcutaneous tissue and using bovie cautery to divide the fascia (Fig. 9.2a). This step requires special attention to ensure that the incision is distinct from the incision for exploratory laparotomy; the peritoneal pelvic space boundary should not be violated, preventing the tamponade effect of PPP. After dissection through the midline fascia, the pelvic space can be entered, leaving the peritoneum intact; at this time, it is often apparent that the pelvic hematoma has performed a majority of the pelvic space dissection, which extends around the bladder down to presacral plane (Fig. 9.2b). Once the paravesicular pelvic space is entered, packing can be performed by retracting the bladder to the contralateral side and inserting a lapa-

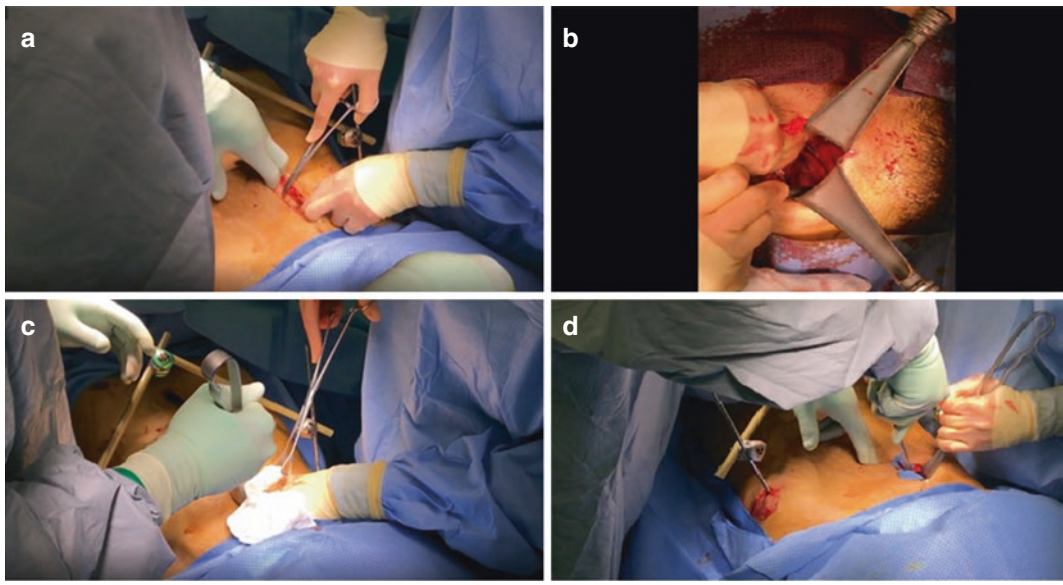


**Fig. 9.2** Intraoperative pictures of preperitoneal pelvic packing technique

rotomy pad into the pelvic space (Fig. 9.2c). The laparotomy pads should be inserted deep towards the sacrum down to the presacral space using a ringed forceps or Cobb elevator to place them deeply into this space (Fig. 9.2d). The second laparotomy pad is placed laterally along the wall of the bladder, and the third laparotomy pad is placed anteriorly along the pubic rami bilaterally. A total of six laparotomy pads is most commonly used. While laparotomy pads are consistent with the traditional description of PPP, there are newer reports of using hemostatic gauze for packing to optimize hemorrhage control and decrease transfusion requirement [42].

Rarely, in the cases of vertical shear injuries, only one hemipelvis is affected and unilateral packing can be performed to avoid dissecting the pelvic space contralaterally. Once packing has been completed, suprapubic tubes for urethral or bladder injuries may be placed through separate stab incisions just lateral to the vertical PPP incision; it is essential at the end of the procedure that there is a mechanism in place to drain the bladder. The fascia is closed with a running 0-PDS suture, and the skin is closed with staples. Upon completion of PPP, remarkable increases in systolic blood pressure may be observed, with near doubling of the SBP after packing [43]. Once PPP and other operative procedures are performed during the index surgery, transfer to the ICU should be arranged and CT imaging performed.

After PPP, packs are left in place until the patient's physiologic derangements, including coagulopathy, have resolved, usually within 24–36 h. When removing the pelvic packs, hemostatic interventions including suture, electrocautery, and topical agents should be used preferentially over the option of repacking the pelvis. Repacking of the pelvic space is associated with a marked increase in infections complications; with almost 50% of repacked patients developing pelvic space infections, repeat packing should be avoided [38]. While the optimal timing of definitive internal fixation of pelvic fractures remains debated, internal fixation at the time of preperitoneal pack removal has been described; in a retrospective review of patients with hemodynamically unstable pelvic fractures who underwent PPP, internal fixation at the time of pack removal resulted in shorter length of stay in the intensive care unit, faster time to definitive pelvic fixation, and less infectious complications [44].

## 9.5 Role of Angiography

Angiography and angioembolization are reserved for patients who have persistent hemodynamic instability present after external fixation and PPP [38, 45–47]. The trigger for diagnostic angiography after external fixation/PPP is transfusion of more than four units of red blood cells (RBC) in the 12 h post-packing after normalization of coagulation indices. Diagnostic angiography may identify arterial sources for angioembolization, but as previously noted, an arterial source of pelvic hemorrhage only occurs in approximately 15% of patients and is usually from internal iliac artery branches, gluteal artery branches, obturator artery, or pudendal artery [38, 48]. Even in patients with an arterial source, the likelihood of concomitant venous bleeding is nearly 100% [45]. In the small percentage of patients who ultimately undergo angiography after PPP, 80% have positive findings for arterial injury which can be localized and targeted [49]. Empiric embolization should not be pursued given the risk of perineal necrosis, infection, impotence, and persistent hemorrhage [50, 51]. While research has explored the predictors of angioembolization need in patients with pelvic injuries, it remains difficult to predict in the first hour of admission which patients will require angioembolization after PPP; the only predictor in external fixation/PPP series described thus far is post-packing PRBCs [2].

## 9.6 PPP Outcomes

Since its first description in Europe in the 1990s, PPP has shown promise in reducing morbidity and mortality in patients with severe pelvic fractures and pelvic hemorrhage, with both decreased transfusion rates and decreased mortality from exsanguination [12, 31, 52–54]. Adoption of PPP

into institutional protocols for management of patients with pelvic fractures and related hemorrhage has been shown to decrease mortality by up to 30% post-PPP adoption [43, 55, 56]. In a retrospective cohort of patients, outcomes after progressive protocolized implementation of angiography and then PPP, overall 30-day mortality decreased from 63% to 42% after implementation of angiography and then even further to 30% in PPP, suggesting that PPP had a greater impact on overall survival than angiography [55]. A comparison of several modern day series finds similar findings. There was a 32% mortality rate for modern management of complex pelvic fracture patients in shock [6], 41% mortality for those managed with angioembolization alone [57], 35% mortality for an algorithm guided protocolized care using angiography [4], and 37% mortality in a study that prioritizes hemostatic resuscitation [5]. Patient managed with PPP/EF followed by complementary angioembolization demonstrated a 21% mortality [39, 48], and when REBOA was added to PPP/EF mortality which was only 14% with no deaths due to pelvic fracture bleeding [19].

While PPP has been associated with improved morbidity and mortality in treatment of pelvic hemorrhage, there are a few notable complications which occur infrequently. Surgical site infections have been described at a particularly high rate in patients who undergo repeating packing (47% versus 6% in patients with single packing) [38, 54]. Infectious complications are also more common in patients with open fractures, acetabular fractures, and associated perineal wounds (bladder injuries) [48, 58]. In addition to infectious complications, a case report of lower extremity abdominal compartment syndrome with PPP has been described [36]. Recently, a case series described a high rate of venous thromboembolism (VTE) in PPP patients, with a deep venous thrombosis incidence of 23% and pulmonary embolism incidence of 8% [59]. With such a high incidence of VTE in this patient population, patients should undergo bilateral lower extremity surveillance duplex ultrasounds following PPP.

## 9.7 Conclusion

Pelvic ring injuries continue to pose a great clinical challenge to trauma providers, as the addition of physiologic insult can drastically increase mortality risk. Despite advances in trauma care, the mortality rates of pelvic fractures patients in many modern series have failed to decrease in a corresponding manner and remain high [1–5, 10, 11]. Adoption of targeted protocols for patients with pelvic fractures and hemodynamic instability can drastically improve outcomes in these high-risk patients [56, 60, 61]. The addition of PPP with complementary angioembolization appears to result in the lowest mortality rate for hemodynamically unstable patients with pelvic fracture.

**Key Concepts**

- The primary cause of early death in severely injured patients with pelvic fractures and hemodynamic compromise is hemorrhage.
- In the ED, a pelvic binder or pelvic stabilization with a sheet should be placed at the level of the greater trochanters for patients with hypotension (systolic blood pressure [SBP] <90 mmHg); pelvic stabilization significantly reduces pelvic volume, prevents shifting of bony elements, and improves hemorrhage control.
- Intraperitoneal or intrathoracic sources of hemorrhage should be excluded; the FAST exam reliably identifies clinically significant hemoperitoneum in life-threatening pelvic fracture-related hemorrhage, with a false-negative rate as low as 2%.
- External fixation and PPP are performed if a patient remains hemodynamically unstable despite initial resuscitation with 2 units of packed red blood cells.
- REBOA catheter should be considered for Zone III inflation in patients with

hypotension unresponsive to resuscitation (persistent SBP <80 mmHg).
- Patients undergoing laparotomy for intraabdominal hemorrhage that have an associated pelvic hematoma may require PPP if they remain hemodynamically unstable despite control of intraabdominal bleeding.
- PPP should be preceded by external fixation to stabilize the bony pelvis, create a smaller pelvic volume, and provide a stable counter-pressure for the pelvic packing.
- PPP can be completed in less than 10 min.
- PPP is effective in pediatric trauma patients.
- Patients who require transfusion of more than four units of PRBCs in the 12 hours post-packing after normalization of coagulation indices should also undergo diagnostic angiography.
- Repacking of the pelvic space should be avoided, with almost 50% of repacked patients developing pelvic space infections.

**Take Home Messages**
- Patient managed with PPP/EF followed by complementary angioembolization demonstrated a 21% mortality, and when REBOA was added to PPP/EF mortality was only 14% with no deaths due to pelvic fracture bleeding.
- The addition of PPP with complementary angioembolization appears to result in the lowest mortality rate for hemodynamically unstable pelvic fracture patients.

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# Part III

# Primary Period (First 72 h)/Clinical Phase

# 10 Pathophysiology: Trauma-Induced Coagulopathy

Navin Ganesh Vigneshwar, Hunter B. Moore, and Ernest E. Moore

**Learning Objectives**

- Define the current understanding of physiologic coagulation
- Understand the pathophysiology of trauma induced coagulopathy by evaluating the components of coagulation, namely thrombin, platelets, the vascular endothelium, and fibrinogen

## 10.1 Introduction

Trauma-induced coagulopathy (TIC) refers to an alteration in the coagulation capacity that is attributable to injury, and manifests in a variety of phenotypes from hypocoagulability to hypercoagulability which are dynamic and time dependent. Considering this complexity, there is no standard definition of TIC, the diagnosis is generally a combination of laboratory testing and clinical symptoms. Clinical studies, based on conventional coagulation studies, suggest that TIC is evident in 25% of severely injured patients at the time of hospital arrival [1, 2], is associated with increased morbidity and mortality the coagulation status changes over time [3]. The hypocoagulable state, usually seen early after injury (<6 h), is characterized by inadequate hemostatic clots that can result in diffuse bleeding from sites uninvolved in the injured tissue, which is difficult to control with mechanical means such as compression, ligation, or embolization. On the other end of the TIC spectrum is a hypercoagulable phenotype that usually manifests with delayed (>24 h) post-injury micro and macrovascular thrombosis leading to a deep vein thrombosis, pulmonary embolism, acute respiratory distress syndrome (ARDS), and multisystem organ failure (MOF). Understandably the underlying pathophysiology of TIC is of intense interest to the medical community to tailor therapy to mitigate the associated complications. Though much remains to be elucidated, this chapter will attempt to consolidate the current understanding of TIC mechanisms.

## 10.2 Cell Mediated Hemostasis

The classical clotting cascade is taught as intrinsic and extrinsic systems of circulating plasma proteins that converge with the production of

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thrombin, factor IIa. Thrombin is then responsible for the cleavage of fibrinogen to fibrin and the formation of a hemostatic clot [4]. In the late 1990s, the cell-mediated hemostasis model was proposed by Hoffman et al. [5, 6]. After the introduction of this model, emphasis on circulating plasma proteins shifted to individual cells playing key roles in activating and regulating coagulation reactions surfaces [7]. In this model there are three defined phases of clot formation: initiation, amplification, and propagation. In the initiation step, vascular endothelium is disrupted exposing tissue factor which then binds to factor VIIa. This forms a Xase complex that promotes the formation of factors Xa and IXa leading to a low-level production of thrombin. Platelets then bind to the disrupted vascular endothelium and in combination with tissue factor and von Willebrand factor form an initial platelet plug. In the amplification phase, the low level of thrombin serves to activate platelets and factors XI, V, and VIII. These activated platelets release key procoagulant factors [8] such as adenosine diphosphate, thromboxane A2, and factor V. Through combination of proteolytic activation of clotting factors and procoagulant factors, factor Xa complexes with factor Va to form the prothrombinase complex that catalyzes the thrombin burst required to cleave fibrinogen and form a hemostatic fibrin clot over the disrupted endothelium.

There are several regulatory mechanisms that exist within this cell mediated hemostasis model that serve to prevent aberrant clot formation. The first is the vascular endothelium which must be breached by injury to allow for tissue factor exposure and clot initiation. The next regulators are protease inhibitors such as antithrombin (AT) and tissue factor pathway inhibitor (TFPI) that prevent the spread of coagulation beyond the site of injury where clot formation is needed. This coagulation spread is also prevented by the activated protein C system found in the endothelium that cleaves factor Va preventing thrombin generation in uninvolved endothelial cells. When these otherwise protective mechanisms are disrupted; i.e., lack of homeostasis, patients experience coagulopathy ranging from hypocoagulable to hypercoagulable states.

## 10.3 Diminished Thrombin Generation

Thrombin, a serine protease, is the final procoagulant enzyme of the clotting cascade that serves to cleave fibrinogen to fibrin allowing for clot formation [9]. Additionally thrombin stimulates platelet activation and aggregation via release of protease-activated receptors on their cell membrane and activates multiple other coagulation factors and inhibitors [10]. As normal coagulation subsides after injury, thrombin generation diminishes. This regulation is carried out by anticoagulants, such as antithrombin, thrombomodulin-protein C/S, and tissue factor pathway inhibitor (TAFI) [10].

Thrombin generation is influenced by a variety of factors that contribute to TIC including dilution of coagulation factors during resuscitation and post-injury consumption of coagulation factors. The correlation between coagulation factor levels and thrombin generation is inconsistent. Some studies have reported up to 20% of major trauma patients experience significantly low levels of clotting factors (<30%) [11]. In particular, severe trauma has been associated with low levels of FV, FVII, and FX. However, the majority of studies report coagulation factor levels >50% consistent with levels adequate for coagulation [12, 13]. Of note, when coagulation factor levels are found to be reduced, it does not necessarily correlate with diminished thrombin generation and may even be associated with elevated thrombin generation [12, 14]. This may reflect discrepancies between in-vitro coagulation assays and actual in-vivo activity as the assays may reflect coagulation factor consumption in-vivo that have resulted from enhanced thrombin generation. Indeed, trauma patients exhibit 2.5-fold higher average plasma thrombin generation compared to uninjured subjects with low thrombin generation present in 17%. Within these thrombin deficient patients a peak level of <250 nM was linked to a four-fold increased odds for a massive transfusion and three-fold greater odds of 30-day mortality [15]. Furthermore, there may be substantial differences between traditional plasma-based and

newer whole blood thrombin assays [16]. Recent data from whole blood assays indicate that patients who required a massive transfusion had thrombin generation levels below healthy controls [17]. With respect to late TIC, thrombin is at the cross-road of coagulation and inflammation, and excessive thrombin generation may have an important role in delayed hypercoagulability in injured patients [18].

Hypothermia and acidosis are also associated with diminished thrombin generation. In swine models of trauma, hypothermia resulted delayed thrombin generation initiation secondary to effects on the FVIIa/tissue factor pathway (193). In contrast, acidosis seems to affect the propagation phase of thrombin generation (193).

## 10.4 Platelet Dysfunction

Platelets have important hemostatic, endothelial [19], and immune-regulatory [20] functions that are critical to coagulation [21, 22] and thrombocytopenia and platelet dysfunction have important roles in TIC. The initial platelet plug is formed after vascular endothelial injury exposes tissue factor, collagen, and von-Willebrand Factor (vWF), resulting in platelet adhesion and aggregation. The resulting thrombin release and platelet glycoprotein VI-collagen binding cause platelet structural change to a spherical shape, calcium release, degranulation of procoagulant factors and glycoprotein IIb/IIIa conformation change to allow for fibrin crosslinking [7]. Additionally platelet degranulation causes the release of plasminogen activator inhibitor (PAI-1) and antiplasmin-2 which inhibit clot dissolution and promote clot formation [23, 24]. Degranulation also plays a role in recruiting immune cells and creating a local environment conducive to wound healing [25].

Qualitative platelet deficits due to dilution or consumption can cause major problems in trauma patients with studies reporting increased mortality in bleeding patients with platelet counts of less than 100,000/uL [26]. However, the majority of trauma patients have normal platelet counts and instead demonstrate impaired platelet function. Indeed a recent study reports up to 45% of trauma patients having platelet dysfunction measured by platelet aggregometry [27]. After severe traumatic hemorrhage, endothelial release of tissue factor, platelet activating factor, and vWF can result in platelet exhaustion and poor platelet aggregation [28, 29]. The lack of appropriate platelet degranulation results in increased tissue plasminogen activator (tPA) sensitivity and dysregulated fibrinolysis due to decreased PAI-1 release [30]. Platelet mediated inflammatory pathways involving toll-like receptor-4 (TLR-4) signaling, platelet-derived high mobility group box-1 (HMGB-1), and platelet-histone H4 interactions [31–33] may play significant roles in TIC hypercoagulability.

Despite improving understanding of these wide changes in platelet function after trauma, the question remains as to whether these alterations in platelet behavior are truly pathological or represent an adaptive response to an external insult [34]. Further research into platelet biology and platelet biochemical markers for targeted TIC therapy is sorely needed.

## 10.5 Endotheliopathy

The vascular endothelium allows for a barrier separating the hypocoagulable intravascular system, designed to prevent clot formation and enhance tissue profusion and prothrombotic extravascular system, which allows for hemostasis when the endothelium is breached. The endothelial architecture involves a glycocalyx of polysaccharides linked to membrane and transmembrane proteoglycans [35] and the intravascular hypocoagulable homeostasis is mediated by activation of endothelial protein C resulting in the inhibition of factors V and VIII promoting an anticoagulant environment where thrombin cannot be generated [36].

Endotheliopathy of trauma (EOT) is driven by hypoperfusion and is associated with endothelial barrier compromise, endothelial activation, altered leukocyte adhesion, a wide spectrum of coagulopathy, and ultimately end organ dysfunction [37]. The endothelial glycocalyx which

provides protection to endothelial cells and membrane integrity plays a role in maintaining the hypocoagulable intravascular state and when disrupted can result in thrombotic complications associated with TIC. Syndecan-1, a glycosaminoglycan component of the endothelial glycocalyx, has been implicated in TIC [35]. Cleavage of the heparan sulfate domain of syndecan-1 occurs during the hypoperfused state after hemorrhage [38] and results in an endogenous autoheparinization [39] contributing to TIC and resulting in prolonged PTT, increased inflammation, elevated fibrinolysis, and increased mortality [40]. Protein C may be an important systemic anticoagulant; when cleaved by the complex of thrombin and thrombomodulin, activated protein C (aPC) inactivates factors Va and may reduce PAI-1 [41, 42]. In critically injured trauma patients, early coagulopathy is associated with elevated levels of aPC and soluble thrombomodulin, and patients who demonstrate persistent protein C depletion are at higher risk of ventilator pneumonia, acute lung injury, multi-organ failure, and death [42, 43]. In addition to the anticoagulant properties of aPC, depletion of aPC leads to reduced endothelial protective signaling via the aPC receptors protease-activated receptor-1 (PAR-1) and endothelial protein C receptor (EPCP) resulting in endothelial dysfunction [43].

## 10.6 Hypofibrinogenemia

Fibrinogen is a large glycoprotein that is cleaved to fibrin by thrombin and plays a central role in hemostasis. Fibrinogen depletion is an important component in TIC and is the first coagulation factor to be depleted early after life-threatening hemorrhage [44]. Hypofibrinogenemia has been reported to occur in 14% of severely injured trauma patients, is associated with higher injury severity and higher levels of shock, and is reported as an independent predictor of mortality [45–47]. Fibrinogen supplementation during trauma resuscitation is thought to improve outcomes by increasing clot strength [48] and decreasing life-threatening hemorrhage [49]. Higher fibrinogen to RBC ratios during resuscitation have been associated with improved survival [50]. Current guidelines recommend fibrinogen supplementation at levels below 1.5 g/L [51].

Hypofibrinogenemia may occur secondary to blood loss, hemodilution during resuscitation, consumption during coagulation, hypothermia, and acidosis [52]. In swine models of trauma, hypothermia has been shown to decrease fibrinogen synthesis but has no effects of fibrinogen degradation [53]. Acidosis after trauma in swine models has been shown to result in an 1.8-fold increase in fibrinogen breakdown [54]. This profound effect of acidosis on fibrinogen plasma concentrations was supported in a human study of 675 patients that showed 81% of trauma patients who presented with a base excess of $< -6$ mmol/L manifested a fibrinogen level of <2 g/dL and 63% of patients had a fibrinogen level of <1.5 g/L. With a worsening base deficit of $<-10$ mmol/L, the percentages increased to 89% and 78%, respectively [55].

## 10.7 Fibrinolysis Dysregulation

The body maintains homeostatic microvascular patency through the fibrinolytic system. This physiologic level of fibrinolysis allows for normal clot dissolution and end organ perfusion. Dysregulation of this system is a key component of TIC. Fibrinolysis after traumatic injury manifests in three distinct phenotypes: physiologic fibrinolysis, hyperfibrinolysis, and fibrinolysis shutdown with the latter two phenotypes representing pathologic states that occur in approximately 80% of severely injured trauma patients [56].

Hyperfibrinolysis thought to be driven by overwhelming endothelial tissue plasminogen activator (tPA) release, and a decrease in circulating plasminogen activator inhibitor-1 (PAI-1) in the setting of hemorrhagic shock [57, 58]. This hyperfibrinolytic state is associated with increased clot dissolution, and uncontrolled, diffuse hemorrhage often from areas uninvolved in the traumatic injury [59–62]. Trauma patients with hyperfibrinolysis experience mortality rates upwards of 40% [56, 59, 63]. Rapid hemorrhagic

shock associated with elevated tPA levels and subsequent hyperfibrinolysis is exacerbated by crystalloid administration in both animal [64] and human studies [59]. This shock induced hyperfibrinolytic state is attenuated by plasma resuscitation and hypothesized to be related to improved platelet function with plasma resuscitation allowing for degranulation of antifibrinolytic factors released in platelet degranulation [65]. TPA is thought to be stored in Weibel–Palade bodies in the vascular endothelium and after co-localization with von-Willebrand Factor (vWf) is released into the circulation [66]. The leading hypothesis the stimuli for release involves trauma induced sympathetic activation and catecholamine surge [67].

In addition to tPA release, the loss of antifibrinolytic factors, including PAI-1 and alpha 2-antiplasmin exacerbates hyperfibrinolysis. Additionally, C-1 esterase inhibitor [68], alpha-1 antitrypsin, and vitronectin [69] all act to decrease PAI-1 activity and enhance fibrinolysis. Thrombin activated fibrinolysis inhibitor (TAFI) plays a role in clot degradation and factor XIII is vital to clot stability by cross-linking fibrin and alpha-2 antiplasmin which helps protect a newly formed clot from plasmin cleavage. Both of these factors are depleted in hyperfibrinolytic patients [69], but the exact mechanism by which TAFI and factor XIII are altered in TIC remains under investigation.

On the other end of the spectrum, fibrinolytic shutdown is the most common hypercoagulable phenotype in severely injured patients [70] and is associated with delayed morbidity and mortality secondary to venous thromboembolism and microvascular occlusion causing end organ dysfunction [71]. Patients in fibrinolytic shutdown have elevated D-Dimer and plasmin-antiplasmin complexes evidencing prior activation of the fibrinolysis system in conjunction with low tPA activity and diminished systemic fibrinolysis [69]. The mechanism behind fibrinolysis shutdown remains under investigation but is hypothesized to be regulated via PAI-1 [72, 73]. Emerging evidence also implicates S100-A10 pathway in tPA inhibition and subsequent fibrinolysis shutdown [74, 75]. Tissue injury is currently implicated as the driving force through the release of damage associated molecular patterns (DAMPs) which promote platelet release of alpha granules that contain a number of antifibrinolytic products [76–78]. The release of cellular breakdown products after tissue injury such as actin [79] and α-globin (manuscript submitted) has also been implicated in plasmin inhibition and enhanced clot propagation and fibrinolytic shutdown in vitro.

## 10.8 Conclusion

The definitive mechanisms behind trauma induced coagulopathy remain difficult to quantify though it is clear that alterations in thrombin generation, platelet dysfunction, endotheliopathy, hypofibrinogenemia, and pathologic fibrinolysis all play a significant role. The current literature describes aberrations in each of these areas, but it is still unclear whether these aberrations are all harmful or adaptive responses that serve a protective purpose in the injured trauma patient. Questions remaining include the appropriate level of thrombin generation after trauma, the critical level of hypofibrinogenemia that requires replacement, the role of whole blood in trauma resuscitation, and the appropriate time to treat hyperfibrinolysis with anti-fibrinolytics. The answers to these questions require further investigation with improved, real-time assessment of the behavior of these coagulation systems. The effects of injury mechanism on TIC and the temporal changes in coagulation after trauma are also an evolving field, with shock and tissue hypoperfusion appearing to be the inciting factors early in TIC, but tissue injury also playing a role in the dysregulation of fibrinolysis, particularly fibrinolysis shutdown. Ultimately, with improved understanding of TIC mechanisms, trauma surgeons can better provide personalized and precise care for their patients. We have seen this trend towards personalized medicine with the introduction of goal-directed resuscitation using viscoelastic assays of whole blood coagulation [80]. With advances in fields such as omics and microfluidics, we believe that the treatment of

trauma induced coagulopathy can be successfully tailored to the individual patient at a specific point in time.

**Key Concepts**

- Trauma-induced coagulopathy (TIC) is an alteration in the body's coagulation capacity that is attributable to injury and manifests in a spectrum of dynamic and time-dependent phenotypes ranging from hypocoagulable to hypercoagulable states.
- The pathophysiology behind TIC is complex and involves an intricate interplay between diminished thrombin generation, platelet dysfunction, vascular endothelial cell dysfunction, fibrinogen depletion, and dysregulated fibrinolysis.
- Improved understanding of the pathophysiology of trauma induced coagulopathy will allow for more personalized and precise care for patients (Fig. 10.1)

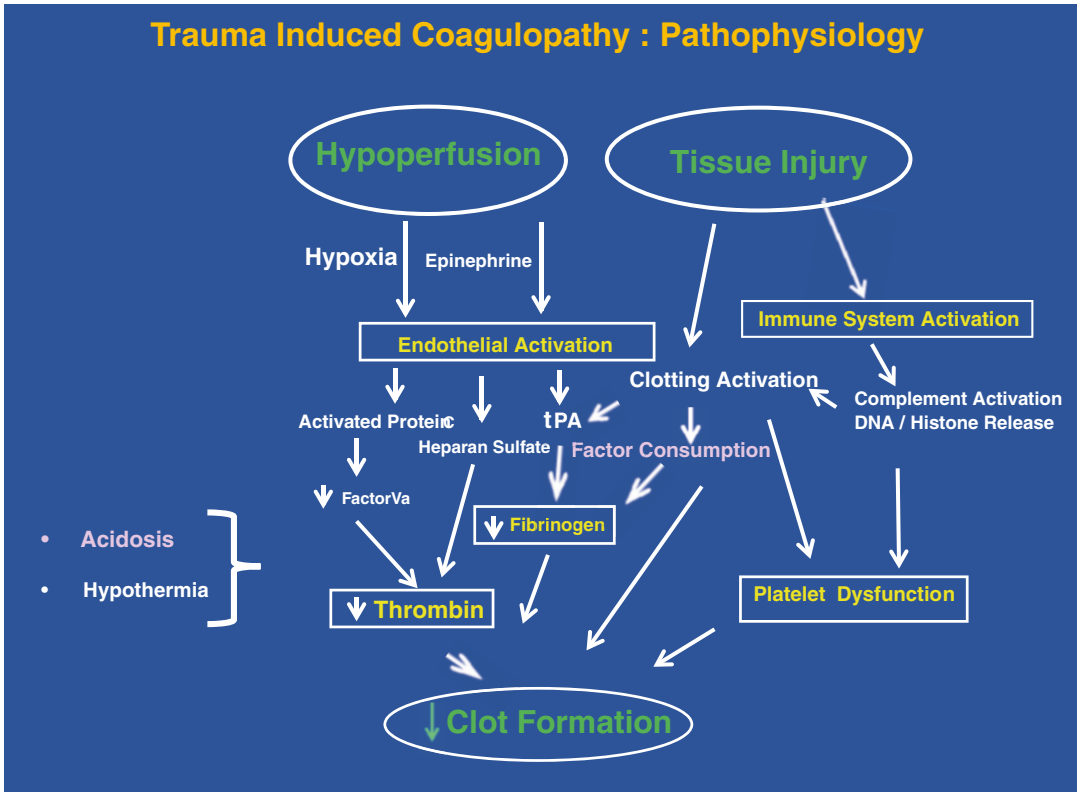


**Fig. 10.1** The pathophysiology of trauma induced coagulopathy: a complex interplay between numerous factors such as diminished thrombin production, platelet dysfunction, endotheliopathy, hypofibrinogenemia, and dysregulated fibrinolysis, resulting in alterations in clot formation and stability

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# The Inflammatory and Barrier Response After Polytrauma

11

Ebru Karasu and Markus Huber-Lang

**Learning Objectives**

- To define PAMPs and DAMPs in the context of polytrauma
- To know how the body senses exogenous and endogenous molecular danger
- To comprehend principle of mechanisms of the posttraumatic immune response
- To differentiate static and functional immune monitoring
- To understand the immunopathophysiology of barrier dysfunction after trauma
- To comprehend how barrier dysfunction is connected to immune- and multiple-organ dysfunction

## 11.1 Sensing of Danger After Polytrauma by the Immune System

At the very moment of polytrauma, the inflicting multidimensional trauma vector impacts various tissues of different musculoskeletal regions and organs. The resulting damage to organs, tissues and cells is associated with an instant, but also a retarded, release of damage-associated molecular patterns (DAMPs) [1]. The DAMPs [2] originate from the host cells and represent "internal danger" elicited by subcellular structures, including membrane fragments, histones, DNA, RNA, mitochondria, vesicles, various cytoplasmic proteins (e.g. high mobility group box 1 (HMGB-1)) and cellular debris [1, 3]. Furthermore, with superficial wounds the host is also exposed to "external danger" by microbe-associated molecular patterns (MAMPs) generated from microorganisms invading the patient from outer and/or inner microbial barriers. How is this occult or evident danger to the organism sensed in the first place?

### 11.1.1 Sensing of DAMPs

Within seconds after injury, tissue damage and DAMPs are sensed by three major systems: the peripheral and central nervous system, the coagulation cascade and the complement system (Fig. 11.1) [1]. Upon challenge by a major traumatic impact and/or major traumatic bleeding, the patient becomes rapidly unconscious, which helps in preserving energy sources and establishing a minimal circulation. In addition, the autonomic nervous system (ANS) becomes rapidly activated, resulting in alterations of the haemody-

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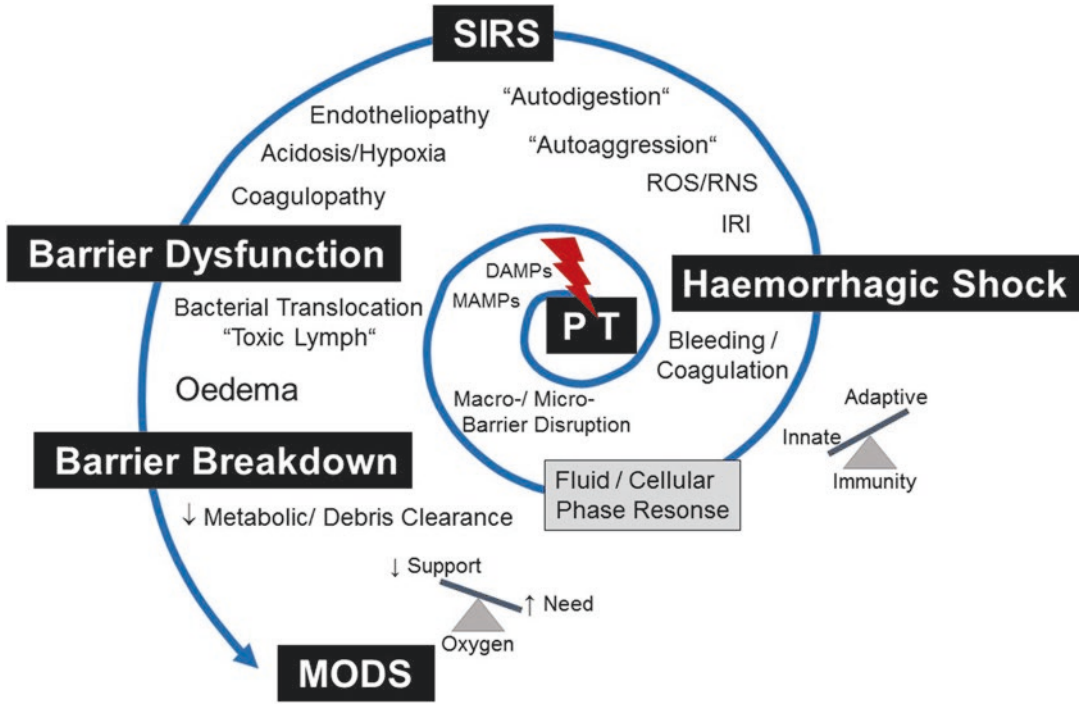


**Fig. 11.1** Immunological response after polytrauma escalating to multiple organ dysfunction syndrome (MODS). *DAMPs* Damage-associated molecular patterns, *MAMPs* Microbe-associated molecular patterns, *IRI* Ischemia reperfusion injury, *ROS* Reactive oxygen species, *RNS* Reactive nitrogen species, *SIRS* Systemic inflammatory response syndrome

namics, thereby guaranteeing a minimal perfusion of vital organs. The ANS also activates a mainly anti-inflammatory pathway [4].

The classical function of the coagulation system is to stop bleeding and preserve red blood cells as oxygen carriers. However, the coagulation system also functions as an "immune cascade", being central in the thromboinflammatory response [5, 6]. Key coagulation factors, including thrombin, act proinflammatory and contribute to endothelial barrier damage [7]. Similarly, the fibrinolytic system, for example, plasmin, plays a distinct role as a modulator of the immune system.

Another DAMP sensing system is provided by the evolutionary ancient complement cascade. The three canonical pathways of complement activation (i.e. classical, alternative and mannose-binding lectin (MBL)-pathway) can all effectively sense cellular damage. Complement activation after polytrauma is mainly caused by initiation of the alternative pathway [8]. In addition, (natural) antibodies and C-reactive protein bound to neoepitopes of damaged cells are recognised by the classical pathway via C1q. Moreover, mitochondria and corresponding debris abundantly generated after trauma [9], which in accordance with the endosymbiotic theory represent MAMPs, can rapidly be sensed by the MBL-pathway [7, 10]. Other non-canonical mechanisms have been proposed to play a role in the context of polytrauma, including the coagulation-complement crosstalk [11], nonspecific (serine) proteases and oxidative stress during hypoxic and acidic conditions, and appear to activate the complement system post severe trauma [7, 12].

### 11.1.2 Sensing of MAMPs

MAMPs as classical "foreign" molecules are also sensed by the described protease systems (coagu-

lation and complement), but also by cellular pattern recognition receptors (PRRs). This innate defence strategy provides pre-expressed PRRs on various patrolling immune cells but also on stationary cells. The membrane-bound PRRs in particular comprise formyl-peptide receptors, toll-like receptors (TLRs) (e.g. TLR2 and 4), complement receptors (e.g. CR1, CR3), the receptor for advanced glycation end products and purinergic receptors (e.g. P2X7R) [1, 13–16].

Of note, PRRs are not only expressed on the cellular surface for instant MAMP recognition, but even more intracellularly to maintain the danger sensing throughout the entire clearance process. The effective arsenal of intracellular PRRs involves specific TLRs expressed on the endoplasmatic reticulum, including TLR3, TLR7, TLR8 and TLR9. In the cytoplasm, the main protectors are nucleotide-binding oligomerisation domains (NODs), for example, NOD1 and NOD2, which sense essential parts of most gram-negative and gram-positive bacteria: peptidoglycan-related molecules and muramyl dipeptides, respectively [17]. As a prerequisite for intracellular MAMP sensing, the MAMPs and/or bacteria need to enter the host cells, which is accomplished by various partly unknown mechanisms. Bacteria can release MAMPs (e.g. lipopolysaccharide (LPS)) from phagosomes or in shed microvesicles [18]. Upon intracellular sensing of MAMPs, the NOD-like receptor family pyrin domain containing 3 assembles the inflammasome, which in turn cleaves caspase-1 and generates interleukin (IL)-1β, which propels the early inflammatory response [19].

## 11.2 Innate Immune Response After Polytrauma Drives Inflammation

Upon sufficient danger recognition, the body provides several innate immune strategies for effective early defence and clearance of debris and pathogens as well as induction of tissue repair processes [1, 3, 20]. Following severe injury, the trauma-induced immune response attempts to limit both, further tissue damage and propagation of microorganisms, both of which could feed in increasing amounts of DAMPs and PAMPs in a vicious circle of an escalating systemic inflammation with subsequent organ failure (Fig. 11.1) [1]. How does the early innate immune response accomplish a balance of the inflammatory response?

### 11.2.1 Fluid Phase

The innate immune response consists of the broadly pre-programmed highly interactive fluid and solid (cellular) phases. The complement (and coagulation) cascades reflect the main representative of the fluid phase. Within the first 30 min after polytrauma, enhanced blood concentrations of the complement activation products C3a, C5a and sC5b–9 were found, mirrored by a loss in complement haemolytic activity, which can put the patient at increased risk for infections [21, 22]. Accordingly, the development of sepsis, including enhanced sequential organ failure assessment scores, after polytrauma was associated with elevated C5a plasma levels [23, 24]. Of note, the generated anaphylatoxin C5a can induce all the classical signs of local and systemic inflammation (swelling, pain, reddishness, hyperthermia), which per se is designed to resolve any DAMP/PAMP challenge [25, 26]. C5a acts as a very potent chemoattractant for leukocytes, enhances phagocytic activity and induces an oxidative burst and release of proteases and furthermore converts the endothelium to a pro-adhesive state, but upon excessive generation can render the inflammatory and organ responses dysfunctional [25, 27, 28]. Furthermore, an enhanced ratio of C3a/C3 in plasma from polytraumatised patients as early as at the scene of the accident and in the emergency, room has been associated with a poor outcome [29]. Nevertheless, C3a also has multiple anti-inflammatory features and the balance between C3a and C5a appears to be important for the immune response [30]. Formation of the terminal complement complex (sC5b–9) was also found in the blood from polytrauma patients within the first few hours after polytrauma [21]. Reflecting massive complement

activation and subsequent depletion, the global function of complement as determined by complement haemolytic activity, was almost lost [21]. Taken together, systemic activation of the fluid phase mirrored by activation and depletion of complement occurs early after polytrauma, which leaves the patient extremely vulnerable to infection and organ dysfunction.

### 11.2.2 Cellular Phase

Polytrauma as "first hit" results in rapid activation of the "first cellular line of defence". This innate immune defence [20] involves mainly leukocytes, particularly neutrophils and monocytes/macrophages, which are recruited to the injured tissue by DAMPs and PAMPs and by locally generated chemokines (Fig. 11.2). Upon arrival, the leukocytes become activated and undergo a "genetic storm", which re-prioritises the majority of cellular pathways and functions after critical trauma [31]. This results in the rapid release of various inflammatory mediators, cytokines and further chemokines ("cytokine/chemokine storm") and thereby augment immigration of further inflammatory cells. The recruited cells phagocytise the sensed tissue debris, damaged cells and pathogens, and for effective clearance they release proteases and mount an oxidative burst to kill the ingested danger [1, 3]. For extracellular danger clearance, neutrophils, primed by traumatic shock and pro-coagulatory conditions, release reactive oxygen species (ROS) [32]. In support of this, neutrophil extracellular traps (NETs) are generated after major trauma [33].

Remarkably, neutrophils become more resistant to apoptotic processes after polytrauma [34] and thus not only attack injured cells and microorganism but also remaining healthy host cells and tissues, which results in the greatly debated "second hit" [31]. Furthermore, the appearance of different neutrophil phenotypes, including $CD16^{dim}/CD62L^{bright}$ neutrophils, appears to be

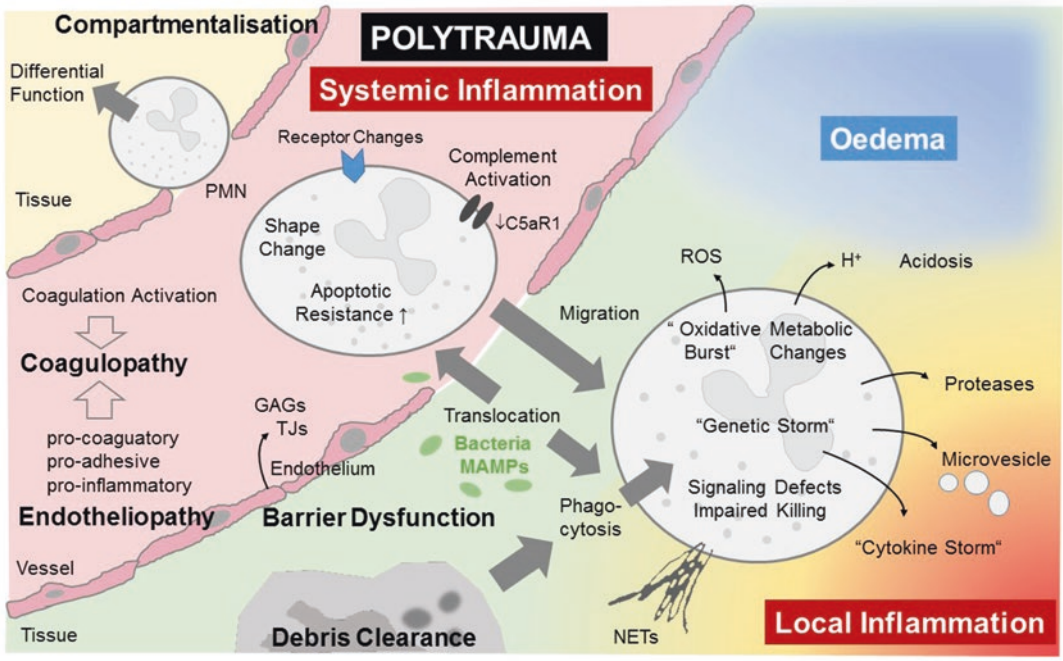


**Fig. 11.2** Simplified scheme of the spatial-temporal cellular and fluid phase response after polytrauma. *GAGs* Glycosaminoglycans, *TJs* Tight junction molecules, *ROS* Reactive oxygen species, *MAMPs* Microbe-associated molecular patterns, *NETs* Neutrophil extracellular traps

useful for the early detection of polytrauma patients at risk to develop infectious complications and poor outcome [35–37]. The surfaces of neutrophils can also switch into pro-coagulatory platforms [38]. Upon excessive exposure to inflammatory milieus, for example, to complement activation products, multiple neutrophil functions can even become suspended, as evidenced by depressed phagocytic function [26, 39]. Furthermore, the posttraumatic micromilieu can also alter the cellular pH balance and metabolic response of neutrophils and thus contribute to lactic acidosis even in the absence of an oxygen debt [40]. The cellular communication of neutrophils after trauma is also fine-tuned by microvesicles. Following polytrauma, increased neutrophil-derived C5a-receptor-containing microvesicles were found in the circulation, which could transfer some pro-inflammatory information to other cells on the one hand and which could induce a concomitant loss of the neutrophil complement C5a receptor 1 (C5aR1) with cellular impairments on the other hand [41].

Of note, the posttraumatic inflammatory response also affects monocyte function and can induce a shift of monocyte differentiation towards macrophages rather than dendritic cells (DCs). Consequently, a dysbalanced inflammatory cytokine production is observed in polytrauma patients, which appears to be associated with multiple organ dysfunction syndrome (MODS) development and infectious complications. [42]. In addition, several studies revealed that this aberrant monocyte differentiation dramatically affects adaptive immune cell functions and is associated with immunosuppression. A decreased monocyte differentiation into DCs negatively affects naive T-cell activation and long-term T-cell survival in severely injured patients [42]. The impaired monocyte-T-lymphocyte interaction is further triggered by polytrauma-induced downregulation of human leukocyte antigen-DR isotype expression on monocytes [43]. Severely injured patients also exhibited a decrease in monocyte IL-12 production, which is suggested to be responsible for the strong shift towards a more pronounced anti-inflammatory T-helper-2 ($Th_2$)-directed lymphocyte response [44].

Another significant impact on the adaptive lymphocyte response after multiple trauma is manifested by a reduction in total lymphocyte counts, CD4+ T-lymphocytes and natural killer cells, particularly in those patients who develop MODS [45]. Clinical evidence demonstrates that the increased susceptibility of these patients to infection can be partially explained by a shift of the T-lymphocyte phenotype $Th_1$-type immune responses toward increased Th2-type [46]. Moreover, B-lymphocytes exhibited an impaired capacity of specific antibody production after multiple trauma, which was proposed to be caused by a failure of the antigen recognition and/or lymphocyte activation in patients [47, 48].

In addition to the leukocyte response, in principle, many other cells from the endothelium and epithelium (e.g. hepatocytes, intestinal cells, kidney cells) can contribute to the immune response after polytrauma, making this response highly interactive and infinitely complex [1, 49].

## 11.3 Monitoring of the Posttraumatic Immune Response

Additionally, monitoring of vital organs is a prerequisite for up-to-date, patient-tailored, minimally invasive surgical and intensive care management of polytrauma patients. In this regard, it is essential to achieve a better insight and pathophysiological understanding of the (cross-talking) organ performance in the posttraumatic course. However, whereas continuous monitoring of key organ functions such as the heart (electrocardiogram), lungs (ventilation parameters) and kidneys (urine output) is well established, the performance of the immune system as a vital "organ" is hardly developed. The questions remains, how can the immune response post trauma be reliably monitored?

### 11.3.1 Static Immune Monitoring

During recent decades, the measurement of various surrogate parameters for the immune func-

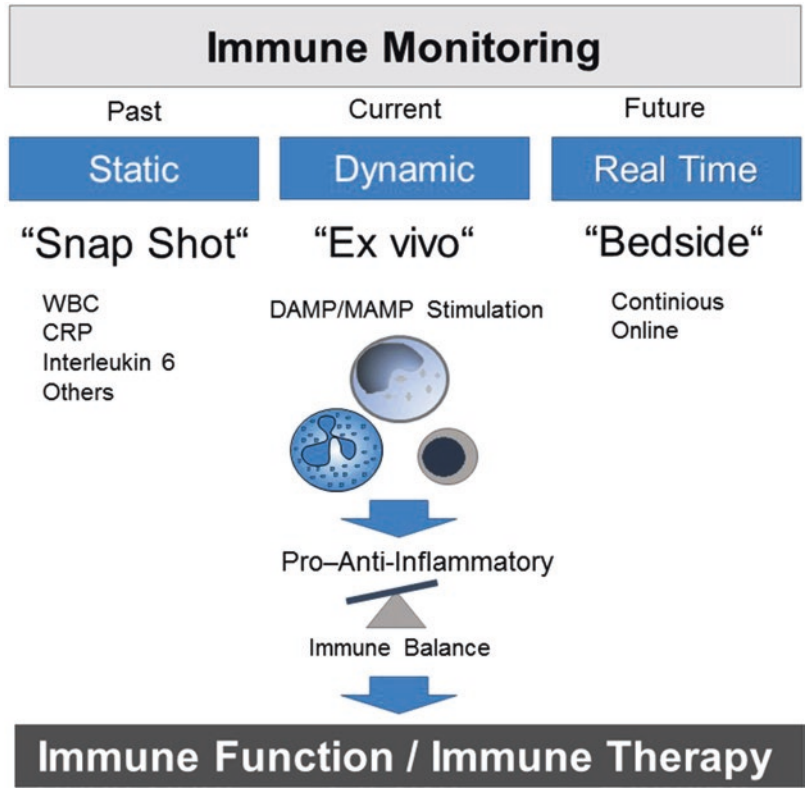


**Fig. 11.3** Immune monitoring after polytrauma in the past, presence and future. “Snap shot” determination reflects a single measurement in plasma or serum or other body fluids at a given time point. “Ex vivo“ monitoring determines the immune response and capacity of leukocytes (e.g. whole blood) to react to defined DAMP or MAMP stimuli. In the future, “real time” immune monitoring will help to visualise immune performance and to adjust immune-modulatory therapeutic approaches

tion was suggested as indicators for injury severity, tissue damage and prognostic prediction. IL-6, for example, has been shown in various studies to be a valuable marker to assess tissue damage, the subsequent inflammatory response and prognosis after polytrauma [50] as well as the development of multiple organ failure depending on the invasiveness of the surgical treatment [51, 52]. Further surrogate biomarkers in the context of polytrauma have been proposed, including among others IL-8, IL-10 and IL-1 receptor antagonist (IL1-RA) [53–55]. Whereas lower IL-22 and IL-23 levels have been reported to be predictive for MODS development after severe tissue injury [54]. By contrast, IL-2, -4, -5, interferon γ, granulocyte-macrophage colony-stimulating factor and even tumour necrosis factor appear neither to sufficiently reflect the extent of tissue damage nor to function as a variable for the outcome prediction [55]. A combination of some markers, such as IL-1RA and Clara club protein 16 (CC-16), has been shown to be predictive of MODS development after severe trauma [53]. However, the determination of defined markers at one time point might rather present a snapshot of the current situation than a reliable picture of the spatial-temporal immune performance and its remaining capacity to fight pathogens and clear debris (Fig. 11.3).

### 11.3.2 Functional Immune Monitoring

To reliably monitor the immune function post multiple injuries, a single inflammatory mediator is of rather limited use and may only present one “heart beat” of the immune dynamics. Therefore, phenotyping of the posttraumatic immune response and prediction of (multiple) organ dysfunction have been proposed by kinetic or functional immune analyses (Fig. 11.3) [56, 57]. Following polytrauma, a multiparametric cytometry by time-of-flight (CYTOF) defined blood immune cell subtypes, such as monocytes with a lower pro-inflammatory mediator release in

response to ex vivo exposure of MAMPs, with high temporal resolution of individual cytokines [58]. Similarly, several functions, such as mounting of an oxidative burst or changes in size or form, have been used as a functional read-out for leukocytes to assess immune performance [59, 60]. Functional innate immune monitoring of whole blood from polytrauma patients 24 h after injury by ex vivo exposure to MAMPs, that is, LPS, revealed a decrease in the generation of monocyte-derived mediators, but in contrast an unchanged or even enhanced cytokine production in the context of T-cell maturation and function. Of note, the ex vivo generated cytokine profile (by a 4-hour LPS incubation) demonstrated a significantly enhanced mediator release of the above-mentioned key factors, including IL-6, IL-8 and IL1-RA [61]. Some other surface expression markers, including decreased HLA-DR on monocytes and activated C5aR1 on neutrophils, have been proposed to predict infectious complications and septic development [62, 63]. For adaptive immune monitoring, defined changes in blood lymphocyte populations were described [45]. However, although in the past, the ex vivo incubation time for such flowcytometric or functional analyses could be significantly shortened for clinical practicability, an onsite real-time ("bedside") innate and adaptive immune monitoring of the polytraumatised patient remains to be realised (Fig. 11.3).

## 11.4 Posttraumatic Immune and Organ Dysfunction is Driven by Haemorrhagic Shock

Approximately 30% of multiple injured patients present with haemorrhagic shock after admission to the emergency room in Germany. These patients are at a much higher risk to develop MODS, which is also associated with an increased mortality [64, 65].

Clinical and experimental studies revealed that haemorrhagic shock is the main driving mechanism of systemic inflammation, gut barrier disruption, endothelial damage and coagulation dysfunction in patients with severe trauma (Fig. 11.1). Therefore, haemorrhagic shock is suggested as a crucial predictor for developing MODS in polytrauma patients.

In a clinical study, polytrauma patients with an additional HS displayed a significant increase in organ-specific damage markers for lung (CC-16), kidney (neutrophil gelatinase-associated lipocalin), liver (liver-fatty acid binding protein), and intestinal (intestinal-fatty acid binding protein, I-FABP) injury. Moreover, plasma tight junction molecules correlated with shock parameters in patients with an additional shock, decisive for barrier dysfunction [66]. Higher catecholamine release after haemorrhagic shock can further contribute to an increase in barrier damage because of glycocalyx shedding from the endothelial surface in patients [67, 68]. In agreement with the clinical situation, a murine polytrauma and haemorrhagic shock model demonstrated that haemorrhagic shock can exacerbate pulmonary damage and worsen renal and endothelial function, which might lead to the development of early MODS [69]. Moreover, haemorrhagic shock significantly reinforced the inflammatory response and increased the release of IL-6 and HMGB1 protein and neutrophil influx into organs [69]. Haemorrhagic shock has also been demonstrated to exacerbate the inflammatory response via the release of mitochondrial DAMP, which in turn increases pro-inflammatory neutrophil activity [9]. Accumulation of superoxide anions, hydrogen peroxide and hydroxyl radicals because of shock-induced tissue hypoperfusion can further damage cell membranes, induce apoptosis and necrosis and release local inflammatory mediators [70–72]. Furthermore, posttraumatic bleeding is also considered to play a central role in the development of coagulopathy and complementopathy [21, 73, 74]. Haemorrhagic shock-induced excessive complement activation in the kidney is suggested to drive acute kidney injury [75]. Coagulopathy is mainly triggered by alterations in platelet function, including hypo-responsiveness to procoagulant stimuli and impaired clot formation, which can reinforce the risk for bleeding after severe tissue injury [76]. The risk for additional

bleeding is further increased by a "lethal triad", consisting of hypoxia, acidosis and hypothermia, which is also suggested as a driver for MODS [77, 78].

## 11.5 Polytrauma-Induced Barrier Dysfunction

The human organism as a "cosmos" is clearly delineated from the surrounding environment by manifold barriers. Based on the FFF-principle stating that "form follows function", evolutionary development of specific functions is only enabled by spatial compartmentalisation. This is realised by highly controlled barriers, which thereby can form a sterile environment, preserve a sea-like salt-water concentration, effectively ward off intestinal microorganisms, generate specific pH and electronic gradients and guarantee many other functions. However, in the case of polytrauma, the structure is primarily (and secondarily) damaged, which leads to the reversal of the FFF-principle, that is, "function follows form". Consequently, traumatic damage and deformation lead to musculoskeletal and organ dysfunction. However, which barriers are affected?

### 11.5.1 Macrobarriers

In the "first hit" of polytrauma, the inflicting trauma vector directly damages complex barriers on a supra-cellular level, including the skin, fasciae, pleura, peritoneum, meninx, and intestinal and vessel walls. Consequently, the damaged macrobarriers expose the patient to the surrounding environment with the risk for the invasion of bacteria, viruses and other microorganisms with foreign DNA and RNA structures and subsequent development of infectious complications. Vice versa, damaged barriers can also lead to life-threatening air–blood barrier problems, massive bleeding and efflux from body fluids as well as thermal loss. The loss of circulating volume, including erythrocytes, coagulation factors, colloid-osmotic proteins and electrolytes, represents a major risk for the oxygen transport to the cells, which in the management algorithms have the highest therapeutic priority.

### 11.5.2 Microbarriers

Microbarriers exist on a cellular and subcellular level and are generally formed by any membrane structure. When damaged, these structures allow the release of the micro-compartmentalised content to the microenvironment and circulation. The extracellular appearance of damaged intracellular structures, including mitochondria, mitochondrial debris, histones, RNA- and DNA-fragments, microtubule fragments, haem [79] and ATP [80] among others, can all lead as DAMPs to the initiation and progression of a systemic inflammatory response [1].

In addition to the exposure to DAMPs and MAMPs, polytrauma-induced pathophysiological conditions such as sympathicoadrenal stress, hypoxia, hypothermia, acidosis and coagulation activation can also result in changes of cell-cell-adherence. Clinical and experimental polytrauma resulted in the loss of tight junctions and appearance of these connecting proteins in the circulation, including the junctional adhesion molecule 1 [81]. These events lead to enhanced paracellular leakage of proteins and fluids and the development of a dysfunctional pro-adhesive, pro-coagulatory and pro-inflammatory endothelium [1, 82] as well as the manifestation of tissue oedema. As a direct consequence of disturbances of the microbarriers, diffusion and transport distances increase significantly, leading to an exacerbation of the reduction of the vital oxygen supply and metabolic waste removal [1]. Furthermore, changes in electrophysiological performance and channel and transporter expression on cellular membranes can result in subsequent disturbance of the cellular homeostasis [1, 83].

## 11.6 Barrier Breakdown Drives Organ Failure After Polytrauma

Polytrauma-induced disruption of macro- and microbarriers can progress from a single cell to immune and multiple organ dysfunction (Fig. 11.1). Of note, although severe functional defects may exist, the cellular structures can remain microscopically integer for a relatively long time period. By striking contrast, clinically, this state might already exhibit severe MODS. However, when barrier damage, tissue oedema and associated immune response are excessive and prolonged, also structural damage and apoptotic and necrotic cell death can occur, finally leading to a frequently irreversible organ damage.

In particular, mucosal and barrier breakdown in the gut has been proposed as a driver of systemic inflammation and multiple-organ failure [1, 84]. A rapid onset of apoptotic cell death early after trauma has been reported for intestinal epithelial cells and lymphocytes [85]. However, it has been debated for decades whether direct bacterial translocation from the vast gut microbiome to the circulatory system may occur or indirectly via a "toxic lymph" and subsequently induce remote infections and functional problems [86, 87]. In a complex murine polytrauma model, it was suggested that thirty-eight-negative kinase 1 contributes to intestinal injury and multi-organ failure by inducing crypt-specific apoptosis [88]. Furthermore, injury to the central nervous system also alters the gut barrier. Traumatic brain injury opens the intestinal barrier [89]. By contrast, vagal stimulation can significantly protect the gut barrier as evidenced in an experimental trauma-haemorrhagic shock model [90]. However, the underlying mechanisms remain unclear. In a rat trauma-haemorrhagic shock model, decreased expression of the tight junction molecule zonula occludens-1 was found in the colon [91]. Another mechanism focused on endogenous proteases, which are claimed to be released early after trauma-haemorrhagic shock and may contribute to barrier dysfunction and MODS development by autodigestion of host cells and tissues [92].

Of note, polytrauma and haemorrhagic shock together also lead to remote intestinal barrier damage as a "second hit". In murine and human polytrauma, intestinal damage markers such as I-FABP increased and key mucosal components such as mucin-2 also appeared systemically [66, 69], reflecting severe damage to the intestinal barrier even in absence of direct gut trauma.

The lungs and alveolar barrier also represent a major target and actor of the inflammatory response as well as MODS after polytrauma [1, 93]. In addition to rapidly recruited neutrophils [94], alveolar macrophages with their high immunological plasticity trigger and resolve pulmonary inflammation time-dependently post tissue trauma [95, 96]. Furthermore, clinically necessary mechanical ventilation adds significantly to the pathophysiological and immunological response. For example, in ventilated lungs, mucosal components are altered (e.g. alveolar lavages revealed increased muc5AC concentrations, which results in the recruitment of neutrophils and driving of the inflammatory response) [97]. In concert with the immigrated immune cells, the alveolar epithelium also plays a major role in the orchestrated pulmonary immune response post trauma by altering the profile of surfactant factors and released inflammatory mediators [98–100]. Taken together, the lungs and gut represent major target organs for barrier alterations and compartment diversity in the innate immune response after polytrauma and during infectious complications [101]. These organs also drive trauma-related acute kidney injury [49], brain barrier dysfunction and other organ performance disturbances. This may finally lead to decompensation and a poor outcome, which necessitates immune-based therapeutic approaches.

## 11.7 Conclusion/Outlook

Immunomodulatory strategies such as complement modulation [102] in addition to surgical and anaesthesiological management are needed and are under current investigation, but are to date not established in the clinic. To favourably improve

the outcome of polytraumatised patients, it is essential to "measure what you target". Consequently, this advocates for the establishment of a real-time immune monitoring and—depending on the results—needs highly specific inhibition or supporting of corresponding immune cell performance. Such an immunemodulatory intervention aims to improve danger sensing, DAMP and MAMP clearance and the induction of tissue repair and regeneration, which will lead to an improved "form and function" and thus improved quality of life and survival.

**Take Home Messages**

- Polytrauma evokes a rapid fluid and cellular phase immune response
- An excessive immune response promotes development of organ barrier dysfunction and multiple organ dysfunction syndrome
- Haemorrhagic shock is a major driver of the immune and barrier dysfunction after polytrauma
- The barrier dysfunction facilitates development of tissue oedema which hampers both oxygen supply to the cell and clearance of cellular waste
- Real-time immune monitoring is a prerequisite for future immunomodulatory therapies after polytrauma

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# 12 Pathophysiology: Remote Organ Injury

Martijn van Griensven

**Learning Objectives**

- Understand the causal and intricate relationship in the posttraumatic pathway of DAMPs, immune cells, and cytokines.

## 12.1 Introduction

Trauma inflicted to a person is primarily characterized by the primary injuries. However, during the past traumatic course, the body reacting in these reactions can lead to injuries to remote organs. As a matter of fact, the remote organ injury is one of the main causes for prolonged hospital stay and there is considerable risk of dying. The remote organ injury is not due to direct trauma to that organ. It is occurring due to mechanisms that are derived from the injured organs or due to mechanisms that were activated by the injured organs. In this case we are speaking especially about danger associated molecular patterns (DAMP) and the immune system. In the early phase of trauma to the innate immune system plays a major role as the first line of defense. The DAMPs are important mediators in activating the innate immune system among other polymorphonuclear granulocytes. There is also an interaction with the vascular system and also oxygen and the lack thereof plays a role in the pathogenesis of remote organ injury.

Due to the specifics of the circulation and of cell interactions, the main organs affected by remote organ injury damage are the long, kidneys, liver, and heart. The intestine is often also failing and may be even considered as the motor of multiple organ dysfunction syndrome. As these organs have essential functions for the organism as a whole, damaging these organs in a remote manner is detrimental for the patient. Therefore, understanding the pathophysiology of remote organ injury is necessary for both the treating clinician and scientists investigating new diagnostic and/or therapeutic pathways.

In this book chapter the different aspects playing a role in the pathophysiology of remote organ injury will be discussed.

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## 12.2 Danger Associated Molecular Patterns

DAMPs are endogenously released molecules derived from cells or cellular compartments such as the nucleus, mitochondria, or the cytosol. Within the cell they have normal physiological roles. However, when released in the extracellular space due to injury with concomitant cell damage, they can be recognized by the immune system, both innate and adaptive, and thereby elicit a pathological cascade. Per se, this cascade is important for homeostasis as the body is warned that something is wrong. However, when the burden of DAMP is too much, the reaction to them and their subsequent processes lead to an overexaggerated reaction such as hyperinflammation, hypercoagulation, etc. This may also lead by overstimulation to a shutdown of such processes leading to immunosuppression. Both hyper- and hypo-inflammation are situations that are detrimental for an organism that has just sustained a traumatic impact. The DAMPs are recognized by pattern recognition receptors. Those receptors can be found on a vast majority of cells within the body. Especially, cells of the immune system carry such pattern recognition receptors. After binding of the DAMP to the pattern recognition receptors, they are switched on and thereby the cell is activated. This means, for instance, that polymorphonuclear granulocytes are activated as well as antigen presenting cells, etc. When this stays local, it is important for removing debris and needed for the regeneration of the tissue. However, in the case of systemic trauma or trauma with a very high impact, this reaction is too strong and it spreads from the local site to the entire organism.

In a consensus conference in 2006 [1], it was determined that trauma-relevant DAMP are:

- immediately released upon the traumatic insult
- activating immune cells in a concentration dependent way in conjunction to the severity of trauma
- initiate a pro-inflammatory response also in vitro
- able to be determined in plasma and the levels correlate with the extent of the inflammatory response and/or the severity of the trauma

### 12.2.1 Protein DAMPs

As stated above, the DAMPs originate from cell compartments. Protein DAMPs include intracellular proteins such as HMGB-1, heat shock proteins, and other intra cellular proteins (e.g., S100). Also, proteins that are produced by the cells to build the extracellular matrix (e.g., biglycan, decorin, heparan sulfate) can serve as DAMP at the moment they are damaged.

HMGB-1 is found upon injury and correlates with the severity and the development of multiple organ dysfunction syndrome (MODS) [2]. This can be observed by HMGB-1 levels in lavage fluid during pulmonary dysfunction with the need of longer mechanical ventilation times [3]. It is also involved in the dysfunction of the blood–brain barrier [4]. During traumatic events, oxidative stress is present in my cells. This environment triggers strong pro-inflammatory actions of HMGB-1 [5, 6].

Heat Shock Proteins (HSPs) are upregulated during any kind of pathological stress [7, 8]. HSPs act as chaperones and have both intracellular and extracellular activity. HSPA1A levels increase upon trauma and correlate with the development of MODS [9]. This may be associated with the immunosuppressive properties of this HSP. Two other HSPs, namely HSP27 and HSP70, are also upregulated in multiply traumatized patients. This upregulation was even higher in those patients suffering from thoracic trauma. Higher levels of these two HSPs are correlated with MODS and poor outcome of those patients [10].

The family of calcium-regulating S100 proteins functions as DAMPs by binding to Toll-like receptor (TLR)-2, TLR-4, and receptor for advanced glycation end products (RAGE). S100B has been extensively studied in multiply traumatized patients with and without brain injury [11]. Increased levels in multiply traumatized patients correlated with the development of MODS and poor outcome [12]. Furthermore,

S100B levels depend on the severity of hemorrhagic shock and may be associated with the subsequent occurrence of MODS [13]. Similarly, fractures and soft tissue trauma also result in increased S100B serum levels [14].

### 12.2.2 Non-protein DAMPs

Moreover, non-protein DAMPs exist and those include nucleotides and nucleosides, uric acid, and DNA.

During trauma cells are damaged and release their contents into the extracellular environment. Thereby, mitochondria are also damaged and their DNA content is exposed. Together with other mitochondrial contents, the mitochondrial DNA functions as a DAMP and causes a strong inflammatory reaction [15, 16]. This mitochondrial DNA activates polymorphonuclear granulocytes [15] and subsequently also neutrophil extracellular traps [17]. Both entities will be discussed in a subsequent section. Thus, the DAMP mitochondrial DNA is involved in the pathogenesis of MODS and multiply traumatized patients [18].

Damaging of the cells by injury also leads to the exposure of nuclear DNA as well as messenger RNA. These ribonucleic acid structures are recognized by monocytes and macrophages mainly through Toll-like receptors (TLR3 for mRNA and TLR9 for DNA and mitochondrial DNA). Nuclear DNA gives rise to the secretion of interleukin-6. Messenger RNA after stimulating TLR3 induces the production of interleukin-8.

Nucleosides can also function as DAMP. Nucleosides are derived from the nucleotides that are also present in the cells like ATP and GTP for energy resources. Upon injury the energy is needed and the nucleotides are catabolized in the nucleosides remain. Again, cell damage leads to the spill over of nucleosides in the extracellular environment. Adenosine, for instance, binds to a purinergic receptor and activates a G protein coupled signal transduction pathway. This leads then to the activation of an inflammatory response such as the production of cytokines and the differentiation in a Th2-type reaction. The nucleosides can also activate dendritic cells and thereby a tolerogenic profile evolves. Overall, the latter actions described may lead to immunosuppression.

## 12.3 Immune Cells and Organ Dysfunction After Trauma

As described above the DAMPs can result in both immunostimulation and immunosuppression and thereby lead to either an overexaggerated immune response or a severe immunosuppression leading to multiple organ dysfunction syndrome. These DAMPs are a direct effect of cell damage through the injury. The subsequent pathways are a reaction to that. As described above, many times cells of the immune system such as polymorphonuclear granulocytes, monocytes, macrophages, dendritic cells, and T cells among others are involved. Therefore, in the following the role of these cells in the pathophysiology of multiple organ dysfunction syndrome will be described.

### 12.3.1 Polymorphonuclear Granulocytes

Polymorphonuclear granulocytes are the first line of defense upon injury. They are activated due to multiple mechanisms such as ischemia reperfusion, oxygen radicals, cytokines, etc. They express adhesion molecules and interact with the endothelium leading to an extravasation of polymorphonuclear granulocytes to the organs. One of the first adhesion molecules involved is L-selectin that causes the rolling of polymorphonuclear granulocytes. Integrins, such as CD18, lead to firm attachment and finally molecules such as intercellular adhesion molecule-1 enable extravasation. L-selectin shows an increased expression on polymorphonuclear granulocytes between 3 and 12 h after the infliction of multiple injuries [19–22]. Subsequently, a decreased expression on circulating polymorphonuclear granulocytes is found and this is also correlated to the develop-

ment of multiple organ dysfunction syndrome with a gender discrepancy [22]. Similar observation has been done for monocytic L-selectin that correlates with the development of posttraumatic MODS as well [23]. Consequently, soluble L-selectin levels are also observed after trauma [19, 24]. However, a clinical phase II study using an anti-L-selectin humanized antibody did not decrease the incidence of posttraumatic MODS [25].

Besides this association of diapedesis of polymorphonuclear granulocytes, a reduced apoptosis rate of these cells was detected in multiply traumatized patients suffering from inflammatory complications including MODS. Furthermore, polymorphonuclear granulocytes can release neutrophil extracellular traps also called NETs. These neutrophil extracellular traps contain neutrophil derived circulating free DNA, histones, and neutrophil derived proteins such as proteases. Trauma leads to an increase of NETs and highest levels are correlated with subsequent development of posttraumatic MODS. This development is independent of the presence of sepsis or not [26].

### 12.3.2 Monocytes/Macrophages

Trauma induces monocytosis. However, the responsiveness of monocytes is decreased. This can be deducted from a decrease in CD14 expression [27] as well as HLA-DR expression [28]. Concomitantly, soluble CD14 is increased after trauma. Patients with decreased cellular CD14 and HLA-DR and increased soluble CD14 are prone to develop infectious complications after trauma. CD47 may also be involved with the development of MODS as seen in severely burned patients, showing similar pathogenetic pathways as upon trauma [29]. Those monocytes start to produce a specific set of immunomodulating molecules among other many cytokines [30]. This may directly or indirectly via immune paralysis or septic complications lead to the development of multiple organ dysfunction syndrome [31–33].

### 12.3.3 Lymphocytes

Lymphocyte numbers decrease upon trauma and are associated with subsequent MODS [34, 35]. On the other hand, the remaining lymphocytes show an inverse CD4+ to CD8+ ratio compared to physiological values and this is related to the development of MODS in trauma patients with concomitant sepsis [36]. This inverse ratio was not observed when trauma patients developed MODS without sepsis [37]. The presence or absence of sepsis after trauma seems also to be important for other T cell functions. Patients that died after trauma due to sepsis and MODS had significantly lower T cell proliferation and responses as measured by cytokine release. Moreover, these patients had also higher T regulatory cell activity and lower Th17 cells [38, 39]. Natural killer cells belong to the family of lymphocytes and they are also increased concerning their dim variant in trauma patients developing MODS. Gamma-delta-low T cells were reduced. Concomitantly interferon gamma increased in the serum [40].

Furthermore, apoptosis of T cells has also been discussed as a possible cause of multiple organ dysfunction syndrome after trauma. Animal studies point towards this. However, in a clinical study there was not a direct relationship between T cell apoptosis and multiple organ dysfunction syndrome. However, unusually high levels of T cell apoptosis resulted in severe T cell depletion. When this occurred early on and before complete activation of an accurate T cell reaction, multiple organ dysfunction syndrome may occur in the trauma patient [34]. This is underscored by the notice that the decrease in certain lymphocyte subsets such as T-lymphocytes and NK-cells was correlated with multiple organ dysfunction syndrome. Especially the inversion of a CD4+/CD8+ T cell ratio and increased activated T cells per se were associated with the onset of multiple organ dysfunction syndrome. Thus, an excessively depressed cellular immune response with concomitant increase depressive mediators may result in the development of multiple organ dysfunction syndrome in multiple traumatized patients [36].

## 12.4 Humoral Factors and Organ Dysfunction After Trauma

Several humoral systems are activated upon trauma, among others by the endothelial cells and the immune cells described before. The humoral factors belong to the complement system, cytokines, coagulation system, etc. These systems are well interconnected and are of course also associated with the cellular system.

### 12.4.1 Complement System

The complement system is the first humoral system that is immediately activated upon trauma. Several studies have indicated close correlations between the presence of C5a, neutrophil activation, and the development of multiple organ dysfunction syndrome and mortality after trauma [41–43]. Thus, the activation of the complement system by different pathways leads to organ damage and unfavorable outcome after trauma. This is in part due to the actions of the complement factors themselves and partially activating immune cells or other cells with detrimental effects.

### 12.4.2 TNF-Alpha

TNF-α is one of the first cytokines that is activated upon trauma. It stands at the beginning of the cytokine cascade that may also lead to a "cytokine storm." This "cytokine storm" has been well described and is also thought to be the main cause for the development of multiple organ dysfunction syndrome. TNF-α in synergy with interleukin-1β increases endothelial permeability [44]. This is also associated with the increased expression of adhesion molecules that enable the extravasation of leukocytes. TNF-α functions through two receptors, namely TNF-RI and TNF-RII. The TNF-RI is increased on polymorphonuclear granulocytes and monocytes during a systemic inflammatory response syndrome (SIRS). This can further result in MODS. The other receptor, TNF-RII, is down-regulated on monocytes in those patients and this leads to less proliferation of T-lymphocytes.

### 12.4.3 Interleukin-1β

Interleukin-1β has a short half-life and is therefore hard to measure in a clinical setting. Some studies state that because of this, together with TNF-α, it is quite irrelevant for predicting organ dysfunction [9]. On the other hand, interleukin-1β stands like TNF-α at the beginning of the immune response. Family members such as interleukin-18 are indeed associated with posttraumatic multiple organ dysfunction syndrome [45]. Thus, interleukin-1β due to its pro-inflammatory characteristics may have an influence on the development of complications such as organ dysfunction. However, as a diagnostic means, this cytokine has not really a relevance due to its very short half-life.

### 12.4.4 Interleukin-6

Interleukin-6 is a second line cytokine that is induced by among others TNF-α and interleukin-1β. It has a somewhat longer half-life than the before mentioned cytokines. Therefore, it can be easier measured in a clinical setting. Interleukin-6 predicts organ dysfunction and also mortality in patients with multiple injuries [46, 47]. Interestingly, female patients suffering from multiple injuries below the age of 50 had lower levels of interleukin-6 and developed also less multiple organ dysfunction syndrome [48]. This correlation of interleukin-6 with the development of multiple organ dysfunction syndrome is also related to a correlation with the injury severity score. A second hit by, for instance, intramedullary nailing may also lead to higher interleukin-6 concentrations in the serum and with a subsequent development of lung dysfunction.

### 12.4.5 Interleukin-10

Interleukin-10 is an anti-inflammatory cytokine that is already elevated during the early posttraumatic phase. During this phase, it may be derived from polymorphonuclear granulocytes and in the later phase from T helper-lymphocytes. Interleukin-10 concentrations correlate with the development of multiple organ dysfunction syndrome. This may be due to its anti-inflammatory nature leading to a compensatory anti-inflammatory response syndrome (CARS).

## 12.5 Conclusion

Trauma results in tissue damage leading to the occurrence of DAMPs that can damage organs, activate cellular and humoral systems. The traumatic event leads also to the activation of the cellular immune system with polymorphonuclear granulocytes as the first line of activated cells. Monocytes and lymphocytes also play a role and changing subsets are associated with the development of multiple organ dysfunction syndrome. Furthermore, soluble factors such as cytokines are produced. They perpetuate the immune response. The so-called cytokine storm is also associated with the development of multiple organ dysfunction syndrome. TNF-α and IL-1β have short half-lives and are therefore irrelevant for clinical measurements. IL-6 as pro-inflammatory cytokine and IL-10 as anti-inflammatory cytokine have, however, a relevance. They correlate with the posttraumatic occurrence of multiple organ dysfunction syndrome and can be measured in a clinical setting.

**Key Concepts**

- From the above described phenomena, it is clear that the pathophysiology of multiple organ dysfunction syndrome is a complex interplay of different systems both humoral and cellular.
- At the very beginning, DAMPs play an important role as they are occurring due to the trauma inflicted.
- As described, these DAMPs have an influence on different cell systems as well as humoral systems.
- In the further course, cells, mainly immune cells, start producing other humoral factors that in their way have own pathogenetic influences and are also perpetuating this cellular immune response.
- Overall, this massive activation of the cellular and humoral response leads to a chaotic condition in which the homeostasis in the different organs cannot be maintained.
- This leads to organ dysfunction and as it is in several organs to multiple organ dysfunction syndrome.
- In the beginning are the DAMP and as long as they are present there is a kind of vicious circle.
- The cellular response may even lead to further organ damage during organ dysfunction and thereby producing other and/or additional DAMPs.
- To break through this vicious circle, it is necessary that the patients are treated with among others the aim of removing the DAMP and the balancing of the cellular and humoral systems.
- Only than the pathogenetic pathway of posttraumatic multiple organ dysfunction syndrome can be stopped and the patient can go to cure.

**Take Home Messages**

- The pathogenesis of multiple organ dysfunction syndrome after trauma is elicited by a number of pathogenetic pathways.
- These are DAMPs, cellular and humoral responses.
- These systems are intertwined, can activate each other, and are involved in a vicious circle.

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# Polytrauma Scoring

# 13

Sascha Halvachizadeh and Hans-Christoph Pape

**Key Points**

- AIS, ISS, and NISS are anatomic scoring systems describing the injury distribution
- Pathophysiologic-based scoring systems increase prediction of mortality at the cost of feasibility
- Clinical scoring systems are intuitive at the cost of predictive capability
- Polytrauma is more than the summary of injuries
- Several different pathophysiological pathways should be taken into consideration during the initial assessment of polytrauma patient

## 13.1 Introduction

Treatment of polytrauma patients is complex and requires multidisciplinary approach [1–4]. Numerous studies investigate the treatment of polytrauma patient with the main goal to improve outcome and to minimize mortality rate. However, the main challenge that had to be overcome was the heterogeneity of polytrauma patients: injury distribution, pathophysiologic responses, and trauma systems. The Association for the Advancement of Automotive Medicine (AAAM) aimed to standardize the heterogeneity of anatomic injuries in polytrauma patients. Evaluating motor vehicle accidents, the AAAM established the Abbreviated Injury Scale (AIS). The AIS categorizes injury severity of each body region scaling from "0" (none) to "6" (not survivable). In 1974, Baker utilized the AUS to further calculate the Injury Severity Score (ISS) [5]. Osler presented a modification of the ISS, the new ISS (NISS) with slight modification of the ISS formula [6]. In the 1980s Advanced Trauma Life Support principles were developed aiming to minimize resources of trauma centers while standardizing the treatment of the severely injured patient [7–9]. Another 10 years later, in the 1990, Tscherne focused that the pathophysiologic response to trauma has a pivotal role and determines the outcome and mortality [10, 11]. These three concepts of defining and scoring a polytrauma patient define the treatment strategy and depend on individual situation:

1. The anatomic injury distribution and injury severity
2. The pathophysiologic response to trauma
3. Logistics of trauma center

This chapter presents these most commonly used scoring systems, discusses advantages and

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**Table 13.1** Abbreviated injury scale

| AIS Code | Degree of severity | Body region |
|---|---|---|
| 0 | Not injured | |
| 1 | Minor | Head |
| 2 | Moderate | Face |
| 3 | Serious | Neck |
| 4 | Severe | Thorax |
| 5 | Critical | Abdomen |
| 6 | Un-survivable | Spine |
| 7 | | Upper extremity |
| 8 | | Lower extremity |
| 9 | Unknown | Unspecified |

disadvantages, and aims to summarize important key points in the initial assessment of polytrauma patients.

## 13.2 Anatomically Based Scoring Systems

### 13.2.1 Abbreviated Injury Scale (AIS)

The AIS is an anatomically based, consensus derived, scoring system that classifies individual injuries by body region. Each injury is grading according to severity and according to body region (Table 13.1). The AIS is not suitable for a prognostic evaluation of injuries but rather build the basis of calculating the ISS. Since the first publication the AIS is subject to constant improvements and updates [12–14]. After stratification according to the AIS, injuries are categorized as discrete variable: Injuries stratified as AIS 1 are not lethal, whereas stratification as AIS 6 is not survivable [13]. While categorizing single injuries according to the AIS body regions, the following points need to be taken into consideration:

- AIS region "head" describes anatomic injuries of the neuro-cranium and the organs
- AIS region "face" includes injuries to the viscero-cranium (facial bone)
- Fractures of the orbita account to AIS region "head"
- Injuries to the cervical spine account to AIS region "head"
- Injuries to the thoracic spine account to AIS region "thorax"
- Injuries to the lumbar spine account to AIS region "abdomen"

The categorization of isolated injuries is one initial assessment step of polytrauma patients. The AIS does not reflect the global injury severity nor has the AIS predictive capabilities, since the correlation of AIS scoring and mortality is not linear [15]. Following the suggestions of AIS 1980, a description of injury severity with the use of maximum AIS (MAIS) is possible [13]. The overall AIS is a remnant that should not be used based on missing objectivity and misinterpretation since the revision of 1980 [13].

### 13.2.2 Injury Severity Score (ISS)

Baker proposed a calculation to describe the anatomic injury severity that is based on the AIS [16]. This calculation aims to describe the total injury severity. The highest AIS of each of the six body regions is eligible for inclusion for calculating the ISS. The ISS is the sum of the square of the three most severely injured body regions:

$$\mathrm{ISS} = \mathrm{AIS}_{\text{Body Region}}\,\mathrm{A}^2 + \mathrm{AIS}_{\text{Body Region}}\,\mathrm{B}^2 + \mathrm{AIS}_{\text{Body Region}}\,\mathrm{C}^2$$

It is important to recognize that the calculation of the ISS only includes one AIS per body region and a total of maximal three body regions. The ISS ranges from 1 point to 75 points. Of note, if any body region reaches 6 points on the AIS, the ISS is per definition 75.

The fact that only one AIS per body region, and maximum three body regions are taken into consideration, is one major drawback of the ISS. This might lead to underestimation of the injury severity [17]. This fact led to development of the NISS.

### 13.2.3 New Injury Severity Score (NISS)

Osler proposed the NISS in 1997 to address issues of underrepresentation of multiple extremity injury [6]. The calculation of the NISS is comparable to the ISS. The main difference is the inclusion of the three highest AIS independent of body region. This allows a multiple injured body region to contribute to the NISS. This might lead to an increase of total injury severity [12]. As a result, the NISS presents with higher sensitivity and specificity for predicting mortality compared with the ISS [18].

The ISS as well as the NISS is based on the classification of injuries according to AIS. This, however, lacks subjectivity and reproducibility [19, 20]. As a result, this leads to a wide observer variation that highlights a potential fallibility [21]. These mere anatomic based scoring systems represent an observation of acute injuries that miss individual pathophysiological reactions that base amongst others on age [22].

## 13.3 Pre-Hospital Scoring Systems

### 13.3.1 Revised Trauma Score (RTS)

Based on data from the Major Trauma Outcome Study (MOTS), Champion proposed the RTS that is one widely used pathophysiologic-based trauma score [23, 24]. The RTS includes three physiologic parameter including the vigilance, measured by the Glasgow coma scale (GSC) [25], the systolic blood pressure ($RR_{sys}$), and the respiratory rate. Initially "capillary reperfusion" and "respiratory working load" were included in the RTS, measures that were omitted due to impracticability [26]. To calculate the RTS the following two steps are necessary:

1. Coding each variable according the RTS value (Table 13.2)
2. Weighing each RTS value with the following coefficient:

**Table 13.2** Revised trauma score RTS

| GCS point | Systolic blood pressure mmHg | Respiratory rate/min | RTS value |
|---|---|---|---|
| 13–15 | >89 | 10–29 | 4 |
| 9–12 | 76–89 | >29 | 3 |
| 6–8 | 50–75 | 6–9 | 2 |
| 4–5 | 1–49 | 1–5 | 1 |
| 3 | 0 | 0 | 0 |

$$\begin{aligned}\text{RTS} = {} & 0.9638 \times \text{GCS} - \text{value} + 0.7326 \times \text{RR} \\ & - \text{value} + 0.2908 \times \text{respiratory rate} - \text{value}\end{aligned}$$

It is eminent that the RTS weighs the GCS highest, followed by the systolic blood pressure and the respiratory rate. According to the RTS the vigilance has the highest predictive value for mortality. The RTS ranges from 0 (death) to 78,408 (healthy). Further, a value of less than 4 points recommends a triage to a Level 1 trauma center [15]. The inclusion of the RTS into a logistic function calculates the direct survival probability [18]:

$$\text{Survival Probability} = \left(1 + e^{-\text{RTS}+3.5718}\right)^{-1}$$

Despite its potential for triage recommendations the RTS is not well established in preclinical situation based on impracticability [15]. Further, the score calculation is based on values only in spontaneous breathing patient, not with values of patients under analog-sedation and intubation. Despite these limitations, the RTS's capability of predicting mortality made it an essential part of the TRISS.

Evidence for use of the RTS is discussed in the literature, but there still is a lack of definitive evidence supporting its use as a primary triage tool and as a predictor of outcomes other than mortality [27]. Further, advancements of treatment strategies and polytrauma management led to a substantial decrease of mortality [4, 28, 29]. The calculated mortality rate based on the RTS is static and not adjustable to advancements of medical treatment. The RTS might therefore lead to an overestimation of mortality.

**Table 13.3** TRISS

| | Blunt trauma | Penetrating trauma |
|---|---|---|
| RTS | 0.9544 | 1.143 |
| ISS | −0.0768 | −0.1516 |
| Age ≥55a | −1.9052 | −2.6676 |
| Constant | −1.127 | −0.6029 |

### 13.3.2 Trauma and Injury Severity Score (TRISS)

TRISS is one example of scoring system that combine the anatomic injury severity with pathophysiologic reactions. Boyd utilized the databank of Major Trauma Outcome Study (MTOS) to develop the TRISS [30]. In the TRISS, ISS represents injury severity and RTS the pathophysiologic changes. Further, TRISS differentiates blunt from penetrating trauma. TRISS calculations include coefficients that for RTS, ISS, age (≥55a), and a constant variable; the coefficients depend on the trauma mechanism (blunt versus penetrating) (Table 13.3).

$$\text{TRISS} = \left(1 + e^{-X}\right)^{-1}$$

$$X_{\text{blunt trauma}} = 0.9544 \times \text{RTS} - 0.0768 \times \text{ISS} - 1.9052 \times \left(\text{age} \geq 55\text{a}\right) - 1.270$$

$$X_{\text{penetrating trauma}} = 1.143 \times \text{RTS} - 0.1516 \times \text{ISS} - 2.6676 \times \left(\text{age} \geq 55\text{a}\right) - 0.6029$$

In pediatric trauma, TRISS does not differentiate between blunt and penetrating trauma; the calculation of blunt trauma is used. If patients are under the age of 55 years, the age coefficient is set 0. TRISS values range from 0 to 1 and indicate the survival probability after trauma. Despite the incorporation of ISS and RTS, with the previously described limitations, the validated TRISS still presents limitations in case of multiple injuries of one body region or in cases of severe traumatic brain injury (TBI) [31].

### 13.3.3 Revised Injury Severity Classification RISC

RISC is a calculation based on the German Trauma registry [32]. The anatomic injury severity is based on NISS, AIS head, AIS extremity, and GCS. Physiologic parameters include partial thromboplastin time (PTT, sec.), base deficit (BE, mmol/L), $RR_{sys}$ below 90 mmHg, hemoglobin below 9 mg/dL, requirement of more than 9 packed red blood cells (pRBCs), as well as cardiopulmonary resuscitation (CPR) (Table 13.4). The coefficients are summarized and subtracted form 5. The resulting value Y is used for the calculation of the survival probability:

**Table 13.4** RISC

| Parameter | Value | Coefficient |
|---|---|---|
| Age | <55 | 0 |
| | 55–64 | 1 |
| | 65–74 | 2 |
| | >75 | 3 |
| NISS | Score value | Score value × 0.03 |
| AIS head | ≤3 | 0 |
| | 4 | 0.5 |
| | ≥5 | 1.8 |
| AIS extremity | ≤4 | 0 |
| | ≥5 | 1 |
| GCS | 3–5 | 0.9 |
| | ≥6 | 0 |
| PTT | <40 | 0 |
| | 40–49 | 0.8 |
| | 50–79 | 1 |
| | ≥80 | 1.2 |
| BE | −9 to −19.9 | 0.8 |
| | ≤−20 | 2.7 |
| CPR | Yes | 2.5 |
| pRBCs | 1 | 0.4 |
| | 2 | 0.8 |
| | 3 | 1.6 |

$$\text{Survival Probability RISC} = \left(1 + e^{-Y}\right)^{-1}$$

Comparing to the area under the curve (AUC) under the receiver operating curve (ROC) of TRISS (0.874), NISS (0.793), or ISS (0.777), the RISC presents with the highest AUC of 0.912 in the dataset of the German trauma registry. However, the RISC was developed based and validated on the dataset and needs validation in an external dataset or a prospective study. RISC based on calculation of data that were collected between 1993 and 2000 [33] leading to an overestimation of mortality rate. The update of RISC is based on calculations of data of the German

trauma registry between 2010 and 2011 and led to the development of RISC II [33]; the internal validation is based on data collected in 2012. The following points were updated:

- NISS was replaced by the highest two AIS
- Gender is included in calculations
- American Society of Anesthesiologists Score (ASA) is included
- Injury mechanism is included
- Pupil status is included

An external validation or a clinical study assessing predictive capability of the RISC II score would proof the value of RISC II and show potential limitations others than the included measures provide.

### 13.3.4 The AdHOC Score

The AdHOC score includes age, severity of head injury, oxygenation with acid-base parameter, and parameters of circulation [34]. It was developed on the data provided by the German trauma registry (TraumaRegistzerDGU®) and included patients ages 16 years and older, ISS of 9 points and higher that were admitted between 2012 and 2015 (development set). A dataset from patients admitted in 2016 served as an internal validation set. The AdHOC score provides a flow chart that assess whether any pathologic finding of the respected field (age, head injury, oxygenation, circulation) is present. Pathologic finding was defined as exceeding a predefined threshold. Thus, the patient might receive one point per field and a maximum of 4 points. The area under the receiver operating curve (AUROC) of the AdHOC score was 0.86 (95%CI 0.85–0.87) for the endpoint mortality. The thresholds and parameter are summarized in Table 13.5.

**Table 13.5** AdHOC score

| Parameter | Threshold |
|---|---|
| Age | 65 year or older |
| Head injury | GCS <12 points |
| | ECS pupil size not normal |
| | ECS pupil reactivity not brisk |
| | Motor function non-specific or none |
| Oxygenation | Hemothorax present |
| | Base excess below -6 mmol/L |
| | Horowitz index in intubated patients below 200 |
| Circulation | Systolic blood pressure below 90 mmHg |
| | Requirement of pRBCs |
| | INR >1.4 |
| | Hemoglobin below 7 g/L |

## 13.4 In-Hospital Scoring Systems

### 13.4.1 Early Appropriate Care (EAC) Protocol

The EAC protocol stratifies patients into low and high risk [35]. EAC recommends definitive surgery in patients stratified as low risk. THE EAC protocol is based on three measurements, all of which represent values of acid-base pathway: pH, BE, lactate. Patients with a pH of 7.25 or higher, BE of 5.5 and higher or lactate values below 4.0 are stratified as low risk. An external validation of this protocol revealed that patients stratified as high risk have significantly higher rate of early death and hemorrhagic shock, but the rate of patients who developed late in-hospital complications (e.g., pneumonia, sepsis, or multiple organ failure) did not differ among these groups [36].

### 13.4.2 Clinical Grading Scale (CGS)

The clinical grading system represents a summary of multiple publications and lists parameters indicative of four different pathophysiologic pathways [37]. Its level of evidence is based on expert knowl-

edge (level IV) and has not been validated in a database. All recommendations rely on studies prior to 2005. The CGS aims to grade the polytrauma patients according to the condition into "stable," "borderline," "unstable," and "in extremis." This categorization based on the following pathophysiologic pathways: shock, coagulation, temperature, and soft tissue injuries. Based on the categorization of the polytrauma patient, a treatment recommendation is provided: early total care (ETC) in stable, or stable borderline patients, damage control orthopedic (DCO) in unstable or in extremis cases. Each pathophysiologic pathway is graded according to the highest grade per measure; the mean of all grades defines the patient's condition.

### 13.4.3 Polytrauma Grading Score (PTGS)

The PTGS is based on calculation of the nationwide German trauma registry [38]. It is based on in-hospital mortality rate. The score is based on blood pressure, BE, INR, NISS, pRBCs, and platelets. According to the measured value each measurement receives a score (Table 13.5). The sum of these scores defines the PTGS. Based on mortality rate, PTGS 0–5 indicate a stable condition, 6–11 a borderline condition, 12–20 and unstable condition, and 20 and higher points an "in extremis" condition.

CGS, EAC, and PTGS have not been validated in a high quality prospective clinical study. The limitations and strengths have been presented based on validation on an external polytrauma dataset from one Level 1 trauma center [36]. Halvachizadeh demonstrated that the predictive capability of scoring systems (including mortality and in-hospital complications) increases when measures of several different pathophysiological pathways are included: shock, acid-base, coagulopathy, soft tissue injury, and anatomic injury severity. Figure 13.1 summarizes and compares scoring systems.

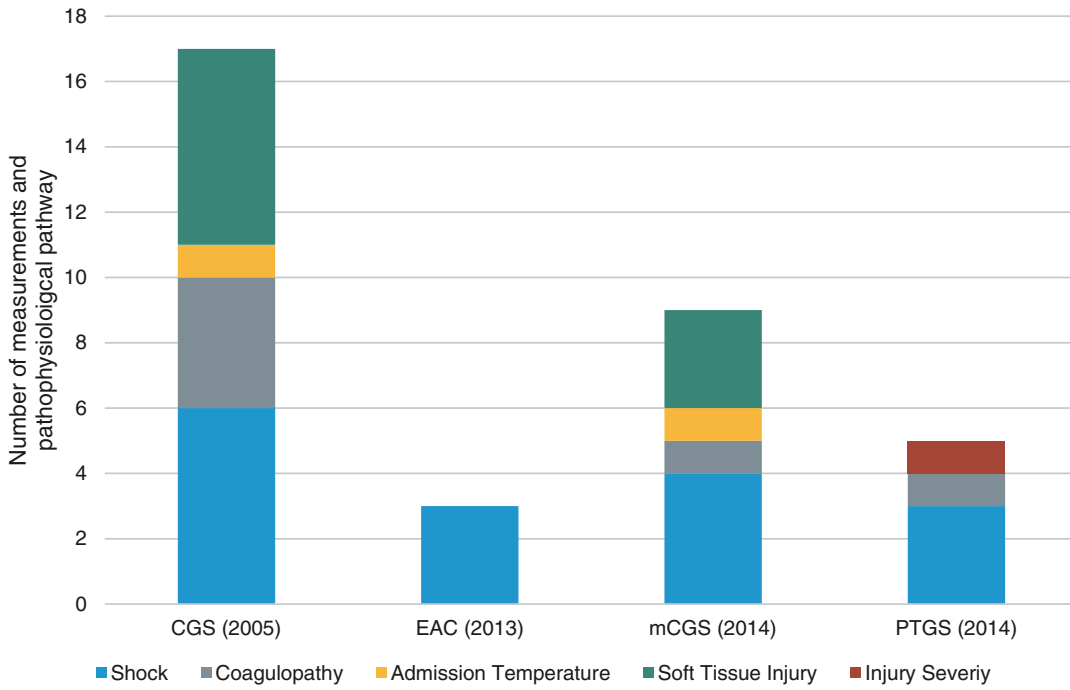


**Fig. 13.1** Comparing different scoring systems; Substantial difference of focus of pathophysiological pathways amongst the scoring systems. Further, the number of measurement per pathophysiological pathway differs amongst each scoring system

## 13.5 Summary of Scoring Systems

### 13.5.1 Pre-Hospital Scoring Systems

The Revised Trauma Score (RTS) is based on the degree of traumatic brain injury, as defined by the Glasgow Coma Scale (GCS) [25], blood pressure, and respiratory rate. Following the Major Trauma Outcome Study (MOTS), Boyed published the Trauma and Injury Severity Score (TRISS) aiming to combine anatomic injuries and physiologic responses after polytrauma [30]. The revised injury severity classification (RISC) [32] and the RISC II [39] are based on statistical analysis of a nation-wide trauma database. The AdHOC score aims to facilitate classification of trauma patients by summarizing pathologic finding of four pathophysiologic systems [34]. Further several scoring systems have been proposed that aim to provide treatment guideline.

### 13.5.2 In-Hospital Scoring Systems

The clinical grading score (CGS) aims to guide treatment strategies (damage control orthopedics, DCO versus safe definitive surgery, SDS) [37]. The early appropriate care (EAC) protocol bases definitive operability on lactate values [35]. Finally, the polytrauma grading score (PTGS) stratifies the stability of polytrauma patients based on mortality risk [38]. Roberts defined indications for damage control based on a scoping review and expert opinions [40]. These scoring systems are summarized in Table13.6.

## 13.6 Conclusion

The use of a combination of anatomic variables and variables from several pathophysiologic pathways is more precise in both defining the current state of polytrauma patients and in predicting the probability of developing complications. The assessment of polytrauma patients should be based on various factors rather than on one isolated aspect. Initial management of polytrauma patients ranges from damage control strategies to safe definitive surgery [2]. Several factors influence the decision-making including patient specific factors (age, comorbidities, physiologic status), and multiple disciplines (general surgeon, anesthesiologists, intensivists, orthopedic surgeon) [41, 42]. Based on several attempts to quantify injury severity and pathophysiologic responses it becomes eminent that scoring and defining polytrauma while giving treatment recommendations are challenging. The inclusion of several pathophysiologic pathways increases predictability for mortality and complication [36] that, however, increases complexity and decreases applicability in routine clinical practice. Observational injury descriptions are subject to high inter-, and intraobserver variability [16]. Statistical based calculations lead to complex and impractical scoring systems that include un-intuitive calculations [32, 39]. Clinical based scoring system is intuitive at the cost of decreased predictability of complications [36]. These limitations lead to an increasing number of literature investigating expert opinions on treatment strategies. Roberts summarized clinical and pathophysiological measured that lead to the recommendation of damage control surgery in polytrauma [43]. These measures include:

- Injury patterns
- Bleeding control
- Amount of resuscitation provided
- Degree of physiologic insult
- Need for staged abdominal or thoracic wall reconstruction

The comprehensive list of measures indicative for damage control surgery is based on an expert panel and is peer reviewed. Yet, the indications represent extreme situations that are comparable to unstable or in extremis situations [36]. There still is a lack of high quality research providing measures indicative for safe definitive surgery in polytrauma patients. The outcome of polytrauma patients depends on comprehensive but precise diagnostic [44, 45] and on medical and surgical expertise. The clinical approach towards a polytrauma patient is based on the assessment of the severity of the polytrauma patient. The treating

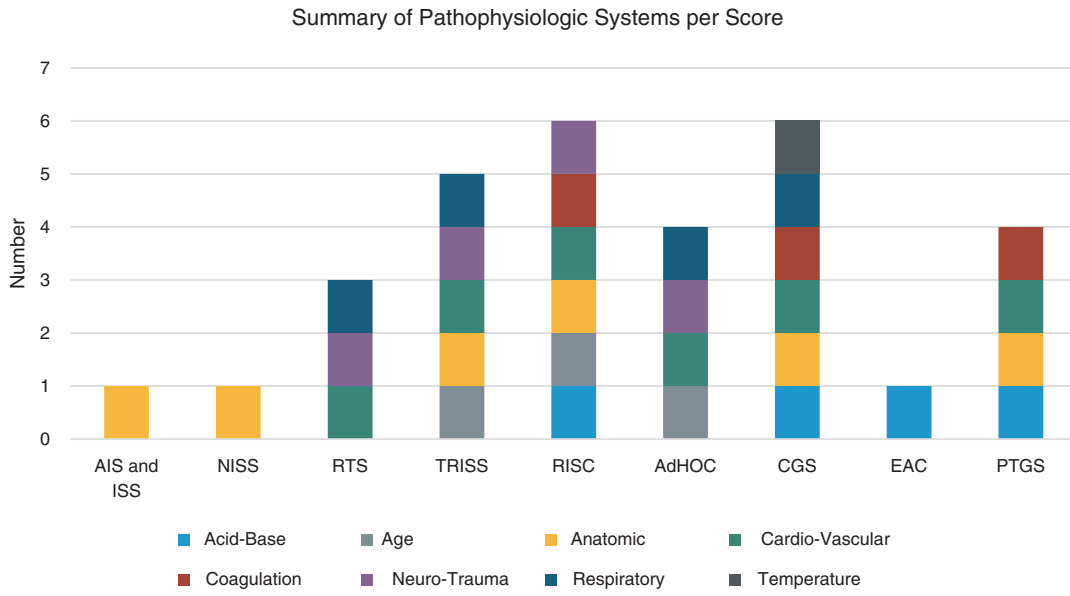


**Fig. 13.2** Summarizing the number and quality of pathophysiologic systems that are used per score

trauma team recognizes patient as a "polytrauma patient" and defines the next appropriate steps based on the clinical stability of the patient [2, 46–48]. In research, the precise definition of a polytrauma is essential to improve comparability and medical progress in this very heterogenic study-population (Fig. 13.2).

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# Head Injuries

# 14

Philip F. Stahel and Colin Buchanan

**Learning Objectives**

- Describe the pathophysiology of head trauma and the distinction between primary and secondary brain injuries.
- Explain the impact of decreased cerebral perfusion pressure in contributing to adverse outcomes.
- Identify serum biomarkers for the diagnostic work-up and outcome prediction in traumatic brain injury.
- Understand the risk of hypoxia and hypotension in contributing to secondary brain injury.
- Establish the concepts of appropriate resuscitation for limiting the risk of secondary brain injury.
- Define the optimal timing and modality of long bone fracture fixation in polytrauma patients with associated head injuries.
- Recognize patients who require early neurosurgical consultation, hospital admission, or transfer to a higher level of care.

## 14.1 Introduction

Traumatic brain injury (TBI) represents the leading cause of death and long-term neurological impairment in mainly young trauma patients worldwide [1–4]. Technological innovation in recent years, with the introduction of neuroproteomics and a new generation of laboratory testing modalities, has improved the diagnostic work-up for TBI patients [5]. However, despite advances in diagnostic imaging, neurointensive care modalities, and the quality of neurosurgical care, the clinical outcome of patients with severe TBI remains poor. Of critical importance, there is currently no specific pharmacological therapy available for the treatment or prevention of secondary cerebral insults [6, 7]. The extent of posttraumatic brain damage is determined by a combination of the *primary* trauma, resulting from mechanical forces applied to skull at the time of impact, and the subsequent evolution of

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*secondary* brain injuries [8]. The primary trauma is characterized by either focal or diffuse brain injury patterns, whereas secondary brain injuries evolve over time and are characterized by a complex cascade of molecular and biochemical events leading to neuroinflammation, brain edema, and delayed neuronal death [9]. The immune-pathophysiological sequelae of TBI are highly complex and involve numerous brain-derived proinflammatory mediators, such as cytokines, chemokines, complement anaphylatoxins, excitatory molecules, electrolyte disturbances, and blood-derived leukocytes that migrate across the blood–brain barrier (BBB) [10–12]. These events culminate in the breakdown of the BBB and allow leakage of circulating neurotoxic molecules from the peripheral blood stream into the subarachnoid space of the injured brain, which is otherwise protected from the systemic circulation under physiologic conditions. The resulting proinflammatory environment in the injured brain promotes the development of brain edema and brain tissue destruction by leukocyte-released proteases, lipases, reactive oxygen species, and terminal complement activation proteins (Fig. 14.1). Ultimately, the extent of secondary brain injury, characterized by neuroinflammation, ischemia/reperfusion injuries, cerebral edema, intracranial hemorrhage, and intracranial hypertension, represents one of the key determinants of poor outcomes after severe TBI. Iatrogenic factors, such as permissive hypotension, prophylactic hyperventilation, overzealous volume resuscitation, and the inconsiderate timing and extent of surgical procedures for associated injuries further contribute to preventable secondary cerebral insults [13]. Early hypoxia and hypotension are significant contributors to the evolution of secondary brain injury and must be prevented during the early resuscitation of polytrauma patients with associated head injuries [14]. In light of the complex underlying pathophysiology and the inherent vulnerability of the injured brain to "second hit" insults, it is imperative for the trauma team to closely coordinate the timing of the surgical priorities for the management of associated injuries in head-injured patients.

## 14.2 The Quest for a Serum Biomarker

At present, there is a lack of reliable serum biomarkers for routine use in the diagnostic work-up and outcome prediction for TBI patients. A mul-

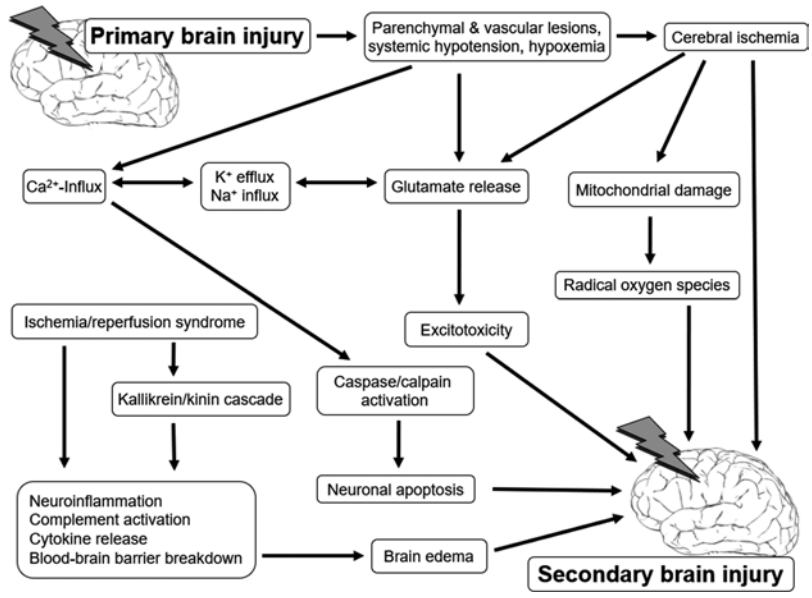



**Fig. 14.1** Pathophysiology of primary and secondary brain injury. (See text for details)

tiplicity of potential candidate molecules has been identified in recent years [15]. Early research from the 1980s defined the properties of an "ideal" TBI biomarker as such: (a) must be highly specific for brain tissue; (b) must be released from the brain only after relevant tissue damage occurred; (c) must appear in cerebrospinal fluid (CSF) and serum rapidly after TBI and mirror the time course of injury; (d) must reflect the severity of neurological injury; and (e) must be of clinical relevance [16]. The currently established and novel speculative biomarkers originating from injured neurons, axons, or glial cells are depicted in Fig. 14.2. There is ongoing debate on the potential advantages of CSF versus peripheral blood samples. Some authors argue that biomarkers in CSF are preferred over serum, due to the close proximity of the intrathecal fluid to the injured brain, independent of the BBB integrity. In contrast, serum biomarkers are more practicable for routine sampling due to access to peripheral blood samples. Confounding variables that alter biomarker serum levels include associated extracranial injuries and presence of traumatic-hemorrhagic shock. This aspect is of particular importance considering that most head-injured patients do not undergo routine CSF sampling, and only selected patients with severe TBI are candidates for CSF drainage through indwelling intraventricular catheters. The currently most widely used serum biomarkers for TBI include neuron-specific enolase (NSE), S100 calcium-binding protein B (S100B), and glial fibrillary acidic protein (GFAP) [16]. NSE is a glycolytic enzyme which catalyzes the conversion of 2-phosphoglycerate to phosphoenol pyruvate during glucose metabolism which is present in high concentrations in neurons and neuroendocrine cells. The release of NSE into serum has been considered a sensitive surrogate of the severity of brain damage. A serum NSE level <10 ng/mL is considered within the normal range. Elevated serum NSE levels correlate with intracerebral CT pathology and are predictive of

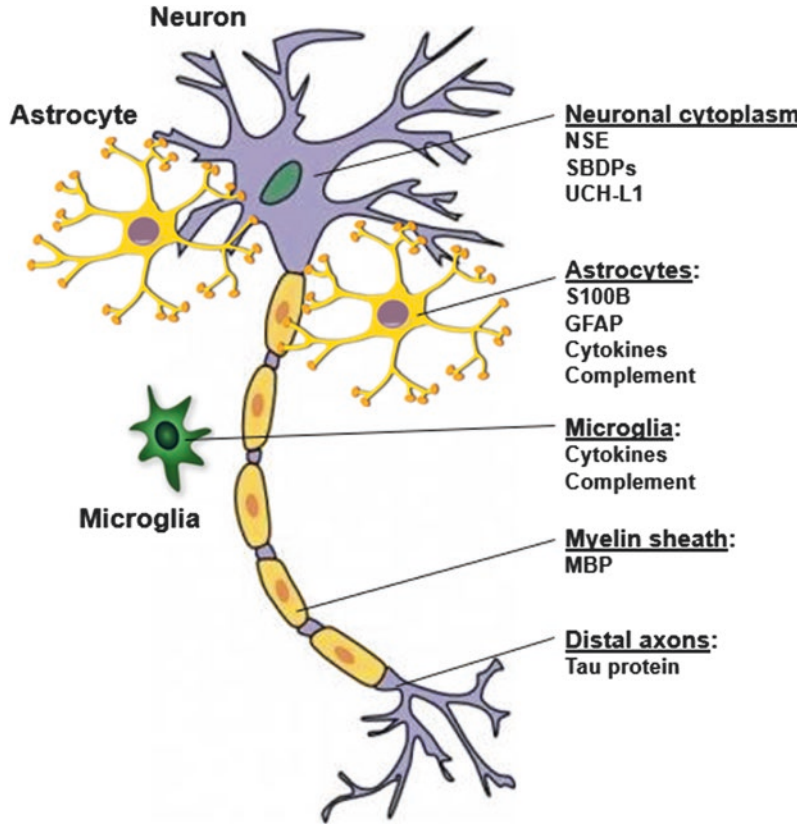



**Fig. 14.2** Cellular source of serum biomarkers for traumatic brain injury
Abbreviations: *GFAP* Glial fibrillary acidic protein, *MBP* Myelin basic protein, *NFL* Neurofilament, *NSE* Neuron-specific enolase, *SBDPs* Spectrin breakdown products, *UCH-L1* Ubiquitin carboxy-terminal hydrolase-L1

poor outcomes after TBI. In patients with DAI, a cut-off at NSE levels >50 ng/mL revealed 100% sensitivity and 100% specificity for predicting post-injury mortality [17]. In contrast, NSE has a low sensitivity for differentiating patients with mild TBI from healthy controls. Recent studies detected extracranial sources of NSE in polytrauma patients, including hemorrhagic shock, long bone fractures, and ischemia/reperfusion injuries, which limits the value of this serum biomarker for isolated head injury.

The astroglia-derived S100B is one of the most promising serum markers for TBI, being released rapidly after trauma with a short half-life of less than 60 min. Significantly elevated S100B levels have been described in the serum of head-injured patients and have been shown to correlate with the severity of TBI and predictive of adverse outcomes. In patients with TBI (GCS ≤8), elevated serum S100B levels greater than 1.0 ng/mL are predictive of secondary brain injury and postinjury mortality after TBI. However, in spite of a high sensitivity, the low specificity represents a shortcoming of S100B as the preferred biomarker, since the protein is not just expressed by astroglial cells but has also been detected in adipocytes, chondrocytes, melanoma cells, and hematopoietic cells. Some studies therefore suggested that elevated S100B levels after TBI are reflective of BBB damage, resulting in protein leakage from the periphery into the intrathecal compartment, rather than reflecting the extent of direct neuronal injury. Finally, GFAP represents a "classic" astrocyte-specific cell marker, and its exclusive brain-specific expression and release renders the protein a very intuitive biomarker for TBI above other candidate molecules, such as S100B or NSE. Clinical studies confirmed this notion by demonstrating significantly elevated GFAP serum levels around 7 pg/mL in TBI patients on the day of admission, compared to tenfold lower levels at 0.7 pg/mL in control subjects without head injuries. Future validation studies in large-scale longitudinal multicenter trials will have to confirm the notion of GFAP as a potential "silver bullet" among the available serum biomarkers to monitor the course of treatment and predict outcomes in TBI patients.

## 14.3 Hypoxia and Hypotension: The "Lethal Duo"

Episodes of hypoxia and hypotension represent the main independent predictive factors for poor outcomes after severe TBI [14]. In a landmark article published in 1993, Chesnut and colleagues analyzed the impact of hypotension, as defined as a systolic blood pressure (SBP) <90 mmHg, either during the resuscitation phase ("early") or in the ICU ("late"), on the outcome of head-injured patients prospectively entered into the Traumatic Coma Data Bank (TCDB) [18]. Early hypotension occurred in 248 of 717 patients (34.6%) and was associated with a doubling of post-injury mortality from 27% to 55%. Late hypotension occurred in 156 of 493 patients (31.6%), of which 39 patients (7.9%) had combined early and late hypotensive episodes. For 117 patients with an exclusive hypotensive episode occurred in the ICU, 66% either died or survived in a vegetative state, as defined by a Glasgow Outcome Scale (GOS) score of 1 or 2 points. The authors furthermore determined that mortality is drastically increased in combination with hypotension (SBP <90 mmHg) and hypoxia ($PaO_2$ ≤60 mmHg) [18–20]. A different study confirmed the notion that severe secondary insults occur during the neurointensive care period in more than 35% of all head-injured patients, including episodes of hypoxia, hypotension, elevated intracranial pressure (ICP), and decreased cerebral perfusion pressure (CPP) [21].

National guidelines by the *Brain Trauma Foundation* recommend that blood pressure and oxygenation be monitored in all head-injured patients, and advocate to maintain a systolic blood pressure >90 mmHg and a $PaO_2$ >60 mmHg, respectively [22]. This notion is of particular importance in view of the ongoing debate on the controversial concept of "permissive hypotension" in patients with traumatic hemorrhage from penetrating or blunt torso injuries [23, 24]. The strategy of "permissive hypotension" is mainly based on a landmark article from the 1990's advocating a modified prehospital resuscitation concept for hypotensive patients with penetrating torso injuries, by delay-

ing fluid resuscitation until arrival in the operating room [25]. This proactive concept is certainly intuitive from the perspective that traditional resuscitation with aggressive fluid administration may lead to increased hydrostatic pressure and displacement of blood clots, a dilution of coagulation factors, and an undesirable hypothermia in critically injured patients [26]. However, in light of the vulnerability of the injured brain to secondary insults mediated by hypoxia and hypotension during the early post-injury period, the concept of hypotensive resuscitation, which has seen an unjustified expansion from penetrating to blunt trauma, in absence of high-level evidence, appears contraindicated for patients with traumatic brain injuries [14].

## 14.4 Classification of Head Injuries

Traumatic brain injuries are classified by *severity*, using the Glasgow Coma Scale (GCS), or by *morphology*, using non-contrast computerized tomography (CT) imaging [27].

### 14.4.1 Severity of Injury (GCS)

The patient's level of consciousness is rapidly evaluated by the GCS score (Table 14.1), which grades the severity of TBI as mild (GCS 13–15), moderate (GCS 9–12), and severe (GCS 3–8). Of the three underlying criteria (eye opening, verbal response, motor response), the *best* motor response represents the most reliable predictor of outcomes. Of note, the GCS must be reevaluated and documented in regular time intervals to detect a deterioration in GCS over time ("patients who talk and die"). Importantly, the post-resuscitation GCS score is needed to grade the severity of TBI due to the confounding influence of cerebral hypoperfusion in patients with traumatic-hemorrhagic shock on the level of consciousness. The "classic" GCS grading scale from the 1970s was recently modified (a) to be more easily applicable; (b) to avoid inflicting pain for testing; and (c) to account for non-testable parameters ("NT," see revised GCS scale in Table 14.1) [27].

**Table 14.1** Glasgow coma scale

| Original scale | Revised scale | GCS score |
|---|---|---|
| *Eye opening (E)*[a] | | |
| Spontaneous | Spontaneous | 4 |
| To speech | To sound | 3 |
| To pain | To pressure | 2 |
| None | None | 1 |
| | Non-testable | NT |
| *Verbal response (V)*[a] | | |
| Oriented | Oriented | 5 |
| Confused conversation | Confused | 4 |
| Inappropriate words | Words | 3 |
| Incomprehensible sounds | Sounds | 2 |
| None | None | 1 |
| | Non-testable | NT |
| *Best motor response (M)*[a] | | |
| Obeys commands | Obeys commands | 6 |
| Localizes pain | Localizing | 5 |
| Flexion withdrawal to pain | Normal flexion | 4 |
| Abnormal flexion (decorticate) | Abnormal flexion | 3 |
| Extension (decerebrate) | Extension | 2 |
| None (flaccid) | None | 1 |
| | Non-testable | NT |

Best possible score: 15. Worst possible score: 3
[a]The GCS score is calculated as E + V + M

### 14.4.2 Morphology of Injury (CT)

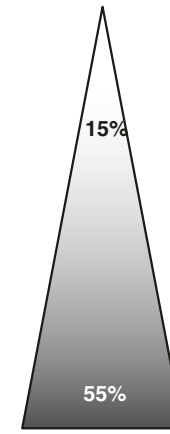
The morphological classification of TBI is determined by a non-contrast CT scan of the head. This includes the descriptive assessment for presence of skull fractures, intracranial hematomas, diffuse axonal injury, cerebral contusions, as well the Marshall classification of axial CT scans which stratifies intracranial lesions as either focal, evacuated vs. non-evacuated hematomas, or as grade I-IV diffuse injuries (Table 14.2) [28].

#### 14.4.2.1 Skull Fractures

Skull fractures in younger patients are generally a sign of high-energy trauma. Fractures occur either in the cranial vault or in the base of the skull. The presence of a linear vault fracture alone is associated with a 400-fold increased risk

**Table 14.2** Marshall classification of head CT scan

| CT classification | Definition | Mortality |
|---|---|---|
| Diffuse Injury (DI) I | Normal CT scan (clinical diagnosis) | |
| Diffuse Injury (DI) II | Open basal cisterns, midline shift 0-5 mm, high- or mixed-density lesions < 25 cc. | |
| Diffuse Injury (DI) III | Compressed or absent basal cisterns, midline shift 0-5 mm, high- or mixed- < 25 cc | |
| Diffuse Injury (DI) IV | Absent basal cisterns, midline shift > 5 mm, high- or mixed-density lesions < 25 cc | |
| Evacuated mass lesion (EML) | Any surgically evacuated intracranial lesions | |
| Non-evacuated mass lesion (NEML) | High- or mixed-density lesion > 25 cc, not surgically evacuated | |



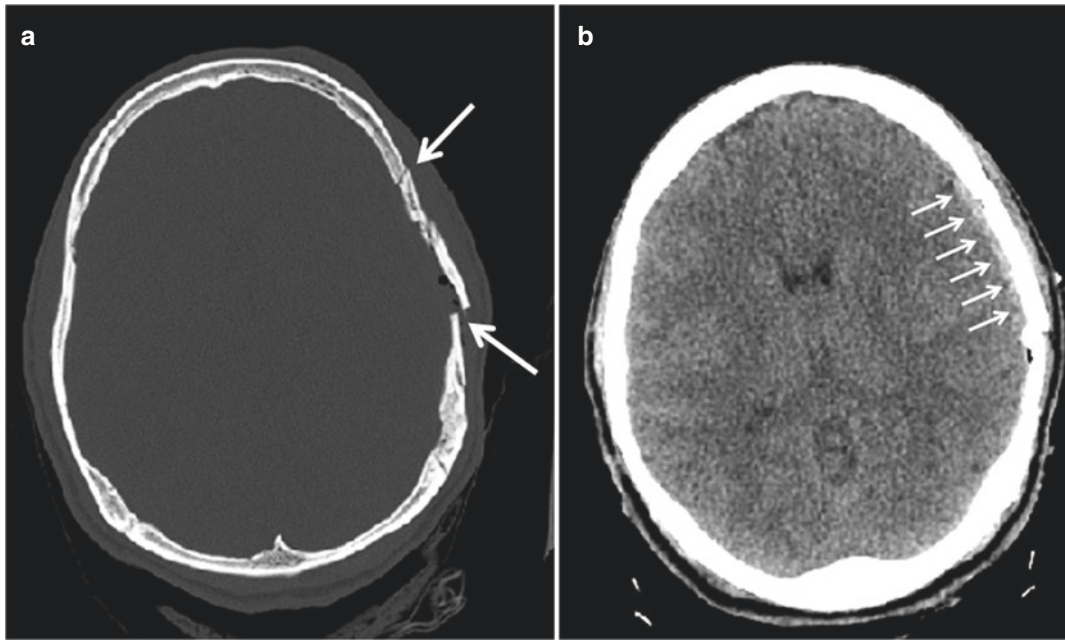




**Fig. 14.3** Skull fracture with associated subdural hematoma

Case example of a 40-year-old male patient who was assaulted with a baseball bat and sustained a segmental comminuted fracture of the left temporal and parietal bone (arrows in panel **a**). The small air bubbles under the skull fracture indicate presence of an open fracture (panel **a**). The non-contrast axial CT scan image demonstrates an underlying subdural hematoma (arrows in panel **b**)

of an intracranial hematoma (Fig. 14.3). Clinical signs of basilar skull fractures include leakage of cerebrospinal fluid (CSF) from the ear (otorrhea) or nose (rhinorrhea), periorbital ecchymosis ("racoon eyes"), and retroauriocular ecchymosis (Battle's sign). Rarely, skull fractures may be associated with neurological dysfunction of the cranial nerves VII (facial paralysis) and VIII (hearing loss), or with a carotid artery dissection. Open skull fractures expose the cerebral surface

and are associated with a high risk of infections (meningitis, meningoencephalitis).

#### 14.4.2.2 Intracranial Lesions

Intracranial lesions are stratified as diffuse or focal injuries. Diffuse brain injuries frequently present normal on the initial CT scan. Mild diffuse brain injury is a simple concussion, whereas *diffuse axonal injury* (DAI) represents a neuronal "shearing injury" from high-energy acceleration-deceleration mechanisms and is associated with a dismal prognosis (Fig. 14.4). Focal lesions include epidural, subdural, and intracerebral hematomas, as well as cerebral contusions. *Epidural hematomas* are uncommon but dangerous due to being underestimated (so-called lucid interval) with the potential for rapid deterioration and adverse patient outcomes. These hematomas present in biconvex or lenticular shape on axial CT scan and typically result from a laceration to the middle meningeal artery (Fig. 14.5). In contrast, subdural hematomas are typically of venous origin due to shearing injuries to bridging veins of the cerebral cortex. *Subdural hematomas* are more common and present in about 30% of all patients with severe head injuries. In contrast to the lenticular shape of epidural bleeding, the shape of subdural hematomas conforms to the contour of the brain (Fig. 14.6). Subdural hematomas are surrogate markers of severe underlying parenchymal brain injury. *Cerebral contusions, subarachnoid hemorrhage, and intracerebral hematomas* are very common injury patterns in patients with severe TBI. Most contusions are found in the frontal and temporal lobes (Fig. 14.7). Contusions can evolve over time and form intracerebral hematomas with perifocal neuroinflammation and cerebral edema which may occasionally lead to a mass effect requiring surgical decompression.

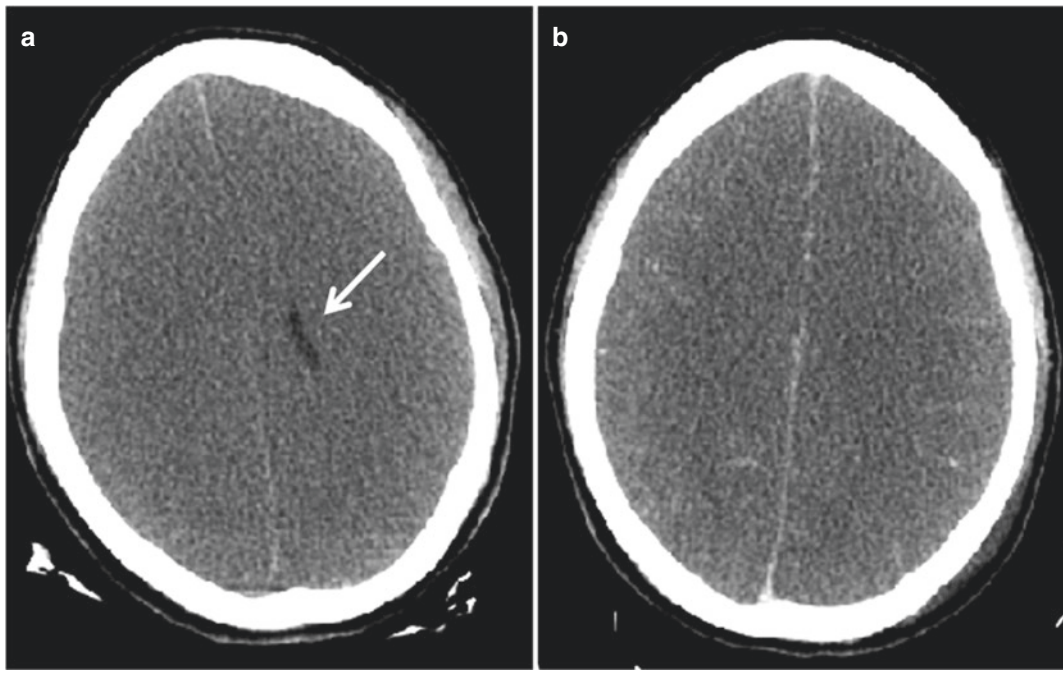



**Fig. 14.4** Diffuse brain injury

Case example of a 43-year-old male patient who sustained a high-speed multivehicle deceleration injury. He was comatose with a GCS of 3 and intubated at the scene. The initial non-contrast CT scan demonstrates diffuse brain swelling with effacement of the intracranial subarachnoid spaces (panel **a**). The arrow in panel A demonstrates the residual lateral ventricle in the left hemisphere. A repeat non-contrast CT scan obtained on day 3 reveals small punctuate subarachnoid hemorrhage (panel **b**). In spite of maximal intensive care therapy, this unfortunate patient died from uncontrolled cerebral edema with tonsillar herniation

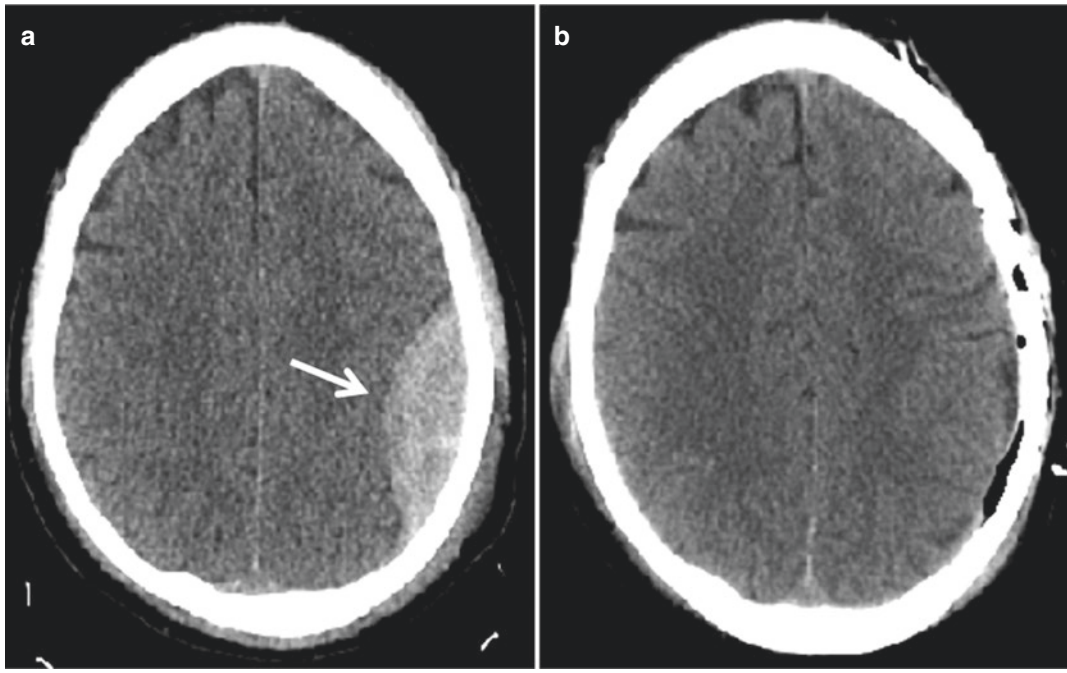



**Fig. 14.5** Epidural hematoma

Case example of a 33-year-old male who sustained a fall on his head while intoxicated. He was brought to the ED with a GCS of 14. The non-contrast CT scan of the head demonstrates a large lenticular shape epidural hematoma along the left frontoparietal convexity, measuring 20 mm in thickness (panel **a**). The patient was taken to the operating room for a craniotomy with hematoma evacuation. The postoperative CT scan demonstrates absence of the hematoma and post-craniotomy intracranial air (panel **b**)

## 14.5 Initial Assessment and Management

The standardized approach to the initial assessment of multiply injured patients with associated TBI is performed by the ATLS® protocol, as described elsewhere in this textbook (see Chap. 6) [27]. The main goal in the early management of head-injured patients is the prevention and restoration of variables which contribute to the evolution of secondary brain injury, including hypoxemia, hypotension, hypercarbia, and hypoglycemia. Patients with severe TBI (GCS ≤8) require immediate endotracheal intubation for airway protection and adequate ventilation and oxygenation. The fluid replacement therapy of choice in TBI patients consists of isotonic electrolyte solutions, such as Ringer's lactate. Urinary output helps guide the patients' response to resuscitation, aimed at >0.5 mL/kg/h in adults and 1–2 mL/kg/h in pediatric patients. A pitfall in TBI patients with increased urinary output may related to a postinjury complication termed "syndrome of inappropriate ADH secretion" (SIADH). Neurologic evaluation of TBI patients occurs after the stabilization of vital systems, per ATLS® guidelines. A head CT should be obtained under the following circumstances: (1) altered level of consciousness with GCS <14; (2) abnormal neurological status; (3) differences in pupil size or reactivity; (4) suspected skull fracture; (5) intoxicated patients. Furthermore, the head CT must be repeated whenever a patient's neurologic status deteriorates. Significant associated injuries, such as blunt chest trauma, intraabdominal hemorrhage, pelvic ring disruptions, and long bone fractures must receive adequate attention due to the potential of contributing to the development of secondary brain damage. Due to the interrelation between cerebral perfusion pressure (CPP) with intracranial pressure (ICP) and mean arterial pressure (MAP), an increased systemic blood pressure should not be therapeutically low-

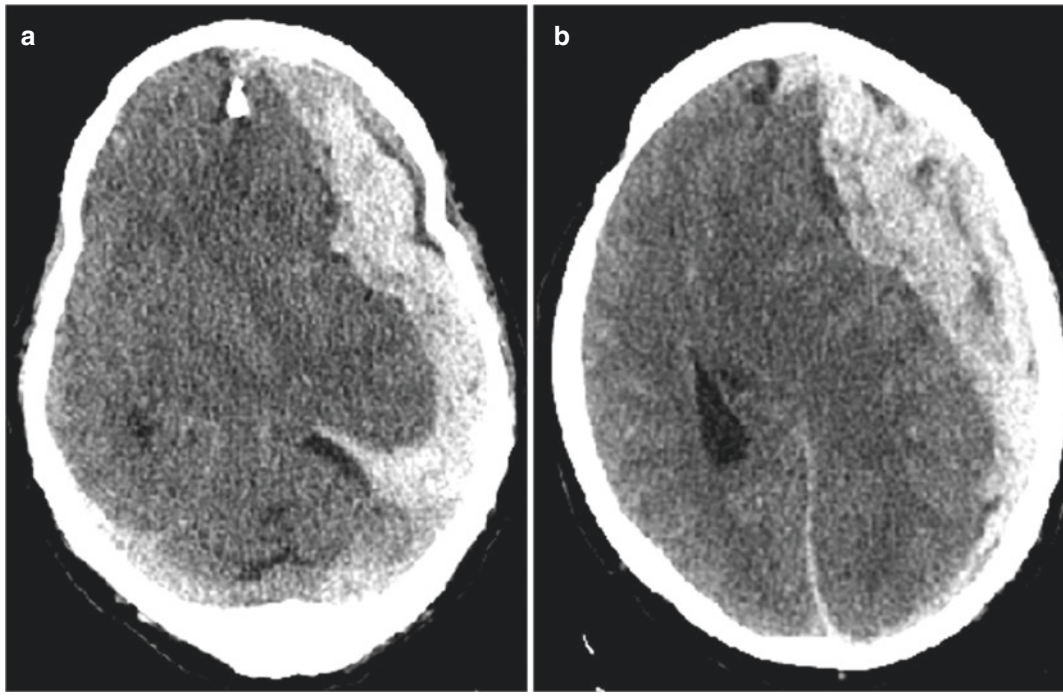



**Fig. 14.6** Subdural hematoma

Case example of a 65-year-old male patient on long-term anticoagulation for atrial fibrillation who sustained a low-energy fall on his head. The patient was brought to the ED with a GCS of 12. The non-contrast CT scan demonstrated a large subdural hematoma of 40 mm diameter over the left cerebral hemisphere (panel **a**). There is a significant intracranial mass effect with rightward midline shift, effacement of the left lateral ventricle (panel **b**), and subfalcine herniation. The patient was taken to the operating room emergently for a decompressive craniectomy (not shown)

ered in head-injured patients, as this may be reflective of "demand hypertension" to retain adequate cerebral blood flow (CPP = MAP-ICP). Similarly, permissive hypotension should not be advocated in polytrauma patients with associated TBI due to the potential detrimental impact on preventable secondary cerebral insults. According to the "Monro-Kellie doctrine," the total intracranial volume remains constant, implying that expanding mass lesions will result in a reduced CPP. Therefore, CPP maintenance above 70–80 mmHg may have to be therapeutically achieved by surgical evacuation of intracranial mass lesions and by attenuation of brain swelling by the use of osmotic drugs (e.g., mannitol) and therapeutic CSF drainage through intraventricular catheters (Fig. 14.8). Since elevated ICP values >20 mmHg are associated adverse outcomes, the indwelling ICP monitoring is generally recommended under the following conditions:

1. S*evere* TBI (GCS ≤8) with abnormal admission CT scan;
2. S*evere* TBI (GCS ≤8) with normal CT scan, but prolonged coma >6 h;
3. Postoperative monitoring after surgical hematoma evacuation;
4. Neurological deterioration (GCS ≤8) in patients with initially mild or moderate extent of TBI;
5. Head-injured patients requiring prolonged mechanical ventilation, e.g., for management of associated extracranial injuries, unless the initial CT scan is normal.

The ICU management of polytrauma patients with associated head injuries primarily focuses on preventing secondary brain injury by maintaining adequate oxygen delivery and hemodynamic stability. This includes the prevention of hypoxemia, hypercarbia, and hypotension, with a

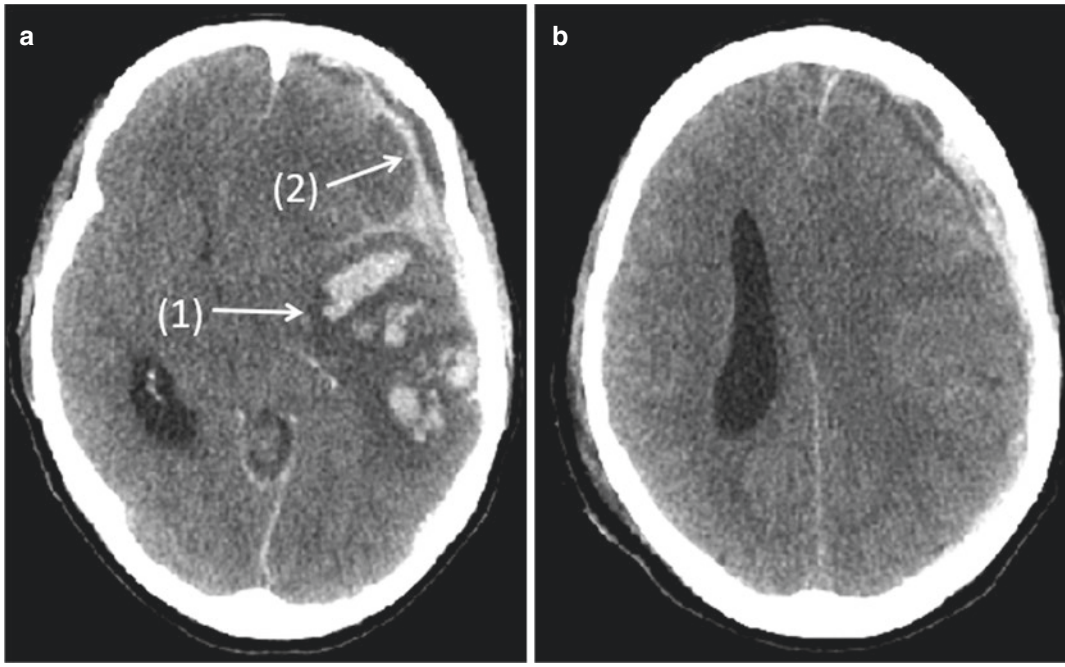



**Fig. 14.7** Intracerebral hemorrhage
Case example of a 54-year-old patient who sustained a fall from a height while rock climbing. The patient sustained multifocal intracranial injuries, including a large intraparenchymal contusion hemorrhage in the left temporal lobe (1), an acute left frontoparietal subdural hematoma (2), and multiple scattered areas of punctuate subarachnoid hemorrhage (panel **a**). The intracerebral contusion hemorrhage led to perifocal brain swelling with left hemispheric edema, complete effacement of the left lateral ventricle, and a significant rightward midline shift (panel **b**)

goal of $PaO_2$ >13 kPa, $PaCO_2$ between 3.3 and 4.5 kPa, and MAP ≥80 mmHg. The historic concept of "blind" prophylactic hyperventilation has been largely abandoned due to inherent the risk of inducing focal ischemic insults. Further aspects of the baseline intensive care for TBI patients include the prevention of hyperthermia, hyperglycemia, and hyponatremia.

For further guidance, the most recent fourth edition of the "Guidelines for the Management of Severe Traumatic Brain Injury" by the Brain Trauma Foundation was published in September 2016, and represents the current evidence-based standard of care [22].

## 14.6 Pharmacological Therapy

Mannitol is used to reduce elevated ICP levels and is typically administered as a 20% bolus (20 g mannitol in 100 mL). Mannitol augments the intravascular volume, increases cerebral blood flow, and diminishes intracranial volume. Classic indications for the application of mannitol include clinical signs of transtentorial herniation (i.e., loss of consciousness, decerebrate rigidity, ipsilateral pupil dilatation, contralateral hemiparesis), or progressive neurological deterioration with decreasing GCS scores. When administering mannitol, serum osmolarity should be kept <315 mOsm/L and hypovolemia must be avoided by adequate fluid replacement. Systemic hypotension is considered a contraindication for mannitol due to the risk of increasing cerebral ischemia. Hypertonic saline in concentrations of 3% or higher represents another therapeutic modality of reducing elevated ICP, and may be a preferrable option in hypotensive trauma patients [29]. High-dose glucocorticoids have been widely used as an empirical treatment of brain edema in TBI patients from the 1960s until 1990s. However, the large-scale prospective randomized, placebo-controlled

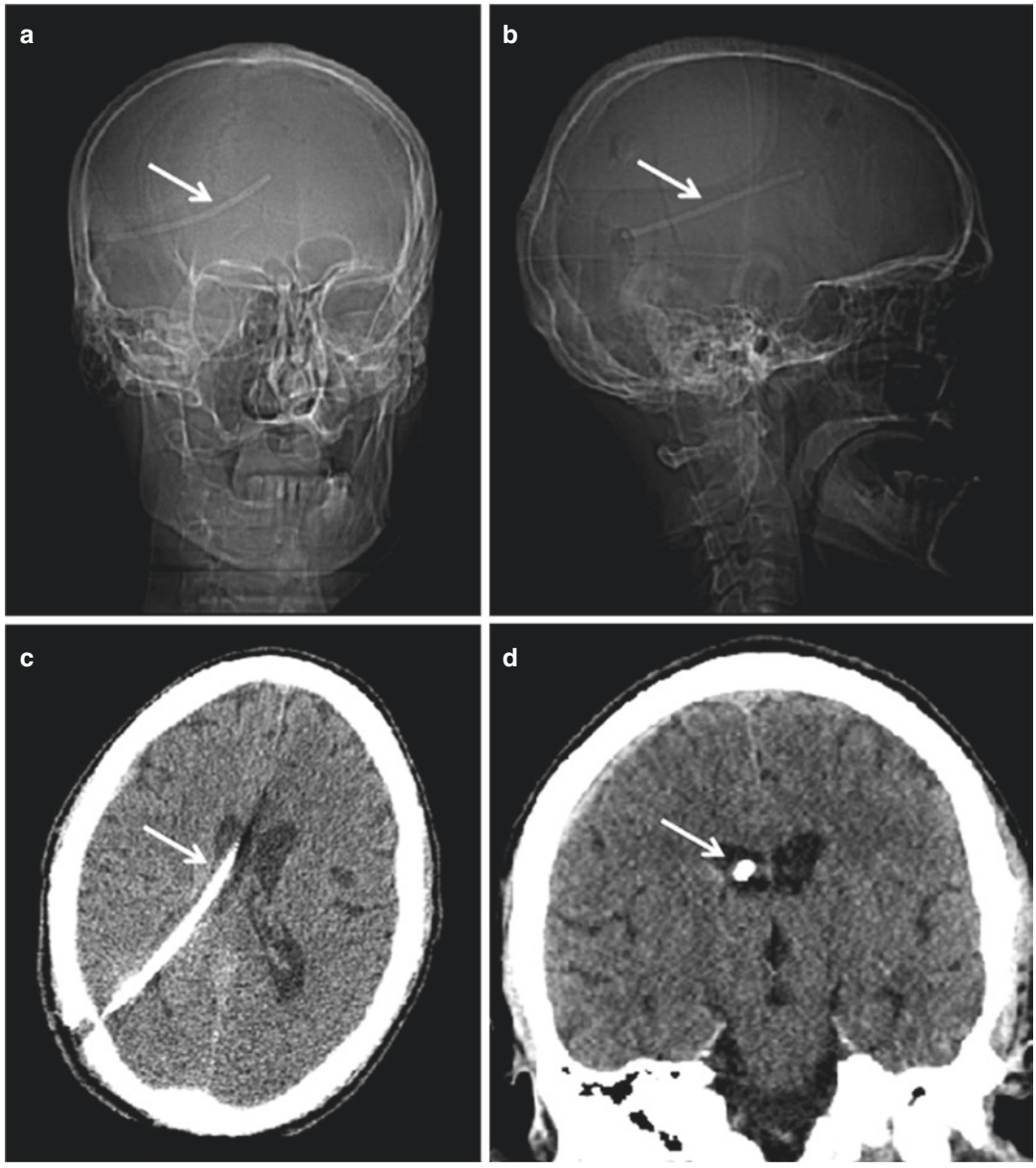



**Fig. 14.8** Intraventricular drain

Case example of a 47-year-old head-injured patient with placement of an intraventricular drain which allows intracranial pressure (ICP) monitoring and therapeutic cerebrospinal fluid drainage for managing increased ICP levels. The arrows demonstrate the intraventricular drain on the CT scout images (panels **a** and **b**) and on the axial (panel **c**) and coronal (panel **d**) non-contrast CT images

multicenter "CRASH" trial (**C**orticosteroid **ra**n-domization **a**fter **s**ignificant **h**ead injury) on 10,008 TBI patients revealed a significantly increased mortality in the steroid group compared to the placebo control group during the first 14 days after trauma (21.1% vs. 17.9%, $P < 0.001$) [30, 31]. Thus, corticosteroids are currently considered obsolete and contraindicated in the pharmacological management of TBI patients. Barbiturates are effective in reducing ICP, however, their use is restricted for intensive care therapy with continuous EEG monitoring [27].

## 14.7 Surgical Management

Surgical indications in patients with TBI include scalp wounds, depressed skull fractures, intracranial mass lesions, and penetrating brain injuries. While scalp wounds can be addressed by a general trauma surgeon, any intracranial lesion is managed by the consulting neurosurgeon.

### 14.7.1 Scalp Wounds

Scalp wounds represent an underestimated source of significant blood loss that can lead to traumatic-hemorrhagic shock. Early control of scalp hemorrhage is therefore imperative by applying direct pressure and bandages. Smaller size scalp wounds can be closed with sutures at the bedside in the emergency room, whereas larger bleeding wounds are best managed in the operating room, which may include ligating or cauterizing larger vessels, if needed. The wounds must be inspected for foreign bodies or depressed skull fractures prior to closure. Presence of CSF implies an open brain injury with a dural tear.

### 14.7.2 Depressed Skull Fractures

Depressed skull fractures should be managed surgically by elevation if the depth of depression is larger than the adjacent skull on CT scan, or if the associated intracranial hematoma requires surgical evacuation (see below).

### 14.7.3 Intracranial Mass Lesions

The specific types of intracranial hematomas associated with severe TBI are depicted in Figs. 14.3, 14.5, 14.6, 14.7. Around one-third of patients with *severe* TBI require emergent surgery for evacuation of mass lesions, most commonly acute subdural hematomas. Of note, even minor lesions in the temporal or posterior fossa may cause compression to the brainstem and obstruction of CSF flow, which place an indication for early surgical intervention. In patients with *mild* or *moderate* brain injuries, a craniotomy is performed for "stable" hematomas on a less urgent basis.

The timing of surgery depends on the clinical condition of the patient, based on the GCS, neurological exam, and CT findings. Surgical hematoma evacuation is typically performed by a craniotomy, whereby the bone flap is replaced by conclusion of surgery. If there is a significant mass effect or swelling of the injured cerebral hemisphere, a decompressive craniectomy is performed, with the bone flap being left off. This helps alleviate elevated intracranial pressure and prevent recurrence of intracranial hematomas. An example of a decompressive craniectomy is shown in Fig. 14.9.

Indications for surgical hematoma evacuation include the following conditions:

- Any type of expanding intracranial hematoma associated with clinical neurological deterioration (GCS) or with >5 mm midline shift (CT) should be evacuated as soon as possible.
- Acute subdural hematoma (SDH) >10 mm thickness ("rule of thumb": larger than the adjacent skull on axial CT scan).
- Acute subdural hematoma (SDH) <10 mm thickness in comatose patients (GCS ≤8) with severe parenchymal injuries and mass effect.
- Acute epidural hematoma (EDH) represents a classic indication for surgical evacuation. Rare exceptions for non-surgical management include patients who are fully awake and alert (GCS 15) with small EDH on initial CT scan. In these selected cases, close clinical monitoring and documentation of clinical findings, in conjunction with short-interval repeat CT scanning, are mandatory to detect worsening hematomas and clinical deterioration, which is associated with dismal patient outcomes.
- Intracranial mass lesions with mass effect and midline shift on CT scan, as well as open or penetrating brain injuries are typically indicated for surgical management by craniotomy/craniectomy with surgical decompression and debridement.

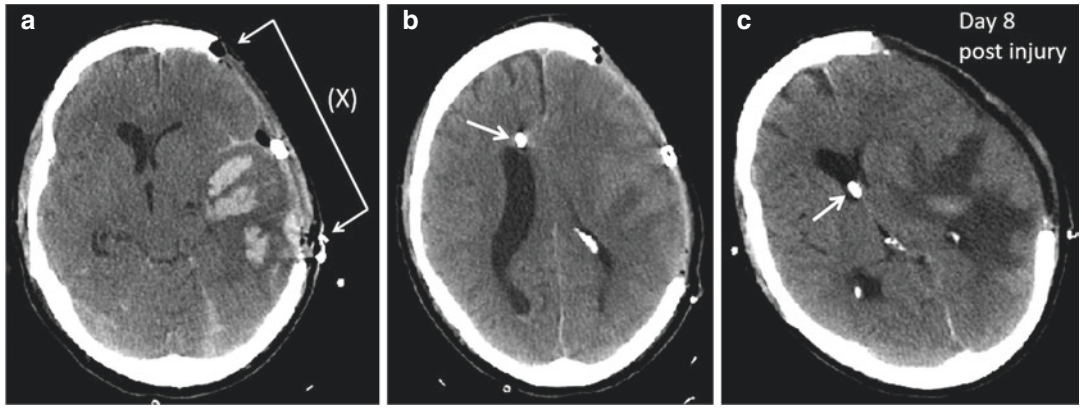



**Fig. 14.9** Decompressive craniectomy
The identical patient as depicted in Fig. 14.8 was taken to the operating room for an emergent left-side decompressive craniectomy (X in panel **a**) and placement of an intraventricular catheter (arrow in panel **b** and **c**). The follow-up CT scan on day 8 post-injury reveals an interval resolution of the intraparenchymal hematoma with residual perifocal edema (panel **c**)

## 14.8 The "Polytrauma Conundrum": TBI with Associated Femur Fracture

Head-injured patients with associated long bone fractures, as classically exemplified by femur shaft fractures, represent a highly vulnerable population due to the risk of sustaining preventable "second hit" insults [32, 33]. The conundrum related to defining the "optimal" timing and modality of long bone fracture fixation in patients with associated head injuries remains a topic of ongoing debate [34]. Early definitive femur shaft fracture stabilization has been advocated by Larry Bone in his historic landmark article from 1989 [35]. However, polytrauma patients with TBI may be highly vulnerable by early definitive fracture fixation due to hemodynamic instability, refractory hypoxemia, or intracranial hypertension. For example, experimental animal studies demonstrated that femoral reaming and nailing lead to increased ICP levels above 15 mmHg in models of hemorrhagic shock/resuscitation with or without associated traumatic brain injury [36, 37]. These data are corroborated by clinical studies that analyzed changes in ICP and CPP in patients with severe TBI who underwent reamed intramedullary nail fixation of associated femur fractures. In this study, the CPP dropped more than 20 mmHg intraoperatively, which was attributed to intraoperative episodes of systemic hypotension during the reaming and nailing procedure [38]. Multiple additional studies have demonstrated that the early definitive femur fracture fixation within 24 h is associated with early episodes of hypoxia and hypotension and adverse neurological outcomes in TBI patients. In order to avoid the adverse effects or "early total care" (ETC) on the vulnerable brain, the concept of "damage control orthopaedics" (DCO) has been advocated by applying a staged approach of initial temporizing external fixation and delayed definitive fracture fixation of femur shaft fractures, as a preferred "neuroprotective" modality for polytrauma patients with TBI (Fig. 14.10) [32, 33].

When compared to ETC, the "damage control" approach with delayed conversion to definitive care has been shown to decrease the initial operative time and intraoperative blood loss without increasing the risk of procedure related complications, such as infection and non-union. The subsequent procedure after DCO related intramedullary reaming and nailing of femur shaft fractures should be performed outside of

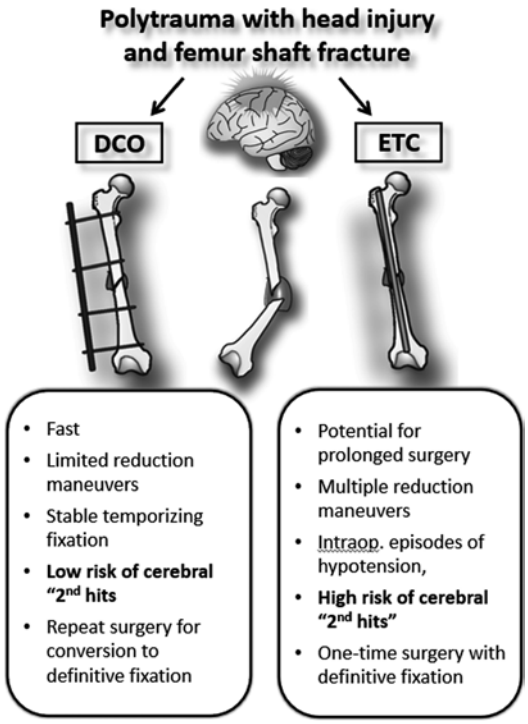



**Fig. 14.10** Management strategies for femur shaft fractures in polytrauma patients with TBI
(See text for details)
Abbreviations: *DCO* Damage control orthopedics, *ETC* Early total care

the neuroinflammatory "priming" window, once the post-injury hyperinflammatory response has subsided, ideally within less than 2 weeks of the initial procedure [39]. The delayed conversion procedure is considered safe once the ICP has normalized and patients are awake, oriented, and fully resuscitated.

## 14.9 Conclusion

Polytrauma patients with head injuries are at risk of sustaining "second hit" cerebral insults which contribute to secondary brain injury and adverse outcomes. The standardized ATLS® approach to the initial assessment and management assures the stabilization of vital functions with the aim of preventing episodes of hypoxemia and hypotension. The presence of intracranial lesions or a deteriorating neurological exam mandates early neurosurgical consultation to assure the optimized coordination of care with the aim of improving long-term outcomes in a highly vulnerable patient cohort.

**Key Concepts**

The following decision-making strategy represents a "key concept" in terms of providing a pragmatic and safe approach for stratifying polytrauma patients with TBI and associated femur shaft fractures "at risk" for adverse outcomes [32, 33].

- "Damage control orthopaedics" by spanning external fixation in all patients with *severe* TBI (GCS ≤8, intracranial pathology on CT scan, including cerebral edema, midline shift, sub-/epidural bleeding, or open head injuries).
- Optional "damage control orthopaedics" in all patients with *moderate* TBI (GCS 9–13), or patients with GCS of 14/15 with "minor" intracranial pathology on CT scan (e.g., traumatic subarachnoid hemorrhage that warrants observation only). Concomitant neurosurgical procedures may be performed at the same time as DCO, e.g., an emergency craniotomy.
- No additional operations ("second hit!) in patients with refractory intracranial hypertension or unexplained deterioration in neurologic exam.
- Conversion from external to internal fixation in TBI patients who recovered from a comatose state and are awake and alert (GCS 13–15), or comatose patients with a stable ICP (<20 mmHg) and CPP in a normal range (>80 mmHg) for more than 48 h.
- "Early total care" for long bone fractures all patients with *mild* TBI (GCS 14/15) and normal initial craniocerebral CT scan.
- Temporary skeletal traction as a valid adjunct for patients "in extremis," i.e., in severe protracted traumatic-hemorrhagic shock and coagulopathy, who are unsafe to be taken to the operating room until adequately resuscitated.

**Take Home Messages**

- Polytrauma patients with TBI represent a highly vulnerable patient cohort due to the imminent risk of inflicting a "second hit" insult to the brain related to episodes of hypotension and hypoxemia.
- The primary goal of managing polytrauma patients with TBI is to prevent secondary brain injury. The most important aspect of preventing secondary brain damage is to ensure adequate oxygenation and blood pressure maintenance by managing the trauma patient per ATLS® protocol.
- Secondary brain injury evolves over time and is characterized by neuroinflammation, cerebral edema, breakdown of the blood–brain barrier, evolving intracranial hematomas, increased intracranial pressure and decreased cerebral perfusion pressure, and ultimately delayed (preventable) secondary neuronal cell death.
- A traumatic epidural hematoma represents a neurosurgical emergency which is frequently underestimated due to a lucid interval in awake and oriented patients with the imminent risk of rapid subsequent deterioration ("patients who talk and die").
- Obtaining a head CT scan in TBI patients should never delay the transfer to an appropriate trauma center capable of managing severe TBI by immediate neurosurgical intervention.

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# 15 Chest Trauma: Classification and Influence on the General Management

Ümit Mert, Hagen Andruszkow, and Frank Hildebrand

**Learning Goals**

- Causes and incidence of thoracic injuries after severe trauma
- Impact of chest trauma on the development of posttraumatic complications and mortality
- Pathophysiologic changes associated with blunt chest trauma
- Diagnostic strategies after chest trauma
- Therapeutic management of thoracic injuries
- Impact of chest trauma on surgical strategies

## 15.1 Introduction

Trauma represents one of the most common reasons for death, particularly in the younger population, throughout the world. Therefore, prompt diagnosis and treatment of the large variety of injury patterns are of the upmost importance. Among the different body regions, the chest represents one of the most commonly affected [1].

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The vast majority of thoracic injuries are caused by blunt trauma, whereas penetrating injuries only account for around 10% of thoracic injury cases. Chest trauma mainly appears as a result of falls, violence, or traffic accidents within the first four decades of life [2].

Isolated blunt chest trauma usually occurs after a moderate traumatic impact, whereas thoracic injuries in the context of polytrauma are caused by high-energy trauma [3, 4]. In general, chest trauma is characterized by injuries (e.g., thoracic bruises and rib fractures) that can be treated conservatively in the vast majority of cases. Still, even in young adults with isolated chest trauma, a mortality rate of 0%–5% is described, with an increase to 10%–15% in the elderly population [5–7]. In this context, geriatric patients aged ≥85 years, with an initial blood pressure <90 mmHg and specific injuries (hemothorax, pneumothorax, serial rib fracture, and pulmonary contusion), have been identified as a population at high risk for the development of posttraumatic complications and an adverse outcome [8]. Given that these specific high-risk groups are particularly endangered by their increased vulnerability to a fatal outcome, an early and accurate diagnosis as well as an adequate treatment of chest trauma is crucial to avoid morbidity and mortality [9–11].

In 80%–90% of cases, severe chest trauma is associated with concomitant injuries [12]. Therefore, thoracic injuries represent one of the


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most common diagnoses in severely injured patients [1]. In addition to the significant clinical implications in the acute posttraumatic phase, severe chest trauma also has a major impact on the later clinical course. In this context, a significant increase in ventilation time and prolonged intensive care treatment has been observed [1]. Furthermore, chest trauma has been shown to result in higher incidences of acute respiratory distress syndrome (ARDS), systemic inflammatory response syndrome (SIRS), multiple organ dysfunction syndrome (MODS), and infectious complications (pneumonia) compared with severely injured patients without severe chest trauma [7, 13–15]. Therefore, chest trauma is one of the most common reasons for fatality among polytrauma patients; it is responsible for approximately 25% of deaths after multiple trauma. In patients with combined chest trauma and severe traumatic brain injury (TBI), even mortality rates of more than 70% have been described [5–7, 13, 16, 17]. Furthermore, 50%–75% of deceased polytraumatized patients had thoracic injuries. Besides severe blood loss and hypoxia, this chest-trauma-related increase in posttraumatic complications might also be partly explained by an enhanced inflammatory response that has especially been described after pulmonary contusions [5–7, 13, 16–18]. Due to this complex character of chest injuries, constant research and effort to cope with its causes and impacts are continuously required.

## 15.2 Injuries After Chest Trauma

According to current clinical studies, chest trauma seems to be responsible for approximately 25% of deaths after multiple trauma. Specific risk factors, such as increasing age (>65 years), preexisting diseases, and serial rib fractures, have been particularly associated with enhanced mortality even after isolated chest trauma [19–21]. One possible explanation for this significant impact is the effect of chest trauma on the physiology of the thoracic wall and the intrathoracic organs (e.g., pleura, diaphragm, lungs, mediastinum, and the great blood vessels).

Among thoracic injuries, rib fractures are known to represent one of the most common injury patterns after chest trauma, especially in geriatric patients. They are frequently associated with additional injuries, such as pneumothorax, hemothorax, lung contusions, or lacerations. Indeed, hemothorax (21.8%), pneumothorax (59.1%), and pulmonary contusion (50%) can be regularly found after relevant chest trauma. In case of severe hemothorax, cardiac tamponade, and tension pneumothorax, emergency diagnoses and treatment are required to avoid life-threatening complications [22, 23].

### 15.2.1 Chest Wall Injuries

Rib fractures account for the majority of thoracic injuries and are found in up to 85% of patients with blunt chest trauma. Either a single rib or multiple ribs can be fractured simultaneously, whereby the morphology of rib fractures (e.g., segmental fractures) reflects the trauma intensity [24, 25]. In general, rib fractures can result in pleural or pulmonary lacerations with the development of pulmonary contusions, hematoma, hemothorax, and pneumothorax. Ribs IV–X are typically affected; however, if the first two ribs are fractured, a particularly severe traumatic impact must be assumed. These two ribs are anatomically close to vital structures, and thus lesions of the brachial plexus and different vessels (e.g., subclavian artery and vein) may occur. Lung contusions are also likely. Fractures of the lower ribs are mainly caused by a direct local impact.

In the younger trauma population, rib fractures are usually caused by a severe traumatic impact and are frequently associated with pulmonary contusions. In elderly patients, however, minor trauma also regularly results in rib fractures due to decreased bone elasticity and osteoporosis. In these patients, the fracture-related pain often results in a reduction of breathing depth with subsequent fluid retention and associated pulmonary complications, such as pneumonia and atelectasis. In older patients, each additional rib fracture increases the probability of

death by 19% and the incidence of pneumonia by 27% [26, 27].

In cases of serial rib fractures, at least three ribs of one or both thoracic cavities are concerned. In more than 90% of these cases, multiple rib fractures are associated with concomitant injuries, such as TBI, extremity, or abdominal trauma (e.g., liver, spleen, and kidneys). Besides the impaired respiratory function due to the reduced stability of the chest wall, these additional injuries are likely to be the reason for the increased morbidity and mortality of serial rib fractures compared with a single fractured rib [25, 26, 28].

Flail chest is found in about 15% of patients with blunt chest trauma [29]. Flail chest is defined as at least two fractures per rib in at least two ribs. This results in a segment of the chest wall that is separated from the rest of the thoracic cage. A separated segment of the chest wall cannot contribute to lung expansion and is associated with paradoxical breathing (inward motion during inspiration and outward motion during expiration). Posterior flail segments are stabilized by overlying muscles as well as the scapula and therefore may not cause severe complications. By contrast, anterior and lateral flail segments are mobile and can seriously impair respiratory function. Due to this restricted ventilation, pneumonia rates of 40% and an increased mortality have been described for patients with flail chest [30].

Sternal fractures are seen in about 5% of patients with chest trauma [31]. Most fractures involve the upper- or mid-part of the sternum. Sternal fractures are frequently accompanied by pulmonary and myocardial injuries, as well as fractures of the thoracic spine. In 95% of the cases, conservative treatment is reported to be sufficient. This includes rest, passive reduction of dislocation, corset fixation, and, especially, analgesia in order to prevent pulmonary complications [32–34].

Sternoclavicular dislocations may occur either in the anterior or the posterior direction. Posterior dislocations are more severe, as they can result in injuries of mediastinal blood vessels, as well as in tracheal or esophageal damage [35]. In general, the more common anterior dislocations can be treated conservatively, whereas posterior dislocations usually require closed or surgical reduction.

Due to the close anatomical relationship, chest trauma is frequently accompanied by clavicular fractures. In particular, a high coincidence of clavicular fractures and specific thoracic injuries (hemothorax, pneumothorax, and lung contusions) has been described. Furthermore, clavicular fractures have been associated with injuries to the upper extremities and the cervical spine, as well as a higher overall injury severity in multiple-trauma patients. Therefore, clinical and radiologic diagnostics are recommended to specifically focus on these body regions in the case of a clavicular fracture [36, 37].

With a prevalence of approximately 4%, scapular fractures are quite uncommon in severely injured patients [38]. Similar to clavicular fractures, scapular lesions are frequently associated with other injuries, such as pneumothorax, hemothorax, and pulmonary and spinal injuries [39]. Most fractures affect the body and neck of the scapula and can be treated conservatively. By contrast, displaced intraarticular glenoid fractures and displaced juxta-articular fractures require a surgical intervention [39, 40].

## 15.2.2 Injuries of the Intrathoracic Organs

### 15.2.2.1 Pleural Injuries

A pneumothorax occurs in 15%–40% of patients with chest trauma [41–43]; it is defined as a collection of air in the chest or pleural space that might result in a partial or entire collapse of the lung. Leading symptoms are a unilateral breath sound and tissue emphysema, which might be caused by either pleural laceration due to fractured ribs (closed pneumothorax) after blunt trauma or by penetrating injuries (open pneumothorax) [31]. Lesions of the tracheobronchial tree might also result in a pneumothorax. In accordance with the Advanced Trauma Life Support (ATLS) guidelines, standard anterior-posterior (ap) chest radiography is distinguished as the gold standard for the primary assessment of chest

injury in trauma patients. Any pneumothorax that cannot be seen on a preceding plain chest X-ray, but that is visible on a computed tomography (CT), is called an "occult pneumothorax" (OPX). 52%–63% of traumatic pneumothoraxes fall into the OPX category. If tension emerges, OPXs can be life threatening, especially if ventilation is required. With an increasing use of CT scans, OPX detection has accordingly increasing [44–47].

In case of a pneumothorax in which air enters the thoracic cavity and is captured during the process of exhalation, a tension pneumothorax can develop. This results in a collapse of the ipsilateral lung with subsequent compression of the mediastinum and the contralateral lung. A suspected tension pneumothorax (distension of jugular veins, unilateral breath sound, and tissue emphysema) must be decompressed immediately by needle thoracostomy or a chest tube.

A hemothorax is found in about 20%–40% of patients with blunt thoracic trauma. It results from vascular lesions by accumulation of blood in the pleural cavity after blunt or penetrating trauma. In this context, a hemothorax can be caused by diverse bleeding sources, such as intercostal arteries, internal mammary arteries, lung parenchyma, and the heart, as well as the lung hila and the great vessels. Detection of a hemothorax usually requires a blood volume of at least 175 mL if conducted via chest radiography or 20 mL in case of ultrasonography [48]. A hemothorax can lead to a tension hemothorax with ipsilateral lung compression and subsequent displacement of the mediastinum [31]. Therefore, any relevant hemothorax (cut-off size: 3 cm) should be drained by a chest tube. For smaller hemothoraces, drainage should only be considered if coexisting findings are present, such as pneumothorax [49]. A chronic hemothorax can be complicated by pleural empyema or a fibrothorax that might result in a restrictive pulmonary disease [18]. A lesion of the thoracic duct can result in the development of a chylothorax. A rupture of the upper part of the thoracic duct is associated with a left-sided chylothorax. Lesions that cross the midline of the lower parts of the thoracic duct results in a right-sided chylothorax.

#### 15.2.2.2 Diaphragm Injuries

A diaphragmatic rupture can result either from blunt thoracic trauma (0.2%–5%) or, more frequently, from penetrating injuries (10%–19%). The outcome can be fatal if the pleural cavity is entered by an abdominal hollow viscus organ or the omentum and causes incarceration or strangulation [50–52]. With an incidence of 88%–95%, ruptures on the left side are three to four times more common than lesions on the right side. In 5%–10% of cases with diaphragmatic injuries, there is a bilateral rupture [18]. The right side is protected by the liver and thus distinctly less affected.

Patients can remain without symptoms for years after trauma, and thus a large number of diaphragmatic ruptures are missed during the initial examination [18], leading to a mortality rate of up to 30%–60%, or in case of strangulation of up to 80% [53]. In addition, radiographic signs of diaphragmatic injury might be overlooked due to the fact that obvious thoracic and abdominal injuries attract the complete attention. Nevertheless, multidetector CT (MDCT) still represents the gold standard in order to detect diaphragmatic injury [54–56].

In case of a traumatic rupture, surgery should be contemplated, especially when symptoms are present, such as chest pain, chronic dyspnea, recurrent abdominal pain, vomiting, development of respiratory failure, and obstructive gastrointestinal complications [57, 58].

#### 15.2.2.3 Lung Injuries

Parenchymal lung injuries appear as pulmonary contusions and lacerations. Pulmonary contusions represent one of the most frequent injuries in thoracic trauma patients [18]; they are associated with an increase in morbidity and mortality. It is assumed that pulmonary contusion can be found in 30%–75% of thoracic trauma patients [59]. Pulmonary contusions are caused by either direct trauma to the pulmonary parenchyma or by indirect mechanisms, such as deceleration and shear forces. Lesions usually occur in peripheral lung sections that are adjacent to bony structures [53]. Pulmonary contusions regularly appear 3–6 h after trauma and generally resolve within

5–7 days [53, 60]. These injuries are histopathologically characterized by blood extravasation and edema in the interstitial and alveolar spaces. Especially in younger patients, pulmonary contusions can also be found without accompanying osseous lesions [61, 62]. However, serial rib fractures and flail chest are commonly associated with pulmonary contusions [63].

Pulmonary lacerations are characterized by a disruption of the parenchymal architecture. With the exception of stab wounds, lung lacerations are always accompanied by pulmonary contusions [64]. Pulmonary contusions and lacerations can be complicated by the development of ARDS, which is a respiratory failure that often already emerges in the early posttraumatic phase within the first 24 hours after trauma [65, 66]. ARDS is a pathophysiological consequence of a systemic inflammatory response after chest or general trauma and caused by the damage of the alveolar-capillary barrier by activated neutrophils resulting in an extravasation of fluid into the alveolar space [67, 68]. This systemic inflammatory response can also affect primarily uninjured pulmonary sections [62, 69]. Based on radiographs, ARDS manifests as a diffuse bilateral pulmonary infiltration [60]. Diverse trauma-related predictive models have been suggested for early prediction of ARDS [70–72]. In this context, age, Acute Physiology and Chronic Health Evaluation (APACHE) II score, injury severity, blunt trauma mechanism, pulmonary contusion, massive transfusion, and flail chest have been associated with an increased risk of ARDS [70].

#### 15.2.2.4 Injuries to the Mediastinum

A pneumomediastinum (mediastinal emphysema) may occur in association with pharyngeal, tracheobronchial, or esophageal lesions after either penetrating or blunt trauma. Besides chest radiography, diagnostics should include esophageal and tracheobronchial endoscopy.

With an incidence of 0.5%–2%, traumatic tracheobronchial injuries are rather uncommon but often accompanied by pulmonary or vascular injuries [40, 41]. Bronchial ruptures are found more often on the right side. This observation can be explained by the different anatomic positions of the two main bronchi. In contrast to the right side, the left main bronchus is surrounded and stabilized by the major vessels. In addition, the right main bronchus is susceptible to the higher weight of the right lung. About 19% of tracheobronchial ruptures emerge in the trachea [73–75]. Tracheal lesions usually appear as transverse tears between the cartilaginous tracheal rings or longitudinal tears in the posterior tracheal membrane. Even though tracheal lesions appear infrequently, they represent the second most common cause for chest-trauma-related mortality among patients who die at the scene of the trauma. In this respect, early detection of tracheobronchial lacerations and immediate stabilization of the airway seem to be crucial to increase survival rates [76, 77]. Airway tears are observed in 0.5%–1.5% of chest trauma patients and potentially result in tension pneumothorax, with 81% mortality. With regard to the diagnostic options, bronchoscopy remains the gold standard to provide the best view of the lesions' extent and location. Tracheobronchial injuries larger than 2 cm require surgical repair to ensure airway continuity [78, 79].

Esophageal injuries after blunt chest trauma are rare. The majority of esophageal lesions are located in the cervical and upper thoracic sections. Depending on their location, esophageal injuries can result in right- or left-sided pleural effusion. In order to avoid subsequent complications, such as edema and infection (mediastinitis), surgical repair is required.

Pericardial injuries (e.g., organ and vascular ruptures) can result in air entrapment (pneumopericardium) or hemorrhagic influx (hemopericardium) into the pericardial cavity with an enlargement of the mediastinum. Mediastinal widening is diagnosed in case of a diameter >8 cm and a mediastinum-to-chest ratio >0.25. A hemopericardium may be complicated by the development of pericardial tamponade with increased pericardial pressure and subsequent hemodynamic instability. In particular, lesions of the intrapericardial aorta and left cardiac ventricle endanger the patients, whereas bleeding of the atrium or right ventricle may not cause noticeable symptoms. The majority of pericardial tam-

ponade occur after penetrating trauma, but also appear in about 1% of blunt chest trauma patients [18, 31]. Immediate pericardiocentesis is indicated for restoration of normal cardiovascular function [80, 81].

Cardiac injuries are observed in 15%–25% of patients with chest trauma [82]. The incidence increases to 75% in cases of sternal fractures, parasternal rib fractures, and diaphragmatic ruptures [83]. Detection of these injuries might be difficult due to its nonspecific nature: The symptoms might be misinterpreted and ascribed to a chest wall contusion. Cardiac trauma can become apparent as coronary artery injury (left anterior descending artery affected in two thirds of the cases) with myocardial ischemia, valve injury, and, especially, myocardial contusion or rupture [84, 85]. Myocardial contusions occur due to rupture of the intramyocardial vessels and can result in structural injuries and functional changes. Structural injuries include perforation of cardiac muscles or the ventricular septum, as well as disruption of the papillary muscles and valves [18]. Furthermore, arrhythmias may arise as a functional complication following myocardial contusion. Cardiac aneurysms are focal evaginations of the septal or ventricular walls. True aneurysms frequently appear in the left ventricular anterior wall or at the apex after severe blunt trauma. Cardiac pseudoaneurysms typically occur after penetrating trauma and are usually located in the left ventricular posterolateral wall. Cardiac ruptures frequently affect the right ventricle due to its thin wall and its anatomical position in the thoracic cavity. Severe torsion forces can also cause a cardiac avulsion with separation of the heart from the great vessels.

Traumatic aortic injuries include a spectrum of lesions due to severe deceleration trauma and most frequently affect the aortic isthmus, where the mobile thoracic aorta joins the fixed arch and the insertion of the ligamentum arteriosus [86], followed by the aortic root and the diaphragmatic aorta. Traumatic aortic ruptures occur in 2% of patients with blunt chest trauma. In approximately 90% of cases, complete aortic ruptures are fatal at the scene of the accident. They can only be survived in cases of pseudoaneurysm formation with containment of active bleeding by the aortic adventitia, a thrombus, or mediastinal structures. Traumatic aortic dissections are characterized by intimomedial tears. Type B (descending aorta) dissections can be treated conservatively, whereas Type A (ascending aorta) dissections require surgical repair due to the risk of pericardial bleeding, coronary artery laceration, and aortic valve rupture. Traumatic aortic aneurysms are focal dilatations that include the entire aortic wall, and these aneurysms are at risk of rupture. Open surgery should be performed in aneurysms of the ascending aorta that are symptomatic, rapidly expanding, or >5.0–5.5 cm in diameter. In aneurysms of the descending aorta exceeding 6.0 cm, repair by endovascular stent-grafting is recommended.

The Society for Vascular Surgery introduced a similar approach for classification; it categorizes blunt thoracic aortic injuries into four categories. Grade I and II are characterized by an intimal tear and aortic wall hematoma with conservative treatment being sufficient. Grade III (pseudoaneurysm of the aortic wall) and Grade IV (free rupture of the thoracic aorta) require surgery [75, 87, 88].

Injuries of the great intrathoracic vessels are only found in 1% of blunt chest trauma patients [18, 31], but in more than 90% of patients with penetrating trauma. After blunt trauma, injuries are mainly caused by deceleration mechanisms and predominantly affect aortic branch vessels and the superior or inferior vena cava, as well as pulmonary veins.

### 15.2.3 The Deadly Dozen

Among the aforementioned thoracic injuries, 12 typically life-threatening injuries have been identified that have been called the "deadly dozen." These injuries are divided into the lethal six and the hidden six. The lethal six—acute airway obstruction, tension pneumothorax, pericardial tamponade, open pneumothorax, massive hemothorax, and flail chest—are immediately life-threatening injuries; they must be promptly identified and treatment must be initiated during

the primary survey. The hidden six—aortic rupture, myocardial contusion, tracheobronchial injuries, diaphragmatic rupture, esophageal rupture, and pulmonary contusion—represent injuries that are easily missed. They must be identified and treatment must be initiated during the secondary phase [89].

### 15.2.4 Pediatric Chest Trauma

Besides TBI, severe chest trauma is also found in pediatric patients as one of the most frequent reasons for morbidity and mortality after severe trauma. Pediatric chest trauma alone is associated with a 5% mortality rate, with a significant increase when there are relevant concomitant injuries. In this context, combined abdominal trauma has resulted in a mortality rate of 25%, whereas additional TBI has been associated with an increase of up to 40%. In contrast to the adult anatomy, the pediatric chest wall is more elastic. Therefore, the energy of the external impact is absorbed by the pliable thorax and passes through the lungs and other surrounding vital organs. Thereby, organ injuries might be induced without affecting the thoracic cage (e.g., no rib fractures). Therefore, a focused pediatric trauma care protocol as defined by the ATLS guidelines is recommended to consider the particularities of pediatric trauma patients [90–94].

## 15.3 Diagnostics

The correct diagnosis of thoracic injuries, as well as prompt assessment of the severity of chest trauma, is crucial for the further clinical course and outcome. Different diagnostic tools are available in the clinical routine, such as plain chest X-ray, CT, thoracic ultrasonography, bronchoscopy, and three-dimensional (3D) printing for planning surgical stabilization of rib fractures. 3D printing has been supposed to be particularly reliable for the identification of intrathoracic injuries after trauma. New bedside techniques, such as electrical impedance tomography (EIT), have the potential to determine the local distribution of lung ventilation by measurements in various body positions [95].

### 15.3.1 Plain Chest X-Ray

Plain chest X-ray is a frequently used diagnostic tool to detect thoracic injuries [96]. In the clinical routine, chest X-rays are performed in the AP and lateral directions of the upright sitting patient in full inspiration. However, in multiple-trauma patients, plain chest radiography must be obtained in the supine position and, therefore, only in the AP direction. Given that a lateral view is not possible under these circumstances, the superimposition of different structures and organs in the ap plane exacerbates the interpretation, thereby limiting the diagnostic value [97]. In addition, pulmonary contusions are frequently either missed or underestimated by chest radiography, especially in the early posttraumatic phase at admission [98–103]. Furthermore, evaluation by X-ray might be impaired by the contraction of the surrounding muscles, thereby foiling the detection of a rib fracture [104].

### 15.3.2 Computed Tomography

The deficits of plain chest X-ray for the diagnosis of thoracic injuries can be compensated by a CT scan, which represents the most important examination method in chest trauma patients [97]. A thoracic CT scan is superior to conventional chest radiography [41, 102, 105] because of its greater sensitivity and specificity. CT can identify rib fractures and other thoracic injuries, such as pulmonary contusion, pneumothorax, and vascular injury [105, 106]. However, there is an ongoing discussion about whether this additional information changes the treatment strategy [107, 108]. Marts et al. [102] reported a change in clinical management in only 6.5% of patients with chest trauma. In another study, CT had been credited with changing the treatment in up to 20% of chest trauma patients [109]. Further studies found therapeutic changes in 30%–70% of the cases due to a CT-related amendment of diagnostic informa-

tion [110–112]. However, a longer duration of time in the emergency department, higher costs, increased risk of cancer due to radiation exposure, and limited availability in low developed countries are the downsides of CT [113–115]. In general, a chest CT scan (*pro re nata* as part of a whole body CT) is recommended in all trauma patients with multiple injuries, suspected chest trauma, abnormal findings in the initial chest X-ray, and in cases of respiratory insufficiency [112, 116, 117].

### 15.3.3 Thoracic Ultrasonography

Ultrasound examinations represent a non-invasive diagnostic tool that offers several advantages, including efficiency, general availability, low procedural time/effort, and the possibility of repeated examinations [118, 119]. With a sensitivity of 81% for the detection of intrathoracic fluid [120], ultrasonography represents a reliable tool for the diagnosis of hemothorax [121]. Furthermore, with a sensitivity of 92%–100%, thoracic ultrasound examinations also seem to be suitable for the detection of pneumothoraces [118, 122–124]. Ultrasonography also seems to be superior in the detection of pleural compared with X-ray [125].

As a potential disadvantage, subcutaneous emphysema aggravates an accurate diagnosis by ultrasound [120]. In addition, evaluation of bony lesions, especially without relevant dislocation, as well as tube and line malpositioning, remain the domain of radiographic diagnosis. Therefore, ultrasound examination cannot be used as an exclusive diagnostic procedure. It has greater utility as a supplement to the diagnostics of chest trauma. In addition, operators will need a certain degree of experience and expertise [115].

### 15.3.4 Bronchoscopy

Bronchoscopy represents both a diagnostic and a therapeutic tool. It is of particular value for the diagnosis of tracheobronchial lesions, supraglottic injuries, aspiration, bleeding, and lung contusions [126]. In addition, early diagnosis and assessment of the severity of lung contusions are supposedly more reliable by bronchoscopy than by conventional chest radiography [127]. Besides its diagnostic use, bronchoscopy is also a therapeutic tool (e.g., clearance of the respiratory tract, prevention of atelectasis formation, and bleeding control). Despite these advantages, indications for bronchoscopy in the acute phase after trauma are rare (e.g., severe bleeding and tracheobronchial ruptures). Given that bronchoscopy also has the potential to enhance respiratory insufficiency [128], it cannot be considered as a routinely used tool in primary diagnostics of multiple-trauma patients.

### 15.3.5 3D Printing for Surgical Stabilization of Rib Fractures

Chen et al. [129] conducted a study in which they utilized 3D printing as a supportive tool for preoperative planning. They used CT images to determine the shape of the patient's bony structures. Subsequently, they printed a 3D model to visualize the patient's rib cage. That endeavor, in turn, allowed them to obtain an exact measurement of length, shape, and curve of the titanium plates that they intended to implement during surgery. Thereby, preoperative planning is facilitated, operation time is shortened, and patients and their relatives are empowered to seize a better understanding of the surgical interventions [129]. However, more research about 3D printing in the field of surgical stabilization of rib fractures is needed. Indeed, it has yet to be clarified how this method can be applied in a timely manner during critical emergency situations [130, 131].

## 15.4 Classification

The evaluation of injury severity and the prediction of outcome are an important function of scoring systems. Early assessment of severe chest trauma is decisive for the clinical course of multiple-trauma patients, such as timing and kind

of surgical interventions (early total care vs damage control), and early and adequate therapy of the chest trauma itself is crucial to avoid posttraumatic complications [5, 7, 18]. Thereby, resources (e.g., length of hospital stay) can be managed efficiently based on prognostic abilities.

Several scoring systems for the classification of blunt chest trauma have been developed, e.g., the Abbreviated Injury Scale (AIS), the Pulmonary Contusion Score (PCS) by Tyburski et al. [132], the CT-dependent Wagner Score [133], and the Thoracic Trauma Severity Score (TTS) in case of isolated thoracic trauma [134, 135]. Most of these scores are based on pathological-anatomical changes. Some scoring systems, such as the TTS, also include physiological parameters [136]. One of the most commonly used scoring systems is the Thoracic Abbreviated Injury Scale ($AIS_{chest}$).

### 15.4.1 Abbreviated Injury Scale

The AIS, first described in 1969 by John D. States and revised in 1998, is an anatomical scoring system that allocates a severity score to every injury of different body regions (head, face, neck, thorax, abdomen, spine, upper extremity, lower extremity, external, and other trauma). The score ranges from 0 to 6, where high severity scores are associated with a lower probability of survival. The AIS represents the basis for calculating the Injury Severity Score (ISS). In general, the AIS correlates with mortality [137, 138], and the $AIS_{chest}$ has been demonstrated to be an independent predictor for prolonged hospitalization [139, 140], duration of mechanical ventilation [141], and a risk factor for the development of posttraumatic MODS [142].

### 15.4.2 Pulmonary Contusion Score

The PCS was developed in 1999 by Tyburski and colleagues [132]. This score is based on a plain chest X-ray at the time of admission and 24 h after trauma. After separation of the lung into an upper, middle, and lower third, pulmonary contusions in each third are assessed by a value of 1–3. The sum of these values represents the PCS. A PCS value of 1–2 is classified as mild, a value of 3–9 as moderate, and a value of 10–18 as severe pulmonary contusion (Table 15.1). An increased severity of lung contusion over the first 24 h has been associated with a higher mortality rate and a prolonged duration of mechanical ventilation [132]. The PCS has been criticized due to the weaknesses of the assessment of pulmonary contusions by plain chest X-ray.

### 15.4.3 Computed Tomography-Dependent Wagner Score

Wagner and Jamieson developed a chest trauma score based on a CT scan [133]. In this score, the severity of chest trauma is classified according to the volume of pulmonary lesions (Fig. 15.1). Pulmonary lesions with ≥28% total air space are classified as grade 1, 19–27% as grade 2, and <19% as grade 3. The authors showed an association between the size and type of parenchymal injuries and the need for mechanical ventilation [133].

**Table 15.1** Pulmonary contusion score by Tyburski et al. [132]

| Calculation of the Pulmonary Contusion Score (PCS) | | |
|---|---|---|
| • Dividing the lung fields into upper, middle and lower third | | |
| • Assigning a score of 1–3 to each region on the basis of the amount of radiologic parenchymal changes | | |
| Mild pulmonary contusion | Moderate pulmonary contusion | Severe pulmonary contusion |
| PCS 1–2 | PCS 3–9 | PCS 10–18 |

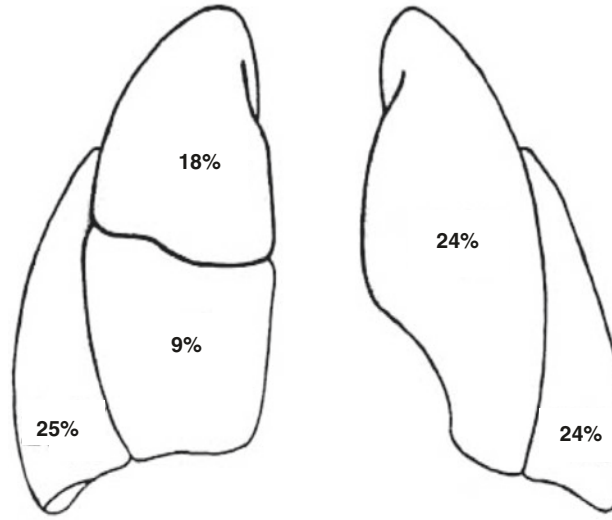


**Fig. 15.1** Computed tomography-dependent score according to Wagner and Jamieson [133]

**Grad 1**

- ≥ 28% of total air space consolidated or lacerated
- all patients require mechanical ventilation for pulmonary insufficiency

**Grad 2**

- 19–27% of total air space consolidated or lacerated
- 60% of these patients require mechanical ventilation for pulmonary insufficiency

**Grad 3**

- < 19% of total air space consolidated or lacerated
- no mechanical ventilation required for pulmonary insufficiency

### 15.4.4 Thoracic Trauma Severity Score

The TTS is a CT-independent scoring system that is based on the combination of five anatomical and physiological parameters at the time of admission: extent of pulmonary contusion, number of rib fractures, pleural lesions, age, and $PaO_2/FiO_2$ (Horowitz) ratio [136]. Each parameter is assigned a value of 0–5 (Table 15.2), and the TTS score ranges from 0 to 25.

The sensitivity and specificity of the different scoring systems for predicting posttraumatic complications and the outcome have not been fully elucidated. In general, CT-dependent scores are thought to be more reliable for the assessment of trauma severity and susceptibility to posttraumatic complications (e.g., ARDS) and thus in predicting the outcome of a blunt chest trauma. By contrast, CT-independent scoring systems might be helpful for early evaluation of the risk profile at admission after chest trauma. However, it has been suggested that these scores should be based on anatomical and physiological parameters due to the limited diagnostic value of conventional chest X-ray. A study recently analyzed the predictive value of the PCS, the Wagner score, and the TTS [143]: The TTS best predicts ARDS, MODS, and in-hospital mortality in multiple-trauma patients [143].

## 15.5 Treatment

Severe chest trauma represents the second most common diagnosis in multiple-trauma patients [1, 12]. Thoracic injuries must be treated according to established guidelines (e.g., the ABCDE algorithm according to the ATLS). In this context, chest trauma is sufficiently treated by airway control (e.g., intubation) and treatment of breathing and ventilation problems (e.g.,

**Table 15.2** Thoracic trauma severity score by Pape et al. [136]

| Grade | $PO_2/FiO_2$ | Rib fractures | Pulmonary contusion | Pleural lesion | Age (years) | Points |
|---|---|---|---|---|---|---|
| 0 | >400 | 0 | none | None | <30 | 0 |
| I | 300–400 | 1–3 unilateral | 1 lobe unilateral | Pneumothorax | 30–40 | 1 |
| II | 200–300 | 4–6 unilateral | 1 lobe bilateral or 2 lobes unilateral | Hemothorax/ Hemopneumothorax unilateral | 41–54 | 2 |
| III | 150–200 | >3 bilateral | <2 lobes bilateral | Hemothorax/ Hemopneumothorax bilateral | 55–70 | 3 |
| IV | <150 | Flail chest | ≥2 lobes bilateral | Tension pneumothorax | >70 | 5 |

mechanical ventilation, placement of chest tube) in >80% of the cases. Operative interventions are required in 2%–16% of patients with chest trauma. Indications for emergency surgery are penetrating or open chest trauma, hemothorax with an initial chest tube output of 1000–1500 mL, pericardial tamponade, or cardiac injury, as well as tracheobronchial or major vessel injuries. Indications for urgent or elective interventions include: a blood loss over the chest tube >200 mL/h over 5 h or >400 mL/h over 2 h; diaphragmatic or esophageal lesions; persistent bronchopleural leakage; pneumato- or hematoceles; valvular damage; non-drainable clots; and flail chest. In an emergency situation, anterolateral thoracotomy represents the standard approach, whereas the posterolateral approach is favored in the hemodynamically stable patient.

There is also a high coincidence of thoracic injuries and extremity trauma (e.g., femoral fractures). Timing and type of fracture stabilization have the potential to substantially influence pulmonary function as well as the development of posttraumatic complications in multiple-trauma patients with chest trauma. Therefore, the following sections focus on both the general aspects of the treatment of chest trauma and the significance of adequate treatment strategies for fracture stabilization in cases of concomitant chest trauma.

### 15.5.1 Airway Management

Oral intubation has usually already been performed at the scene of the accident or in the emergency department. If not, it must be considered in the initial posttraumatic period because early intubation reduces morbidity and mortality in patients with severe chest trauma. Indications for intubation include: TBI (Glasgow Coma Scale <9); chest trauma with respiratory insufficiency (e.g., $SaO_2$ <90%, breathing rate <10/min or >30/min); hemorrhagic shock; and cardiopulmonary reanimation. In cases of a suspected ventilation time of more than 7–10 days, tracheotomy should be recommended. Tracheotomy seems to be favorable due to improvements in respiratory mechanics and the reduction of infectious complications. However, the effect of tracheotomy on total ventilation time and the duration of intensive care treatment have been controversially discussed.

### 15.5.2 Mechanical Ventilation

In the anesthetized, mechanically ventilated patient, a reduction in pulmonary functional residual capacity due to supine positioning has been observed. Furthermore, a posttraumatic reduction in the compliance results in hypoventilated areas, particularly in dorsobasal lung sections, with an increased risk for atelectasis formation. These lung sections show the best pulmonary perfusion, and thus a ventilation/perfusion mismatch with increased intrapulmonary shunting is also observed. In addition, the increased intrathoracic pressure due to mechanical ventilation exerts hemodynamic effects, such as decreased cardiac output. Besides trauma-related pulmonary injuries, mechanical ventilation with high inspiratory pressure also has the potential to cause additional damage to the lung

parenchyma. Therefore, lung protective ventilation with low tidal volumes (5–6 mL/kg), high positive end expiratory pressure (PEEP), and limited inspiratory peak pressure (<35 $cmH_2O$) should be used in case of severe chest trauma.

### 15.5.3 Positioning Therapy

In general, positioning has been reported to have great significance for critically ill patients and can distinctly facilitate their situation. Okgun-Alcan et al. [144] reported that positioning therapy promotes comfort and relaxation, prevents deformities or injuries, stimulates circulation, and improves gastrointestinal functions. Furthermore, respiratory function is improved by an increased clearance of respiratory secretions and prevention of both pressure sores and ventilator-acquired pneumonia [144].

Positioning therapy has also been applied in patients with chest trauma to prevent and treat pulmonary functional disorders. There are a variety of positioning procedures, including the semi-recumbent position, the lateral position, the prone position, and continuous axial rotational therapy. Mechanically ventilated patients should be positioned in a semi-recumbent position (45°) under sedation with or without neuromuscular blockade in order to avoid pulmonary aspiration and ventilator-associated pneumonia. The semi-recumbent position positively affects oxygenation, enhances functional residual capacity (FRC), and reduces respiratory efforts. In patients with unilateral lung injuries, lateral positioning of almost 90° ("good lung down") has been recommended [95, 145–147].

A complete prone position is the 180° contrast to the supine position, meaning that the patient lies with her or his chest down and back up. An incomplete prone position is a transfer between 130° and <180°. According to the European Society of Intensive Medicine, the American Thoracic Society, and the Society of Critical Care Medicine, prone positioning is recommended for at least 12 h a day for patients who suffer from severe ARDS with life-threatening hypoxemia ($PaO_2/FiO_2$ <100) [148, 149]. Contraindications for prone positioning include an open abdomen, unstable spine injuries, TBI with increased intracerebral pressure, severe arrhythmia, acute shock, and substantial facial trauma [145–147]. It results in an increase in pulmonary gas exchange due to an improved ventilation/perfusion ratio [150–152] and recruitment of alveolar space with reduced atelectasis formation [153–157]. These effects occur either immediately (≤30 mins) or up to 12 h after re-transfer into a supine position [158–160]. Incomplete prone positioning is less effective [161]. Compared with continuous axial rotational therapy, prone positioning seems to be associated with stronger and faster therapeutic effects. However, no differences are evident between these positioning procedures after 72 h [162].

Overall, it seems noteworthy that, if applied correctly, prone positioning represents a relatively safe procedure that does not result in a significant increase in intraabdominal pressure in patients without abdominal injuries [163, 164]. However, it can be complicated by facial edema (20%–30%), pressure ulcers (20%), noncompliance of the patient (20%), and arrhythmia (5%), as well as by tube and catheter dislocation (1%–2%) [165]. Despite improved arterial oxygenation, prone positioning does not result in a significant reduction of morbidity, ventilation time, or length of stay in the intensive care unit (ICU) in patients with ARDS [165, 166]. By contrast, a decrease in ventilator-associated pneumonia after prone positioning has been described [165, 166].

Continuous axial rotational therapy is characterized by continuous rotation of the patient about the longitudinal axis in a self-rotating bed. Depending on the bed system, rotation of up to 62° to each side can be achieved. Potential indications are the prevention of pulmonary complications (e.g., atelectasis, pneumonia) in patients with chest trauma [167–169]. Furthermore, it is used for the treatment of ARDS if, for example, prone positioning is contraindicated. Kinetic therapy is recommended for at least 3–5 days [167–169]. The best effects of axial rotational therapy [168–173] are described for a rotation of >40° to each side. Contraindications are unstable

spine injuries, acute shock, and adiposity (≥160 kg). Complications associated with kinetic therapy include pressure ulcers, hemodynamic instability, kinetosis, and catheter dislocation.

The potential benefits of continuous axial rotational therapy have been discussed, albeit controversially [174]. Besides the positive effects that have been observed in some studies, other trials have failed to show a significant effect on morbidity, ventilation time, and length of stay in the ICU [175–180]. Furthermore, recent studies have not found a beneficial effect of mechanical ventilation with prophylactic kinetic therapy compared to early extubation and aggressive weaning in patients with severe thoracic trauma [181, 182]. Due to the small and inhomogeneous study populations, generalizing these results to the treatment of severe blunt chest trauma patients is questionable. Nevertheless, the role of kinetic therapy and its prognostic relevance should be clarified in additional studies. Furthermore, reliable parameters for the indication of kinetic therapy should be validated.

### 15.5.4 Fracture treatment in multiple-trauma patients with thoracic trauma

In patients with severe injuries and hemodynamic instability, initial management should avoid complex operative procedures. Such interventions in the acute phase must be performed rapidly and should not add a further significant burden to the patient. The primary focus under these conditions is hemorrhage control and the performance of other life-saving procedures. Complex reconstructive work is delayed until the patient can withstand the additional surgical trauma. This "damage control" approach has been adapted to patients with extremity trauma. In specific subgroups of these patients, extensive surgical procedures for fracture stabilization have been associated with an increased incidence of complications, such as SIRS and MODS.

Over the recent decades, different concepts for the management of major fractures after severe trauma have been developed. The aforementioned concept of "damage control orthopedics" (DCO) is characterized by temporary external fracture fixation in the primary phase with secondary conversion to definitive osteosynthesis after stabilization of the patient's physiological and immunological status in the ICU. By contrast, primary definitive fracture fixation is performed within the concept of "early total care" (ETC) [183–188]. Although early fracture fixation has been described to be essential to avoid pulmonary complications after multiple traumas [189, 190], the optimal treatment strategy (ETC vs DCO) for fracture care remains the focus of intensive research [183–191]. This is particularly true for multiple-trauma patients with severe chest trauma [191]. Several investigations have demonstrated a decreased risk for infection and pulmonary dysfunction after ETC treatment in these patients [183, 187, 192, 193], whereas other studies have reported an increased rate of pulmonary failure after ETC. There has been inconsistent use of ETC and DCO, as shown in an analysis of the trauma registry of the German Trauma Society in patients with chest trauma [186, 191, 194].

In the majority of studies, it is accepted that stable patients benefit from the ETC concept, whereas unstable patients and patients in extremis might benefit from DCO. In a prospective randomized study, Pape et al. [195] introduced an additional group of patients who were in an unclear condition ("borderline" patients; Table 15.3). These patients were distinguished from stable, unstable, and in extremis patients (Fig. 15.2). In this study, borderline patients had a significantly higher incidence of acute lung injury (ALI) after ETC treatment compared with fracture stabilization according to the DCO concept [186]. For the identification of these patients, the severity of thoracic trauma and physiological pulmonary parameters are of central importance. This approach emphasizes the significance of chest trauma for the development of posttraumatic complications after fracture stabilization in multiple-trauma patients. The timing of secondary definitive osteosynthesis within the DCO concept seems to not be advantageous within 5 days after the trauma [186, 196]. Giannoudis

recommended secondary fracture fixation when certain requirements are met (Table 15.4) [196].

In conclusion, early definitive fracture stabilization seems to increase the risk of adverse outcome in multiple-trauma patients with severe chest trauma. However, further prospective randomized studies are needed to increase the sensitivity and specificity of parameters to identify those patients who might benefit from the DCO concept of fracture care. Additional treatment strategies for fracture stabilization in multiple-trauma patients, including "early appropriate care" (EAC) and "safe definitive surgery" (SDS) have recently been developed [197–201]. The EAC protocol aims to determine the optimal timing of definitive fracture fixation by the presence and severity of metabolic acidosis [70, 200]. In contrast to the dichotomous EAC protocol, SDS represents a dynamic concept for surgical decision-making in multiple-trauma patients [197, 202]. Within the SDS concept, continuous re-evaluation of the clinical situation and physiological parameters allows decision-making according to the current clinical course and physiological status [197, 202]. Another approach in the treatment of multiple-trauma patients with chest trauma is "prompt individualized safe management" (PRISM). PRISM describes a concept that comprehensively considers the patient's individual condition, starting with personal characteristics, such as age, sex, and other relevant information that must be covered within management of the treatment process. PRISM further regards the patient's physiological state and the specific type of her or his injury; it intends to conduct diagnostics at an early stage and eventually evaluates the patient's response to treatment. However, such an assessment process is dynamic because the patient's condition can change rap-

**Table 15.3** Borderline patients according to Pape et al. [195]

- ISS >40
- Hypothermia <35 °C
- Multiple trauma with ISS >20 and $AIS_{chest}$ >2
- Multiple trauma with abdominal/pelvic injury (AIS >2) and hemorrhagic shock ($RR_{systol}$ <90 mmHg)
- Multiple long bone fractures and truncal injury AIS 2 or more
- Bilateral lung contusion in chest radiography or CT
  - Unilateral bisegmental contusion
  - ☐ – Bilateral uni- or bisegmental contusion
  - Flail chest
- Pulmonary artery pressure (PAP) >24 mmHg
- Increase of PAP > 6 mmHg during femoral nailing
- Presumed operation time >6 h intraoperative reassessment:
  - ☐ – Coagulopathy
  - ☐ – Lactate (<2.0–2.5 mmol/L)
  - ☐ – Body temperature stable

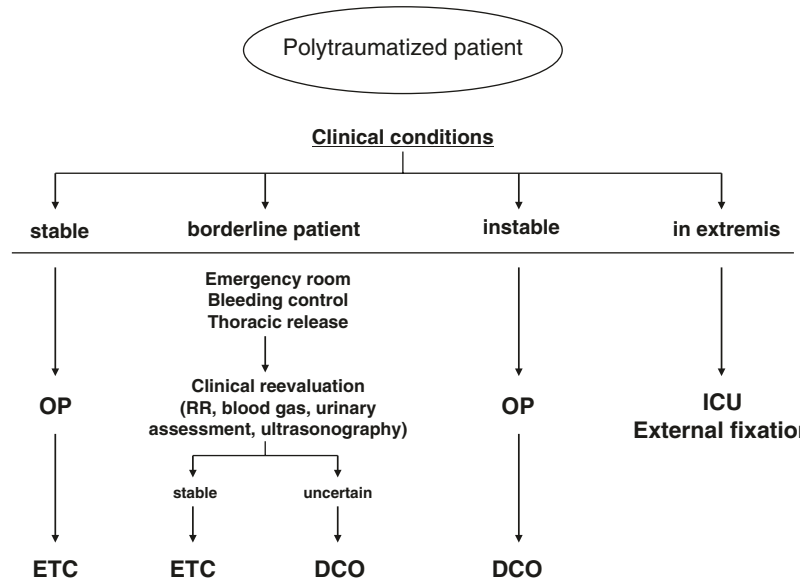


**Fig. 15.2** Treatment algorithm according to Pape et al. [195]

**Table 15.4** Signs of stabilization according to Giannoudis [196]

| |
|---|
| • Hemodynamic stability |
| • Stable arterial oxygenation |
| • Lactate <2 mmol/L |
| • Absence of coagulopathy |
| • Normothermia |
| • Urin production >1 mL/kg/h |
| • No need for catecholamines |

idly. Therefore, the patient's initial physiological factors must be constantly reassessed. This approach enables intra-operative reassessments and allows clinicians to revert from ETC or extended surgery to DCO if necessary, in consultation with anesthesiologists [203–205].

### 15.5.5 Surgical Chest Wall Stabilization

Possible indications for an operative stabilization of the chest include flail chest, reduction of pain and disability, severe chest wall deformity/defect (impression >5 cm), thoracotomy for other indications, open fractures, and symptomatic non-unions. Among these indications, flail chest is considered to represent the best indication for early stabilization [206].

Although many patients with flail chest can be treated conservatively by sufficient pain relief, internal pneumatic stabilization by mechanical ventilation, tracheobronchial toilet [206, 207], pressure dressing, and rib bone traction, operative fixation has been associated with a reduced duration of mechanical ventilation, a decrease in ventilation-associated complications, an avoidance of pulmonary infections or prolonged ICU treatment, and a reduced mortality rate as well as improved long-term results (e.g., pain, respiratory dysfunction) [208, 209]. However, before determining whether surgery is necessary, the patients' individual circumstances should be considered [210].

The best results of rib osteosynthesis have been observed when the stabilization was performed early (24–72 h after injury) and no additional lung contusions or severe TBI were present [206]. Incentive spirometry, another screening tool, can effectively be used to detect highly risked rib fracture patients in order to initialize preventive strategies and save them from pulmonary complications. That makes it an eligible technique for decision finding in whether surgical fixation of rib fractures is indicated [211, 212]. A diverse array of implants are now available that can be used for surgical chest wall stabilization. Plate osteosynthesis with locking bicortical screws is the most common procedure. Fractures can be fixed with the use of intramedullary implants, even if they are difficult to reach. Furthermore, screwless fixation device as well as resorbable implants is available [213–215]. With regard to surgery, there is a general consensus that ribs, such as the first and second as well as the two lower ribs, can be excluded from surgery and do not necessitate treatment, because they are hard to reach and relatively insignificant when it comes to respiratory functions [216].

In the context of sternal fracture, surgery should be applied if the thoracic wall is unstable, if the fracture remains permanently displaced, in case of sternal deformity, respiratory insufficiency, or if extreme pain is present. Two types of fixation techniques are described: fixation with K-wires or plate osteosynthesis. The latter technique has been found to increase stability, to speed up the healing process, and to reduce the risk of complications. Therefore, plate osteosynthesis is currently argued as the superior technique [32, 34, 217].

### 15.5.6 Video-Assisted Thoracoscopic Surgery

In recent years, thoracoscopic surgery has gained increased significance in the diagnosis and treatment of thoracic injuries because it reduces surgery-associated complications, operation time, and bleeding complications. In addition, thoracoscopic surgery speeds up recovery [218–220]. Video-assisted thoracoscopic surgery (VATS) is indicated in case of esophageal or diaphragmatic rupture, progressive or open hemothorax, and a persistent air leak. Besides, it is an acknowledged technique of effectively treating a retained hemo-

thorax, if a drainage by chest tube is insufficient [213, 221, 222]. Due to its accuracy, VATS allows a specific positioning of chest tubes through minimally invasive techniques. VATS is also considered to be a safe and effective technique within the first 24 hours after trauma for patients who are hemodynamically stable. Studies have shown that VATS can decrease the risk of complications like atelectasis or empyema if conducted early. To conduct VATS successfully, the patient must provide sufficient respiratory and hemodynamic stability, hematoma suction must be conducted for at least 30 min, and mechanical ventilation must be applied [213, 223, 224].

## 15.6 Conclusion

With a high incidence in cases of polytrauma, chest trauma presents with a large variety of different injuries (e.g., pulmonary contusion, rib fractures). It is one of the most common injuries associated with posttraumatic complications and mortality. Therefore, accurate diagnosis of thoracic injuries, as well as prompt assessment of their severity, is crucial for the further clinical course and outcome. Furthermore, specific therapeutic strategies for the treatment of chest trauma during the different phases after polytrauma (preclinical, emergency room, first surgical phase, intensive care treatment) is of utmost importance. Although the majority of thoracic injuries can be treated conservatively or by chest tube placement, resources for chest wall stabilization or video-assisted thoracoscopy have to be available. Strategies for fracture fixation in polytraumatized patients might have to be adapted in cases of severe chest trauma to prevent complications in the later posttraumatic course.

**Key Concepts**

- Accurate diagnosis and treatment of thoracic injuries are indispensable to prevent the development of posttraumatic complications during the hospital course.
- It is essential to identify life threatening thoracic injuries in the primary survey. They have to be sufficiently treated before moving on to the secondary survey.
- Specific therapeutic strategies for ventilatory support, pneumonia prophylaxis, and positioning therapy are recommended in polytraumatized patients with chest trauma.
- Although the majority of thoracic injuries can be treated conservatively or by chest tube, resources are available for chest wall stabilization or video-assisted thoracoscopy.
- Stabilization strategies for fracture treatment in polytraumatized patients might have to be adapted in case of blunt chest trauma to prevent complications in the later posttraumatic course.

**Take Home Messages**

- Chest trauma is one of the most common injury pattern in the polytraumatized patient and is associated with a higher incidence of severe posttraumatic complications (e.g., adult respiratory distress syndrome (ARDS), multiple organ dysfunction syndrome (MODS), and infectious).
- In case of clinically suspected chest trauma, radiological diagnosis has to be performed. A computed tomography (CT) scan can compensate the deficits of plain chest X-ray for the accurate identification of thoracic injuries.
- The evaluation of injury severity and the prediction of outcome are an important function of scoring systems. Early assessment of the severity of chest trauma is crucial for the clinical course of polytraumatized patients and has the potential to influence treatment strate-

gies, such as timing and type of surgical interventions.
- Over the different phases of polytrauma treatment (preclinical, emergency room, first surgical phase, intensive care treatment) thoracic injuries must be treated according to specific treatment algorithms.
- Timing and type of fracture stabilization have the potential to substantially influence pulmonary function as well as the development of posttraumatic complications in polytraumatized patients with chest trauma.

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# Blunt Abdominal Trauma

16

Alain Corcos and Andrew B. Peitzman

**Learning Objectives**

- Recognize that most solid organ injury following blunt trauma can be managed nonoperatively.
- Understand that hemodynamic stability is the primary determinant for nonoperative management.
- Recognize that the patient with abdominal solid organ injury necessitating laparotomy after blunt trauma is generally hemodynamically unstable.

## 16.1 Introduction

Mechanisms of blunt abdominal injury include fall, motor vehicle crash, motorcycle or bicycle crash, sporting mishap, and assault. Forces producing injury include compression, crush, rotational shear, deceleration, or sudden increase in pressure. Deceleration forces may tear organs or vascular pedicles. A sudden increase in luminal pressure can lead to perforation of a hollow viscus. Possible cavity hemorrhage or abdominal sepsis demands expedient diagnosis and treatment of intra-abdominal injuries to avoid preventable morbidity or death [1, 2].

## 16.2 Clinical Evaluation

Knowledge of the mechanism of injury is essential to determine the likelihood of an intra-abdominal injury. The force involved and vector of injury (where the abdomen absorbs the force) dictate injury patterns. Importantly, physical examination of the abdomen following blunt force trauma is often unreliable. Frequent confounders that limit findings with physical examination include altered level of consciousness (substance use or traumatic brain injury), distracting pain, usually from associated orthopedic injuries, and spinal cord injury. Although adjunctive diagnostic testing is essential in the evaluation of blunt abdominal trauma, careful, repeated physical examination of the patient is critical for early diagnosis of intra-abdominal injury. Evaluation on primary survey may detect signs of hypoperfusion (obtundation, cool skin temperature, mottling, diminished pulse volume, or delayed capillary refill), which should prompt a rapid search for a source of blood loss. Blood in the peritoneum often does not produce peritoneal signs, and massive hemoperitoneum may be present without abdominal distension. On the other hand, evaluation of the abdomen may reveal

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distension or signs of peritoneal irritation (usually associated with hollow viscus injury). Clinical findings associated with intra-abdominal injury that require laparotomy include significant chest injury, elevated base deficit, complex pelvis fracture, and any episode of hypotension. If the patient is a restrained victim in a motor vehicle crash with a visible contusion on the abdomen from a lap belt (lap belt mark), or a lumbar vertebral body fracture (Chance fracture), an associated hollow viscus injury should be suspected.

## 16.3 Diagnostic Testing

Determine the hemodynamic status of the patient. Follow the history and trend in vital signs, rather than developing a management plan based on a single value. Adjunctive diagnostic testing in the setting of blunt force abdominal trauma depends largely on these data. In the hypotensive patient, or the patient who requires ongoing fluid infusions to achieve normal hemodynamics, rapid evaluation of the abdomen as a source of hemorrhage is accomplished using focused abdominal by sonography for trauma (FAST) or diagnostic peritoneal aspiration (DPA) while the patient is in the trauma resuscitation bay. In the hemodynamically normal patient without immediate need for operation, computed tomography (CT) is the investigation of choice (Fig. 16.1).

### 16.3.1 Focused Assessment by Sonography for Trauma

The FAST exam can identify free fluid in the abdominal cavity, which in the setting of blunt force trauma should be considered blood. FAST can be performed rapidly at bedside without the need for transportation outside the trauma bay. It is non-invasive, widely available, inexpensive, and may be repeated as often as necessary. However, sensitivity and specificity are generally low (60%–85%), and it is not accurate for the detection and anatomic characterization of solid

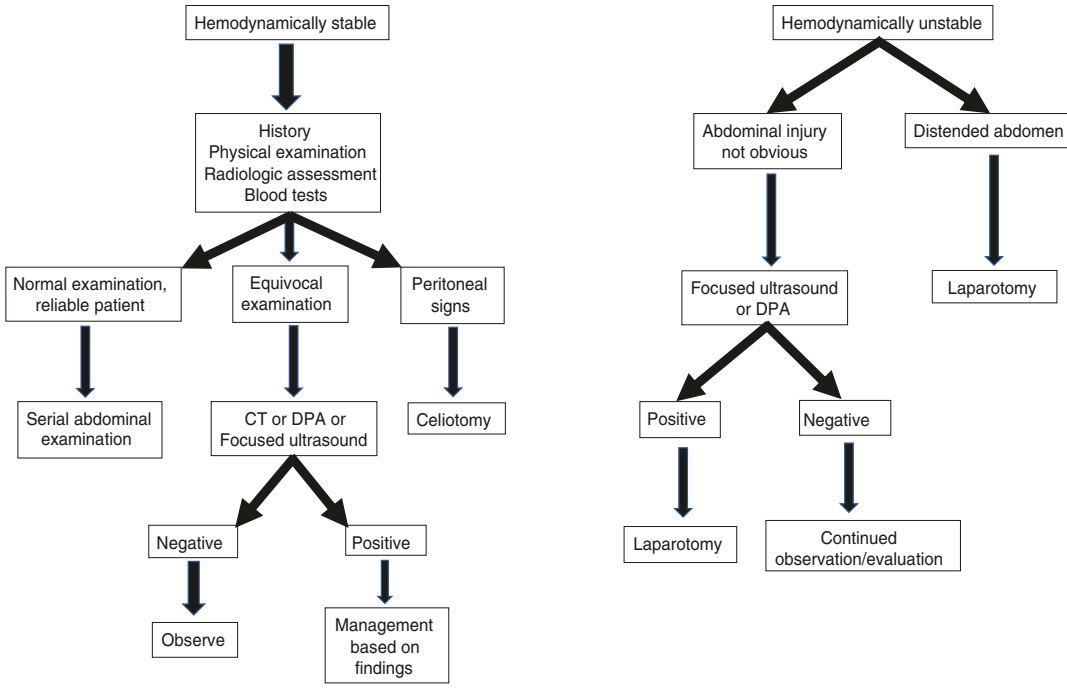


**Fig. 16.1** Algorithm for the management of blunt abdominal trauma (From: Corcos A, Six C, Britt LD, Peitzman AB. Abdominal trauma. In Peitzman AB, Yealy DM, Fabian TC, Schwab CW, Guyette FX, Seamon MJ, Zuckerbraun BS, (eds). The Trauma Manual, fifth edition. Wolters-Kluwer, Philadelphia, 2020, page 426)

organ injury. FAST is most valuable when positive for free fluid in the hemodynamically unstable patient. In this setting, FAST quickly identifies the abdominal cavity as the source of hemorrhage, prompting rapid transfer to the operating room for exploratory laparotomy. On the other hand, with a false negative rate as high as 40%, a negative FAST does not exclude abdominal cavity hemorrhage. In this case, a more definitive diagnostic test, CT or DPA based on hemodynamic characteristics, should be considered with high energy physical trauma [3]. Other limitations to FAST include inability to distinguish fluids (i.e., ascites vs. succus entericus vs. blood), variability in examiner proficiency, requirement for specialized training and continuing competency, and difficulty in interpreting findings in the obese patient or the patient with extensive subcutaneous emphysema. Place a 3–5.0 MHz transducer in the subxiphoid region in the sagittal plane to view the pericardial space and set the machine gain. Sagittal views of Morison's pouch and the splenorenal recess are performed, followed by a pelvic transverse view. Free fluid appears anechoic (black) compared with the surrounding structures. The chest can also be assessed using the ultrasound.

### 16.3.2 Diagnostic Peritoneal Aspiration (DPA)

Surgeon-performed FAST has supplanted diagnostic peritoneal lavage (DPL) as a tool to determine the presence of hemoperitoneum after blunt force trauma. DPA, however, remains an important adjunctive test during the resuscitative phase of care. This is a simple and rapid, although invasive, technique to diagnose hemoperitoneum. A peritoneal dialysis catheter is introduced into the abdominal cavity through a small infraumbilical incision and connected to a 10 mL syringe for aspiration (supraumbilical with an associated pelvic fracture). The subcutaneous tissues are dissected bluntly along the umbilical stalk to the level of the fascia. With upward traction, a dialysis catheter with a trocar is introduced by puncture into the abdominal cavity. The catheter is directed into the pelvis. Any quantity of blood is considered positive for hemoperitoneum. Level III evidence reports sensitivity of 89% for DPA compared to 50% for FAST exam [3]. DPA should be performed when a FAST exam is negative, equivocal, or unreliable but high suspicion for abdominal cavity hemorrhage persists, or in the patient with persistently abnormal hemodynamics or transient response to resuscitation.

### 16.3.3 Computed Tomography (CT)

CT is an accurate diagnostic modality (92–98%) for intra-abdominal organ evaluation and should be obtained in any hemodynamically stable patient suspected of intra-abdominal injury. Hollow viscus, diaphragm, and pancreatic injuries are most likely to be missed by CT. CT is specific for solid organ injury, distinguishes intra-abdominal free fluid from blood, and identifies even small amounts of air in the peritoneum or retroperitoneum. For maximum specificity, CT should be obtained with intravenous (IV) contrast, imaging from the top of the diaphragm through the bony pelvis. Avoid omitting IV contrast because of an elevated creatine or glomerular filtration rate. Recent studies confirm that even in patients perceived to be at the highest risk for post-contrast acute kidney injury (AKI), administration of IV contrast is not an independent risk factor for AKI, dialysis, or mortality [4]. Limitations to CT include cost, exposure to radiation, need for transportation outside the trauma bay, and the need for specialized non-trauma team personnel.

## 16.4 Conduct of the Exploratory Laparotomy for Trauma

Because of refinements in diagnostic capabilities, the trauma laparotomy is now more selectively applied, reducing the frequency of nontherapeutic explorations. Indications for immediate exploratory laparotomy following blunt trauma are based on physical exam findings or clinical signs and symptoms appreciated during the

primary or secondary survey including peritoneal irritation, hypotension with a distended abdomen, or positive FAST/DPA. Findings on CT scan obtained in the hemodynamically stable patient who requires operative repair should follow a similar approach with expeditious transportation to the operating room (OR) and initial exploration.

### 16.4.1 General Considerations and Setup

Once the decision is made to operate, rapidly transport the patient directly to the OR with appropriate airway support personnel, trauma team surgeons, and trauma team nursing staff in attendance. This is a direct transfer to the OR, not the preoperative holding area. If possible and practical, informed consent is obtained from the patient or a relative before laparotomy; the operation should proceed without delay in life-threatening circumstances. In the patient with high suspicion of a vascular injury or pelvic fracture, perform the laparotomy in a hybrid operating room. This allows immediate angiography, embolization, and endovascular techniques in the polytrauma patient. Adequate intravenous circulatory access and arterial lines for blood pressure transduction are placed as necessary in the OR. Do not delay control of cavitary bleeding with attempts at fluid resuscitation. The trauma patient who has been hypotensive should have femoral arterial access secured to facilitate later deployment of the REBOA (Resuscitative Endovascular Occlusion of the Aorta) catheter. Broad-spectrum antibiotic coverage to include gram-negative and anaerobic organisms is administered (an extended spectrum penicillin or a third-generation cephalosporin). Chest tubes placed during the resuscitative phase of care are placed to underwater seal during transport and to suction drainage on arrival in the OR; do not clamp the chest tubes. Collection canisters are positioned where readily visible so blood loss from the thoracic cavity can be monitored. Nasogastric or orogastric tubes and a bladder catheter are inserted prior to laparotomy. However, no procedure should be performed in such a way as to delay control of bleeding and contamination.

Transfer the patient to the operating table with appropriate cervical spine and thoracolumbar spine precautions. Patients immobilized on a rigid backboard, however, should be logrolled and remove the board before beginning the operation to prevent decubitus ulcers. Sequential compression devices are used for hemodynamically stable patients. Make a rapid infusion system and cell-saver system available in the trauma OR and primed for infusion of blood-bank products and cell-saved blood. Ensure that packed RBC units are in the OR and plasma and platelet products are available for any patient with active hemorrhage. In the exsanguinating patient, the massive transfusion protocol (MTP) should be activated to alert the on-site blood bank to the need for blood products. If the patient meets criteria for tranexamic acid (TXA) infusion or the initial bolus was given in the trauma bay or by pre-hospital transport, communicate this information to the anesthesia team so that the process can be initiated or continued. If time allows, shave the patient prior to the skin incision. The sterile preparation should include the entire anterolateral neck (sandbags may replace the anterior portion of the immobilization collar), entire chest and abdomen, both groins and thighs (Fig. 16.2).

### 16.4.2 Initial Priorities

The exploratory laparotomy for trauma is a structured operative procedure with two primary goals—stop bleeding and control gastrointestinal (GI) contamination. A generous midline incision is generally used. Adequate exposure is critical; self-retaining retractor systems and headlights are invaluable. Upon entry into the peritoneal cavity, control bleeding by scooping free blood and clots, rather than using a suction device. Next, rapidly pack all four quadrants with opened laparotomy pads, typically three to four per quadrant. With blunt injury, the most likely sources of bleeding are the liver, spleen, and mesentery.

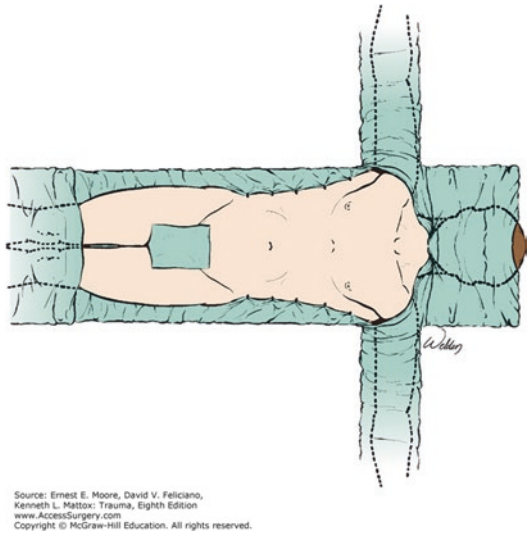


**Fig. 16.2** Position and preparation for exploratory laparotomy of the trauma patient. (From: Salotto J, Jurkovich GJ. Trauma laparotomy. In Moore EE, Feliciano DV, Mattox KL, (eds) Trauma. eighth edition. McGraw-Hill, New York, 2017, page 524)

Pack the upper quadrants and quickly clamp actively bleeding mesenteric vessels. If this does not subdue active bleeding, the source of ongoing hemorrhage should be readily apparent and becomes the highest priority. For rapid contamination control, Babcock or Allis clamps can temporarily occlude bowel lacerations prior to suture repair or segmental resection using a bowel stapler. Once active bleeding is controlled and GI injury temporarily contained, step back and assess the patient's hemodynamic status, units of blood products infused, acid-base status, temperature, coagulation, obvious abdominal and known or suspected nonabdominal injuries. Based on this information, a decision is made whether to proceed with further systematic exploration and definitive repair of all injuries or to abbreviate the operation along guidelines that dictate damage control surgery (see Chap. 26).

### 16.4.3 Systematic Exploration

This stage of the operation involves a systematic evaluation of the entire abdominal cavity after hemorrhage and contamination have been definitively addressed. Start with the liver and spleen, as these solid organs are most often involved in blunt trauma. This is followed by each hemidiaphragm, the anterior stomach, and the omentum. Elevate the omentum and deliver the transverse colon to allow easy evisceration of the entire small bowel, facilitating hand-over-hand palpation and close inspection of the entire jejunum, ileum, and mesentery from the ligament of Treitz to the cecum. The cecum and ascending colon, transverse colon and its mesentery, descending colon, sigmoid colon and its mesentery, as well as the intraperitoneal portion of the rectum are then thoroughly inspected and palpated. Return the small bowel and omentum to the abdominal cavity and enter the lesser sac by dividing the gastro-omental attachment. This allows inspection of the pancreas, proximal duodenum, and posterior stomach. Perform a Kocher maneuver to visualize the entire duodenum if evidence of injury.

Next, retroperitoneal hematomas are assessed for the need to explore. The retroperitoneum, for the purposes of traumatic injuries and exploration, is divided into three zones or regions (Fig. 16.3). In the central region (**zone 1**), resides the abdominal aorta, celiac axis, mesenteric vasculature, vena cava, proximal renal vasculature, portions of the duodenum, and pancreas. The lateral retroperitoneum (**zone 2**) encompasses the distal renal vasculature, kidneys, adrenals, urinary collecting system, proximal ureters, and portions of the ascending and descending colon. The pelvic retroperitoneum (**zone 3**) contains the distal ureters, iliac vasculature, bladder, extraperitoneal rectum, and bony pelvis. Management of retroperitoneal hematomas is dictated by mechanism of injury and zone. All penetrating injuries of the retroperitoneum are explored. Retroperitoneal hematomas resulting from blunt force trauma are approached on a more selective basis. All zone 1 hematomas should be explored since injury to vasculature or organs in this region will generally require surgical repair. When a large or expanding zone 1 retroperitoneal hematoma is found, place a REBOA catheter prior to entering the hematoma. For zone 2 retroperitoneal hematomas resulting from blunt trauma,

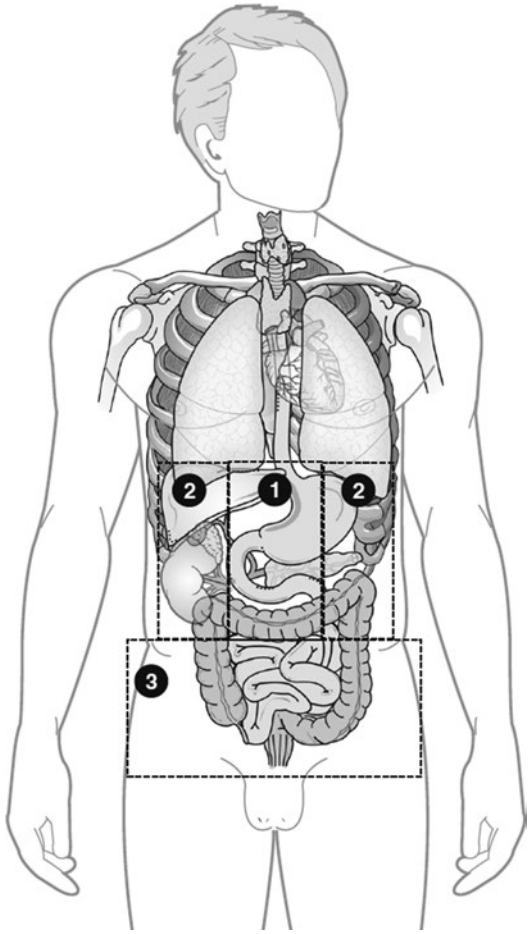


**Fig. 16.3** Zones of the retroperitoneum (From: Corcos A, Six C, Britt LD, Peitzman AB. Abdominal trauma. In Peitzman AB, Yealy DM, Fabian TC, Schwab CW, Guyette FX, Seamon MJ, Zuckerbraun BS, (eds). The Trauma Manual, fifth edition. Wolters-Kluwer, Philadelphia, 2020, page 460)

only pulsatile or expanding hematomas undergo exploration. Gross extravasation of urine, identified pre-operatively or intra-operatively (see Chap. 22), also necessitates exploration. Most renal organ injuries, however, can be managed nonoperatively, and preserving Gerota's fascia is of value if no vascular injury is suspected. Lateral hematomas along the peritoneal reflection of the ascending or descending colon should be universally investigated as they may disclose a posterior colon injury. With blunt trauma, exploration of a zone 3 pelvic hematoma generally is avoided. This finding most likely represents venous or bony bleeding associated with a pelvic bone fracture; application of an external compression device, with or without extraperitoneal pelvic packing, would be the preferred intervention (see Chaps. 9 and 19). The exception is the zone 3 hematoma from blunt injury that is pulsatile or visibly expanding suggesting a vascular injury. In this situation, deployment of the REBOA catheter may be life-saving prior to angiography and embolization or direct control of a vascular injury.

## 16.5 Specific Organ Injury

### 16.5.1 Diaphragm

Diaphragm injury from blunt force trauma most often result from motor vehicle collisions and falls. Rupture occurs with a sudden and severe increase in the intra-abdominal pressure, the left side being more vulnerable than the right. Chest radiograph is the usual initial screening modality. Its diagnostic accuracy is poor but may be improved by the placement of a radiopaque nasogastric tube if the stomach has already undergone herniation into the thoracic space. CT has a low sensitivity (63%) but high specificity (100%) for blunt injury rupture. Thus, it is helpful when positive (i.e., evidence of visceral herniation), but negative or equivocal findings on CT, when suspicion is high, are best treated as false negatives. Diagnostic laparoscopy has emerged as the modality of choice for acute diaphragmatic injury.

In the acute setting, diaphragmatic injuries are best repaired primarily with a heavy, non-absorbable suture. At times, large lateral defects require reattachment of the diaphragm to another rib. Rarely, blunt force ruptures result in significant tissue destruction, necessitating repair with a synthetic mesh. In the event of gross contamination, endogenous tissue, such as latissimus dorsi, tensor fascia lata, or omentum, should be used instead of mesh for the definitive repair. Biologic tissue grafts offer questionable durability and are best avoided. Outcomes for diaphragmatic injuries treated early are good with mortality and morbidity related to associated injuries.

### 16.5.2 Hollow Viscus

Gastric injury secondary to blunt trauma is rare. Shear injury from seat belts or direct blows to the epigastrium are the common causes. Gastric lacerations should be repaired primarily after debridement of non-viable edges, in either a single layer with non-absorbable suture or with a standard two-layer closure. Primary repairs seldom compromise the gastric lumen, and major resections are rarely required.

Small bowel wounds are the most common hollow viscus injury [5]. As with other hollow viscus injuries, all small bowel perforations are treated operatively. The majority of small bowel injuries resulting from blunt force are diagnosed directly or indirectly by CT in the absence of peritonitis on physical exam. With modern multidetector CT scanners, accuracy in diagnosing bowel and mesenteric injuries has improved significantly. Extraluminal gas is detectable in only half of patients with hollow viscus injury; images require scrutiny for indirect findings such as bowel wall edema, free fluid, or mesenteric stranding. Diagnostic laparoscopy is a valuable adjunct to CT in these situations. In addition to a complete perforation, surgically important injuries include seromuscular tears, active mesenteric bleeding, or mesenteric injury associated with bowel ischemia.

If small bowel viability is in question at laparotomy, a segmental resection should be performed. Isolated small bowel enterotomies that are viable can be closed primarily in a single layer provided the closure does not narrow the lumen by 50% or more. Non-viable edges may require debridement prior to closure. Multiple contiguous small bowel enterotomies or an intestinal injury on the mesenteric border with associated mesenteric hematoma are best managed with segmental resection and primary anastomosis. The operative goal is to reestablish intestinal continuity without substantial narrowing of the intestinal lumen, along with closure of any associated mesenteric defeat. The application of a non-crushing bowel clamp can minimize ongoing contamination while the repair is performed. Either hand-sewn or stapled anastomosis is acceptable. In the immediate postoperative period, gastric decompression is prudent.

Blunt colon injury occurs in less than 1% of patients with blunt force trauma. It can occur with sudden deceleration shear forces, such as seat belts or direct blows, that result in bowel wall contusions or serosal tears with associated mesenteric hematomas. These carry a significant risk of ischemic bowel necrosis. The right colon is more commonly injured. CT offers high sensitivity and specificity, whether IV contrast only or with "triple-contrast" (oral, rectal, and intravenous). Current evidence-based recommendations support primary repair of colonic injury in two layers for most non-destructive colon wounds and segmental resection with primary anastomosis for more destructive wounds. Resection with fecal diversion should be reserved for destructive wounds in patients with multiple comorbidities, severe associated injuries, hemorrhage requiring transfusion of six or more units of blood, or damage control laparotomy.

Blunt force rectal injury is usually associated with pelvic fracture. Digital rectal exam (DRE) can reveal blood and should be routine in patients with a pelvic fracture. Proctosigmoidoscopy is recommended whenever there is a high suspicion for rectal injury and absolutely indicated when DRE is positive. Intraperitoneal rectal injuries are managed along similar guidelines as colon. Extraperitoneal rectal injuries are usually managed with proximal fecal diversion to avoid pelvic sepsis [6]. Presacral drainage through an incision in the perineum, midway between the anus and coccyx, should be considered, for destructive wounds within the lower third of the rectum.

Primary closure of the skin incision with colon injuries is associated with a high incidence of wound infections. These can result in fascial dehiscence or necrotizing fasciitis. Leave the skin wound open with colon injuries complicated by fecal contamination to reduce wound infection and fascial dehiscence. Some report good results with delayed primary closure at post-op day four as an alternative to healing by secondary intention. Inadequate empiric antibiotic coverage is an independent risk factor for abdominal sepsis

in patients with colon injuries. Coverage should target both aerobic and anaerobic organisms, i.e., a second-generation cephalosporin or cefazolin plus metronidazole, with even broader coverage at institutions that have identified significant resistance.

### 16.5.3 Duodenum and Pancreas

With a common blood supply, there is a high incidence of concomitant injuries to the pancreas and the duodenum. As they are relatively well protected in the central retroperitoneum, associated intraperitoneal organ injuries are the rule (>3 on average). Blunt force injury to these intimately associated organs occurs most often from a crushing force to the upper abdomen that compresses them between the rigid spine and an external object (e.g., steering wheel, handlebar, or blunt weapon). Preoperative diagnosis is difficult, and management is challenging. Concomitant major vascular injury (aorta, portal vein, or inferior vena cava) is associated with 12% of blunt force pancreatic injuries and is the leading cause of death. Early death from pancreatic or duodenal injury is from this associated vascular injury. Morbidity and late mortality are from the duodenal or pancreatic injury, particularly if diagnosis and treatment are delayed.

#### 16.5.3.1 Duodenum

The anatomy of the duodenum is complex. It extends for 25 cm from the pylorus to the ligament of Treitz and is commonly divided anatomically into 4 portions. **D1** (superior) lies within the peritoneum, while **D2** (descending) enters the retroperitoneum and contains the orifices of the bile and pancreatic ducts. **D3** (transverse) travels medially over the IVC and aorta from the ampulla of Vater to the superior mesenteric vessels, which traverse anteriorly. **D4** (ascending) begins at the mesenteric vessels ending at the jejunum to the left of the lumbar vertebral column. Bile, pancreatic secretions, and gastric secretions flow through the duodenum at rates of one to two liters per day each, making injuries and leaks difficult to control.

Suspicion for duodenal injury must be based on the mechanism of injury. Findings on physical exam are nonspecific and subtle. Retroperitoneal air or obliteration of the right psoas margin may be seen on radiograph or CT. Periduodenal hematomas on CT should prompt an oral contrast study, either by CT or plain radiographs (UGI series), done first with water-soluble contrast followed by barium if negative. The diagnosis of duodenal injury is often made at laparotomy for associated injuries. Adequate exposure of the duodenum is vital to avoid missed injury. As described above, entering the lesser sac and performing a wide Kocher maneuver are essential. Bile staining, air in the retroperitoneum, or central retroperitoneal hematoma mandate a thorough exploration.

In children, *intramural duodenal hematoma* is a common compression injury that can occur in isolation (classically from a bicycle handlebar, although 50% are related to abuse and assault). These present as a "coiled spring" or "stack of coins" appearance on an UGI series or CT. This occurs less often in adults as an isolated injury. Nonoperative treatment with nasogastric tube (NGT) decompression of the stomach and IV alimentation is often successful, but operative decompression should be considered if the obstruction has not resolved after 2–3 weeks. Follow-up gastrografin images should be obtained weekly until outlet obstruction resolves. In adults, intramural hematomas found at trauma laparotomy need careful consideration. Incising the serosa to drain the hematoma is an option; avoid converting a contained injury into a full-thickness laceration. An alternative is to place a feeding jejunostomy tube for enteral nutrition and plan for prolonged NGT decompression.

Full-thickness duodenal perforations require operative repair with many options depending on injury severity. Simple lacerations or perforations less than 50% of the circumference can be closed primarily with one or two layers in a transverse fashion that avoids luminal narrowing. More extensive perforations will require complex repairs, duodenal decompression with or without pyloric exclusion, and wide drainage. When primary closure would compromise luminal integ-

rity, jejunal or omental patching is effective and safe. Complete transections require repair by end-to-end primary anastomosis following debridement. Achieving this without tension can be a challenge and is facilitated by de-rotation of D3 and D4 [7]. With injuries where anastomosis is hindered by proximity to the superior mesenteric vessels, side-to-side duodenojejunostomy at D2 with a closed end distally is the best option. Roux-en-Y techniques are required when end-to-end anastomoses cannot be accomplished without tension. As a general approach, the simplest repair of the duodenal injury is usually best.

The duodenum should be decompressed after repair of an injury. Nasogastric decompression, at times with the tube advanced into the proximal duodenum, is generally effective. Further techniques of duodenal decompression remain controversial. An additional lateral tube duodenostomy is not supported. Decompression via retrograde jejunostomy drainage has been advocated. Pyloric exclusion with oversew of the pylorus from within the stomach and creation of a gastrojejunostomy as diversion has been utilized. Recent data, however, question the need for pyloric exclusion in the management of most duodenal injuries [8]. Truncal vagotomy to prevent marginal ulceration is not indicated as the pylorus will open within a few weeks. Finally, an antegrade feeding jejunostomy can provide enteral nutrition which is superior to IV alimentation. All anastomoses and complex repairs also require closed suction tube drainage to ensure that any postoperative leaks become controlled fistulae.

Mortality rates with duodenal injuries are less than 10% when treated early but increase to as high as 40% when the diagnosis is delayed more than 24 h. Complications occur in 40% of patients with anastomotic dehiscence and resultant sepsis accounting for nearly half of all deaths.

#### 16.5.3.2 Pancreas

The pancreas is almost entirely retroperitoneal with the head lying to the right of midline at the level of the second lumbar vertebra. The body of the pancreas crosses the midline with the tail ending in the hilum of the spleen at the level of L1. The superior mesenteric vessels lie posteriorly in a groove at the neck of the pancreas. The main pancreatic duct of Wirsung typically runs the length of the pancreas with an accessory duct (Santorini) branching from it within the parenchyma, emptying separately into the duodenum. Twenty percent of individuals have an accessory duct that drains into the main pancreatic duct, and 8% have it as the sole drainage of the pancreas into the duodenum.

In hemodynamically stable patients, the diagnosis of blunt force pancreatic injury is made primarily by CT with a sensitivity of only 60–70% [9]. Integrity of the main pancreatic duct is the most important diagnostic question. Injury to the main duct is the principle determinant of morbidity; delay in diagnosis is associated with an increase in complications [10]. A high index of suspicion for ductal disruption, based on mechanism of injury or indirect signs on CT, is of paramount importance. Physical exam is often unreliable, and signs and symptoms may be subtle or only apparent several hours after injury. Hyperamylasemia is neither sensitive nor specific on initial presentation even in the presence of complete pancreatic duct transection.

As with duodenum injury, associated injuries generally prompt surgical exploration; a thorough inspection of the lesser sac will reveal the pancreatic injury. Close visual inspection and bimanual palpation of the pancreas are essential. This approach requires dividing the gastrocolic ligament, opening the retroperitoneum widely, and performing a full Kocher maneuver. This can be accomplished by careful mobilization of the spleen and tail of the pancreas out of its retroperitoneal location as a single unit, based on their shared blood supply. Intraoperative pancreatography performed through the ampulla of Vater (via a duodenotomy) or through the distal main pancreatic duct (via amputation of the tail of the pancreas) has been described to assess the integrity of the main pancreatic duct; we do not advocate this approach. Bimanual palpation of the substance of the gland is preferred to distinguish transection from contusion without the morbidity of unnecessary duodenotomy or splenectomy.

In the patient without immediate indication for laparotomy, repeat CT during a course of

observation is often warranted, particularly when symptoms persist, or hyperamylasemia develops. Endoscopic retrograde cholangiopancreatography (ERCP) is the most sensitive technique short of operative exploration to diagnose pancreatic ductal injury; it may be useful in patients with equivocal CT findings who otherwise meet criteria for observation. Clearly, the logistics of obtaining ERCP during the resuscitative phase of care limits its utility. ERCP and stent placement are utilized far more commonly for treatment of complications rather than in diagnosis of pancreatic injury. The role of magnetic resonance cholangiopancreatography (MRCP) in trauma has not been fully delineated.

Nonoperative management of documented pancreatic injury remains controversial; this approach is more common in children. Suspected pancreatic grade 3–5 injuries should be surgically explored. The status of the pancreatic duct, the location of the injury (proximal vs distal), and the patient's overall clinical status dictate selection of treatment options that adhere to the following important principles: control of hemorrhage, debridement of devitalized tissue, maximum preservation of viable pancreatic parenchymal, wide drainage of secretions with closed suction drains, and strategies for enteric feeding to optimize postoperative nutrition including feeding jejunostomy if necessary. As a rule, restrictive management protocols, such as external drainage and limited pancreatectomy, result in lower mortality and morbidity than more complex procedures that involve extensive resections and pancreatoenteric anastomoses.

At laparotomy, pancreatic contusions and capsular lacerations without injury to the main duct (AAST grade I or II) are best managed by debridement of devitalized tissue and wide external drainage alone [11]. Do not suture the injured capsule or parenchyma as this may result in a pseudocyst. The goal in this scenario is to ensure that any pancreatic fistula that develops be well controlled as these typically close without further intervention. Pancreatic injuries that include the main duct are addressed according to location. Most blunt force main duct transections occur in the body of the gland to the left of the SMA (AAST grade III) and are managed effectively by distal pancreatectomy, preferably with splenic salvage if the patient's hemodynamic status allows. Pancreatic transection to the right of the SMA or massive disruption of the pancreatic head (AAST grade IV and V) is more complicated to manage and more common with penetrating injury. There are no universally recommended approaches. Options include wide drainage of the area to promote a controlled fistula or complex procedures such as on-lay pancreaticojejunostomy or pancreaticoduodenectomy. Simple drainage alone is safest as a controlled pancreatic fistula is easier to deal with and less morbid than the complications arising from more aggressive approaches. Severe injury to both the head of the pancreas and the duodenum may require pancreaticoduodenectomy; however, this is rare. Indications are limited to resections required to control exsanguinating hemorrhage from adjacent vasculature or resection that essentially completes the damage resulting from the severity of the injury. When required, a staged approach is best with the reconstruction phase delayed for 24–48 hours to facilitate creation of multiple anastomoses (Fig. 16.4).

Pancreatic fistula and abscess are the most common postoperative complications (up to 25%). A pancreatic fistula is defined as 100 mL per day output for greater than 2 weeks (minor) or greater than 1 month (major). Most will resolve spontaneously with less than 7% requiring further operative intervention. Pancreatic duct injury and associated colon injuries are independent predictors of abscess formation, most of which can be drained percutaneously. Postoperative pancreatitis complicates 5% of cases. Pancreatic pseudocysts occur in roughly 3% of cases and often related to missed or inadequately treated ductal injuries. Postoperative hemorrhage occurs in 10%, ideally managed with angioembolization.

Overall mortality ranges from 12% to 32% with pancreatic related mortality ranging from 1.6% to 3%. Early deaths are most often from associated vascular injuries while late deaths are often due to delayed diagnosis or treatment of the pancreatic injury.

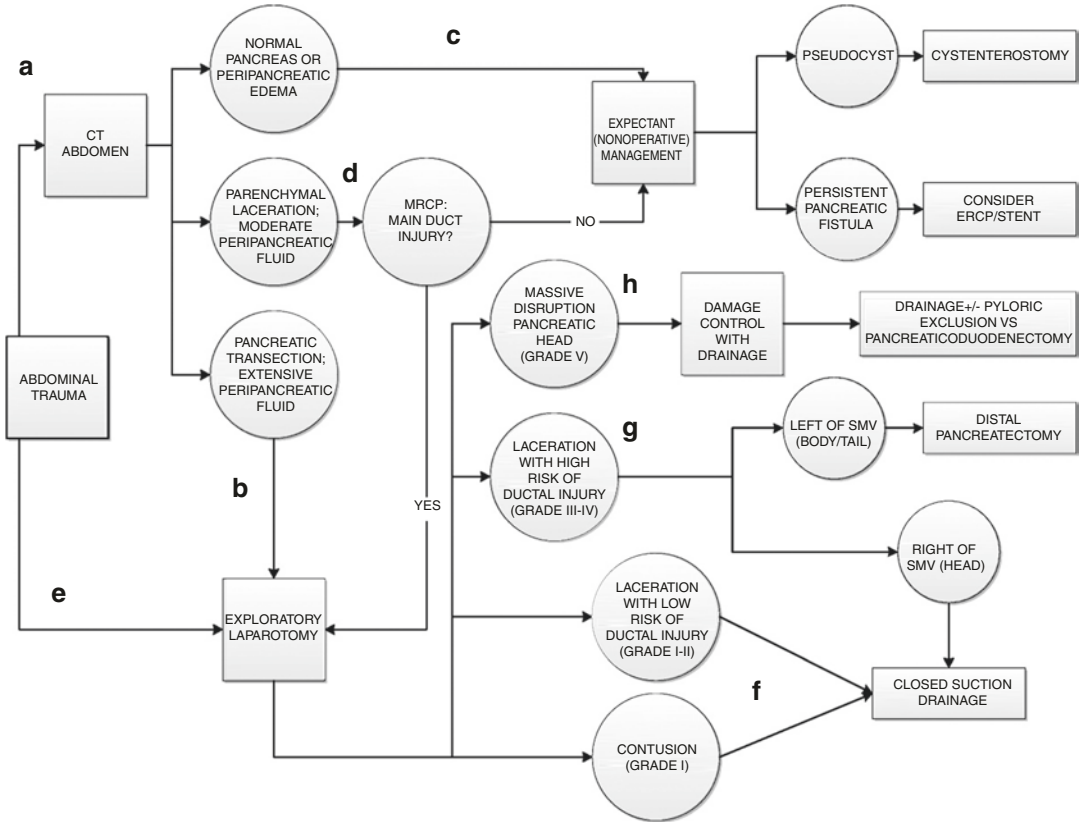


**Fig. 16.4** Western Trauma Association algorithm for the management of pancreatic injury (From Biffl WL, Moore EE. Croce M, et al. Western Trauma Association critical decisions in trauma: management of pancreatic injuries. J Trauma Acute Care Surg 2013: 75: 941–946)

### 16.5.4 Spleen

Blunt splenic injury typically occurs from compression or deceleration forces. The spleen is bounded by the stomach, left hemidiaphragm, left kidney, chest wall, and colonic flexure. The peritoneal attachments define the spleen's relationship to these adjacent organs: gastrosplenic ligament, splenorenal ligament, splenophrenic ligament, splenocolic ligament, and pancreaticosplenic attachments. The spleen receives 5% of cardiac output, primarily through the splenic artery, which courses superior and anterior to the splenic vein in a groove along the superior edge of the pancreas. Along its course, it supplies portions of the stomach and pancreas. The splenic artery bifurcates as an end-artery into superior and inferior polar arteries.

In the hemodynamically unstable patient with blunt injury, ultrasound (or DPA) obtained during the primary survey may reveal hemoperitoneum, and the diagnosis of splenic injury is made subsequently at surgical exploration. In stable patients, the physical exam is insensitive and nonspecific. CT scan with IV contrast of the abdomen should be obtained to define any injuries and allow delineation by AAST grade. On occasion, when hemoperitoneum irritates the diaphragm, the patient may complain of referred pain to the left shoulder (Kehr's sign). Twenty-five percent of patients with left lower rib fractures [9–12] will have an associated splenic injury; this finding on chest radiograph should serve as a marker.

Management of splenic injury depends primarily on the hemodynamic status of the patient at presentation (Fig. 16.5). The hemodynami-

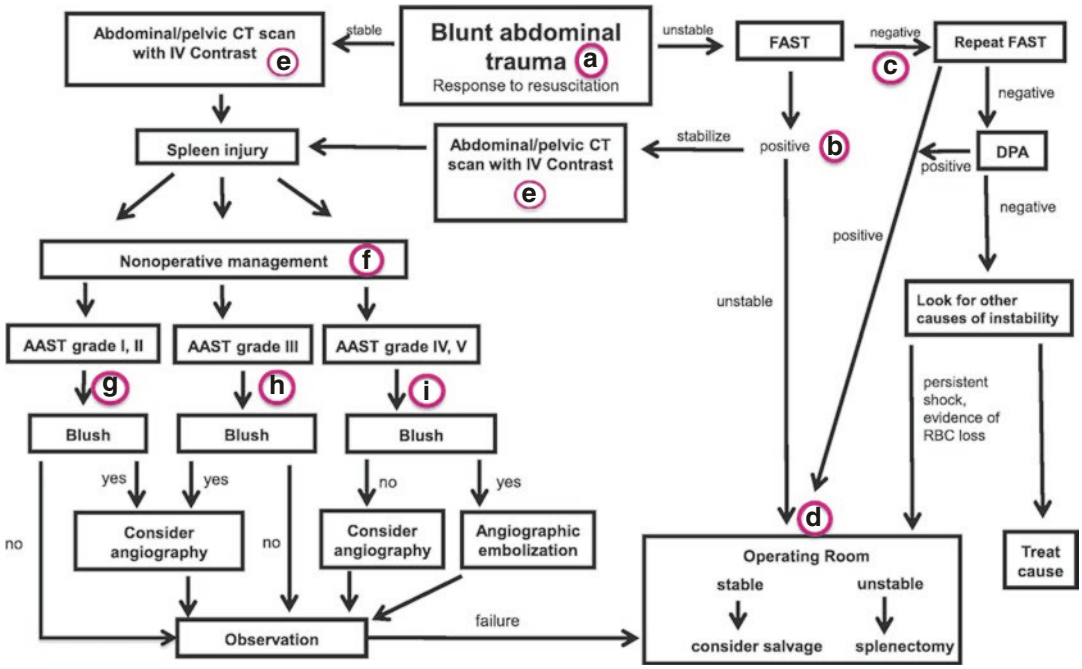


**Fig. 16.5** Western Trauma Association algorithm for the management of adult blunt splenic injury (From: Rowell SE, Biffl WL, Brasel K, et al. Western Trauma Association Critical Decisions in Trauma: Management of adult blunt splenic trauma –2016 updates. J Trauma Acute Care Surg 2017; 82: 787–793)

cally unstable patient with splenic injury requires operative intervention, usually resulting in splenectomy [12].

The ubiquity of CT and an understanding of the importance of splenic function have resulted in the preservation of 60–80% of injured spleens in hemodynamically stable adult patients. In children, nonoperative management (NOM) is successful in over 90% of splenic injury. Children who present in shock, however, still warrant operative management.

Failure of NOM correlates most significantly with grade of injury. According to the multi-institutional study by the Eastern Association for the Surgery of Trauma (EAST), 61.5% of adult patients with blunt splenic injury were initially observed. Of these, 11% failed observation with 61% of failures occurring within 24 h and 90% within 72 h [13, 14]. Failure of NOM by grade was as follows: grade I–5%, grade II–10%, grade III–20%, grade IV–33%, and grade V–75%. In this study, NOM failure also correlated with the quantity of hemoperitoneum. Longitudinal studies from the National Trauma Data Bank also report failure rates of 40% to 50% for grades IV and V. Other factors which increase the likelihood of failure of observation are vascular blush or large pseudoaneurysm on CT, large hemoperitoneum, and high injury severity score (ISS).

The patient with splenic injury treated nonoperatively should be observed in a monitored unit with immediate access to CT, blood and blood components, a surgeon, and an OR. Changes in physical examination, hemodynamic stability, or ongoing blood or fluid requirements indicate the need for laparotomy. Serial hemoglobin levels should be monitored until stable, and the patient should be placed at bed rest during this interval. A follow-up CT scan at 48 h for medium and high grade injuries is recommended based on a high yield of pseudoaneurysm formation, which may require further intervention. Follow-up imaging in children has not shown clear benefits. Splenic artery embolization (SAE) has been shown to significantly improve splenic salvage rates in adults when used in cases of active

extravasation or pseudoaneurysm on CT and empirically in grade IV and V injuries, even in the absence of active extravasation.

At laparotomy for splenectomy, mobilize the spleen entirely to visualize the injury. Start with the operator's nondominant hand providing medial traction to the spleen to facilitate division of the avascular splenorenal and splenophrenic ligament; avoid injury to the splenic capsule (Fig. 16.6). As the organ is further freed from its peritoneal attachments, stay in the plane posterior to the pancreas. At this point, the hilum of the spleen can be controlled with manual compression. The gastrosplenic ligament and short gastric vessels are then divided by suture ligation near the spleen to avoid injury to or late necrosis of the gastric wall. The spleen can now be delivered into the operative field to allow surgical control of the splenic vessels. Vascular staplers, suture ligation, or ligation between clamps are all acceptable. Drainage of the splenic fossa is associated with an increased incidence of subphrenic abscess and should be avoided, except when concern exists for an injury to the tail of the pancreas.

Non-bleeding injuries encountered during laparotomy for associated injuries may occasionally be treated with splenic salvage techniques (splenorrhaphy). Grade I injuries typically require no treatment or simple topical hemostatic agents with or without electrocautery. Grade II or III non-bleeding injuries can be suture repaired with Teflon pledgets or wrapped in an absorbable mesh. Grade IV and V injuries, even if not actively bleeding at exploration, are best treated with splenectomy. When considering splenorrhaphy, remember that one-third of the splenic mass must be functional to maintain immunocompetence. With the emergence and evolution of nonoperative management protocols, splenorrhaphy has become rare.

Rates of re-bleeding following both splenectomy and splenorrhaphy are low. Postoperative pulmonary complications are common. Left subphrenic abscess occurs in less than 10% of postoperative patients; more common with concomitant bowel injury. Thrombocytosis occurs commonly following splenectomy and usually requires no treatment. Platelet counts typically peak by postoperative day 10 and take several weeks to abate. Complications of SAE include re-bleeding (requiring splenectomy or repeat embolization), splenic or pancreatic necrosis, iatrogenic vascular injury, hematoma at the catheter insertion site, and contrast reactions/nephropathy.

Overwhelming post splenectomy infection (OPSI), a rapidly fatal septicemia following splenectomy, is a greater risk to children than adults with an overall incidence of less than 0.5% per year. The most common organisms are the encapsulated bacteria: *Haemophilus influenza, meningococcus, Streptococcus pneumoniae, as well as Staphylococcus aureus, and Escherichia coli*. Following splenectomy, vaccines for pneumococcus (Pneumovax), H. influenzae, and meningococcus should be administered. The timing of injection is controversial with some authors recommending waiting 3–4 weeks after surgery as the patient may be too immunosuppressed in the immediate post-injury period to benefit from vaccination. However, most centers vaccinate patients in the early postoperative period before the patient may be lost to follow-up. Patients who have undergone splenectomy should have a clear understanding of the concerns regarding OPSI. They are typically recommended to start penicillin therapy with the development of any mild infection.

### 16.5.5 Liver

The liver is the most commonly injured intra-abdominal organ with overall mortality rates approaching 10%. The patients with blunt injury to the liver generally present in one of two conditions. The vast majority of these patients are hemodynamically stable or fluid responsive and will undergo CT and planned nonoperative management. However, a small portion of patients with blunt hepatic injury present with significant hypotension (due to high grade liver or juxtahepatic venous injury); prompt laparotomy is required. Thus, major injuries in unstable patients will be diagnosed at laparotomy. The decision-

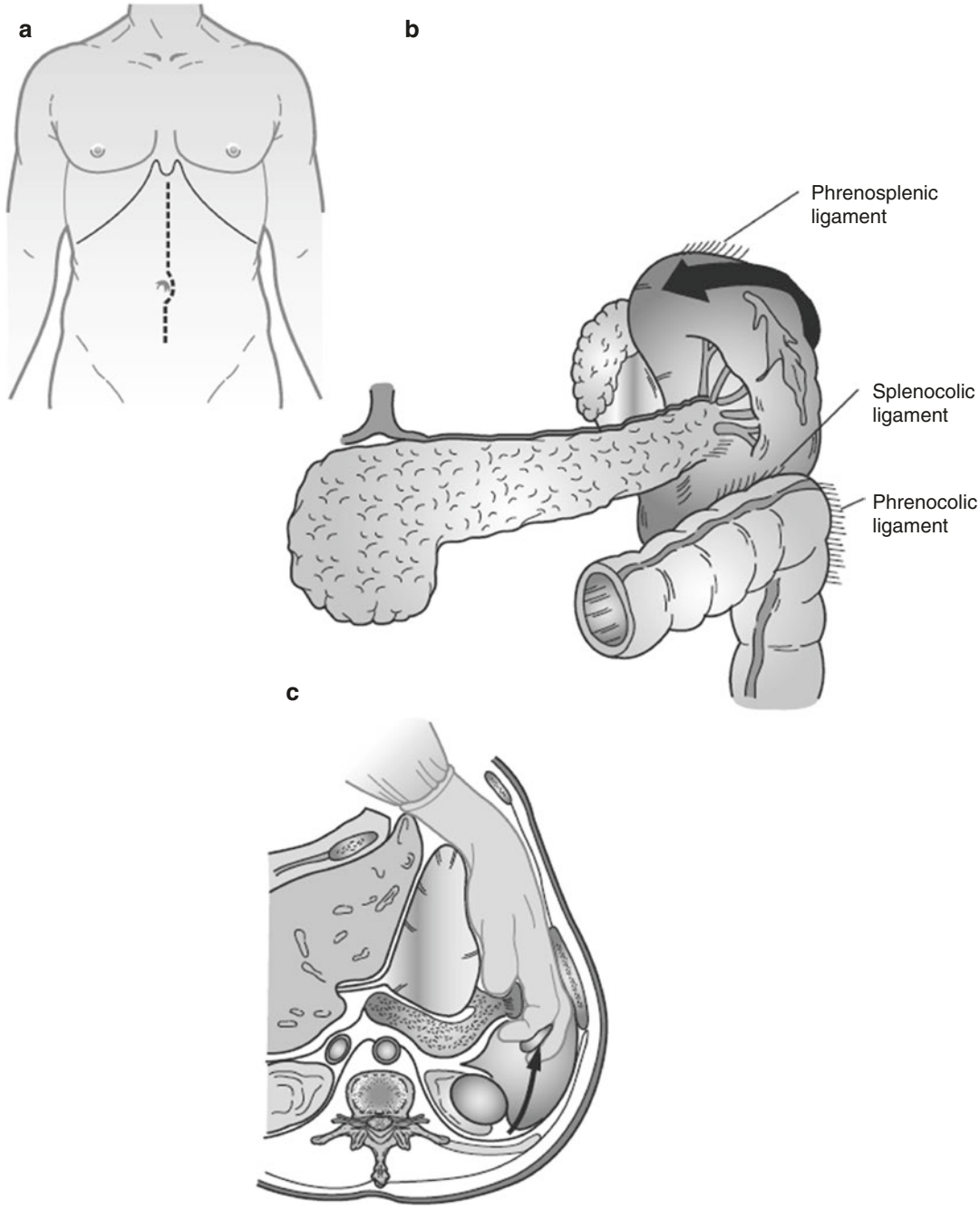


**Fig. 16.6** Laparotomy for splenectomy. A. Midline incision B. Phrenosplenic, splenocolic, and phrenocolic ligaments c. Mobilization of the spleen (From: Corcos A, Six C, Britt LD, Peitzman AB. Abdominal trauma. In Peitzman AB, Yealy DM, Fabian TC, Schwab CW, Guyette FX, Seamon MJ, Zuckerbraun BS, (eds). The Trauma Manual, fifth edition. Wolters-Kluwer, Philadelphia, 2020, page 451)

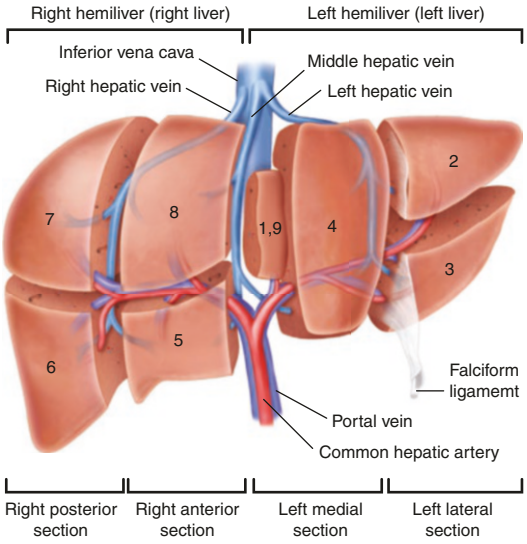


**Fig. 16.7** Hepatic segmental and vascular anatomy (From: Corcos A, Six C, Britt LD, Peitzman AB. Abdominal trauma. In Peitzman AB, Yealy DM, Fabian TC, Schwab CW, Guyette FX, Seamon MJ, Zuckerbraun BS, (eds). The Trauma Manual, fifth edition. Wolters-Kluwer, Philadelphia, 2020, page 453)

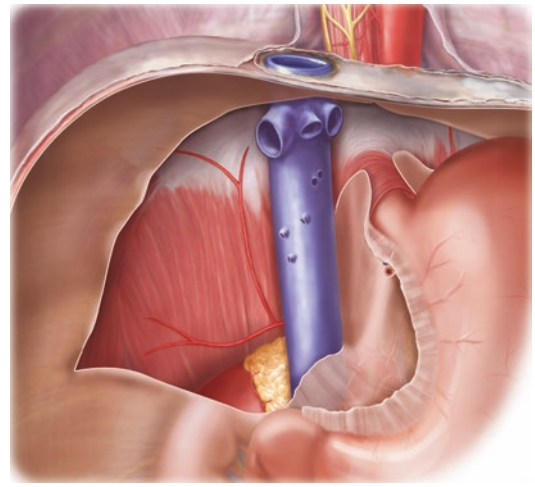

**Fig. 16.8** Anatomy of the retrohepatic vena cava. Note the 3 major hepatic veins and the multiple short hepatic veins. (From: Corcos A, Six C, Britt LD, Peitzman AB. Abdominal trauma. In Peitzman AB, Yealy DM, Fabian TC, Schwab CW, Guyette FX, Seamon MJ, Zuckerbraun BS, (eds). The Trauma Manual, fifth edition. Wolters-Kluwer, Philadelphia, 2020, page 453)

tree with blunt hepatic injury is based on hemodynamic status. If the patient is stable enough for CT, they will generally be successfully managed nonoperatively, irrespective of the grade of hepatic injury. However, 10–25% will require an intervention: angioembolization for bleeding or pseudoaneurysm; ERCP and stent for bile leak; or percutaneous drain for abscess or biloma [15–17].

An understanding of hepatic anatomy is essential when approaching these injuries at surgery for hemorrhage control. A sagittal plane running from the IVC to the gallbladder fossa separates the right and left lobes (Cantlie's line). The segmental anatomy of the liver is shown in Fig. 16.7. The portal triad, containing the portal vein, hepatic artery, and common bile duct, is encased within a tough extension of Glisson's capsule and runs centrally within the segments of the liver. Right and left hepatic arteries usually arise from the common hepatic artery. Anomalies are frequent and include the right hepatic artery originating from the SMA and the left hepatic artery originating from the left gastric artery. The major hepatic veins run between segments of the liver and are not protected by an investing sheath, making them particularly vulnerable to injuries that require operative control of hemorrhage. (Fig. 16.8) The right and left hepatic veins drain directly into the IVC just below the hiatus and have short extrahepatic courses. The middle hepatic vein also drains directly to the IVC in 15% of patients but usually joins the left hepatic vein within the liver parenchyma. The retrohepatic IVC is approximately 10 cm in length and has multiple "short" hepatic veins that enter the cava directly. These average 5–7 in number and may be as large as 1 cm in diameter. This area is difficult to access, and injury here is difficult to control carrying a high mortality [18–20].

Adequate mobilization of the liver requires division of the ligamentous attachments. The falciform ligament divides the left lateral segments (II and III) from the medial segment of the left lobe (IV). The coronary ligaments attach the liver

to the diaphragm by anterior and posterior leaflets and are avascular, as are their lateral extensions, the left and right triangular ligaments. Division of these ligamentous attachments exposes the "bare" area of the liver which is without a capsule and contains the short hepatic veins and cava. Injury to the diaphragm, phrenic veins, and hepatic veins must be avoided when mobilizing the liver.

As mentioned, the majority of patients with blunt injury to the liver who do not have other intra-abdominal injuries requiring laparotomy can be treated with NOM regardless of AAST grade. (Fig. 16.9) In addition, the presence of hemoperitoneum on CT scan does not mandate laparotomy. Grade 4 and 5 injuries are more likely to develop a complication which requires an intervention; bleeding, bile leak, abscess, biloma, or hemobilia. The criteria for NOM of blunt liver injury include the following: hemodynamic stability, absence of peritoneal signs, lack of continued need for transfusion for the hepatic injury, and bleeding amenable to angioembolization.

There is little support for frequent hemoglobin sampling, bed rest, or prolonged intensive care unit monitoring in NOM of blunt liver injury. Similarly, reimaging the asymptomatic patient by CT scan is not necessary. Early repeat imaging is reserved for changes in clinical status (abdominal pain, fever, abnormal LFTs). Evolution of injury on CT, hemodynamic instability, or continued blood product requirement should prompt immediate laparotomy or angiographic intervention.

If the patient is hemodynamically unstable or has indications for laparotomy, operative management is required. The operative approach to major hepatic injury is systematic and logical along the following management principles: manual compression to resuscitate, division of ligamentous attachments for adequate exposure, packing that reconstructs hepatic anatomy, inflow occlusion (Pringle maneuver) if necessary for

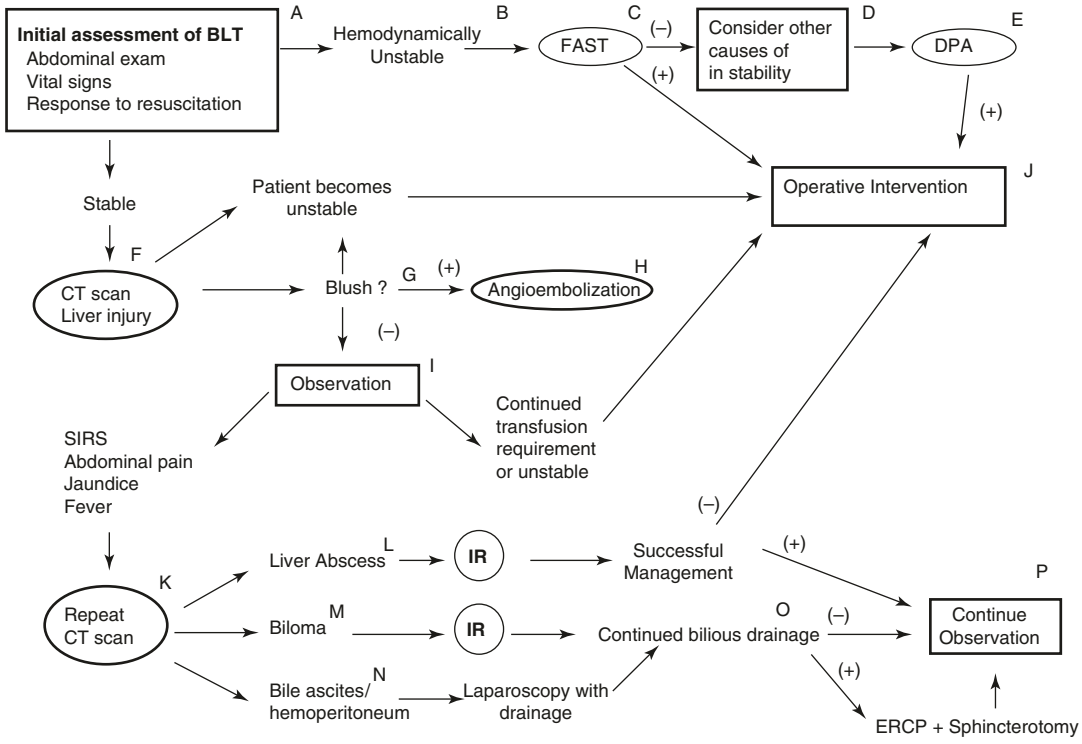


**Fig. 16.9** Western Trauma Association algorithm for the nonoperative management of blunt hepatic injury. (From: Kozar, R.A., Moore, F.A., Moore, E.E., et al., Western Trauma Association critical decisions in trauma: nonoperative management of adult blunt hepatic trauma. J Trauma, 2009. 67 [6]: p. 1144–8)

ongoing bleeding, individual vessel ligation when possible, mobilization of the liver to midline when necessary, and adherence to damage control principles (Fig. 16.10).

In the case of failed NOM when an approach to the liver is the recognized goal, a bilateral subcostal incision will offer excellent exposure. When already at laparotomy via the typical long midline incision for trauma, a transverse extension laterally to the right will facilitate optimal exposure to the entire right upper quadrant. On rare occasion, an extension of the midline incision to sternotomy is needed for complex suprahepatic IVC injury. Use of a self-retaining retractor to lift the upper edges of the wound cephalad and anteriorly is critical. Thoracotomy is rarely useful. Low grade, non-bleeding injuries encountered at laparotomy for other injuries can be managed with simple techniques (electrocautery, simple suture, or topical hemostatic agents).

Complex liver injuries can produce exsanguinating hemorrhage; the only essential goal at the first operation is to stop the bleeding. Ultimate operative goals include controlling bile leak,

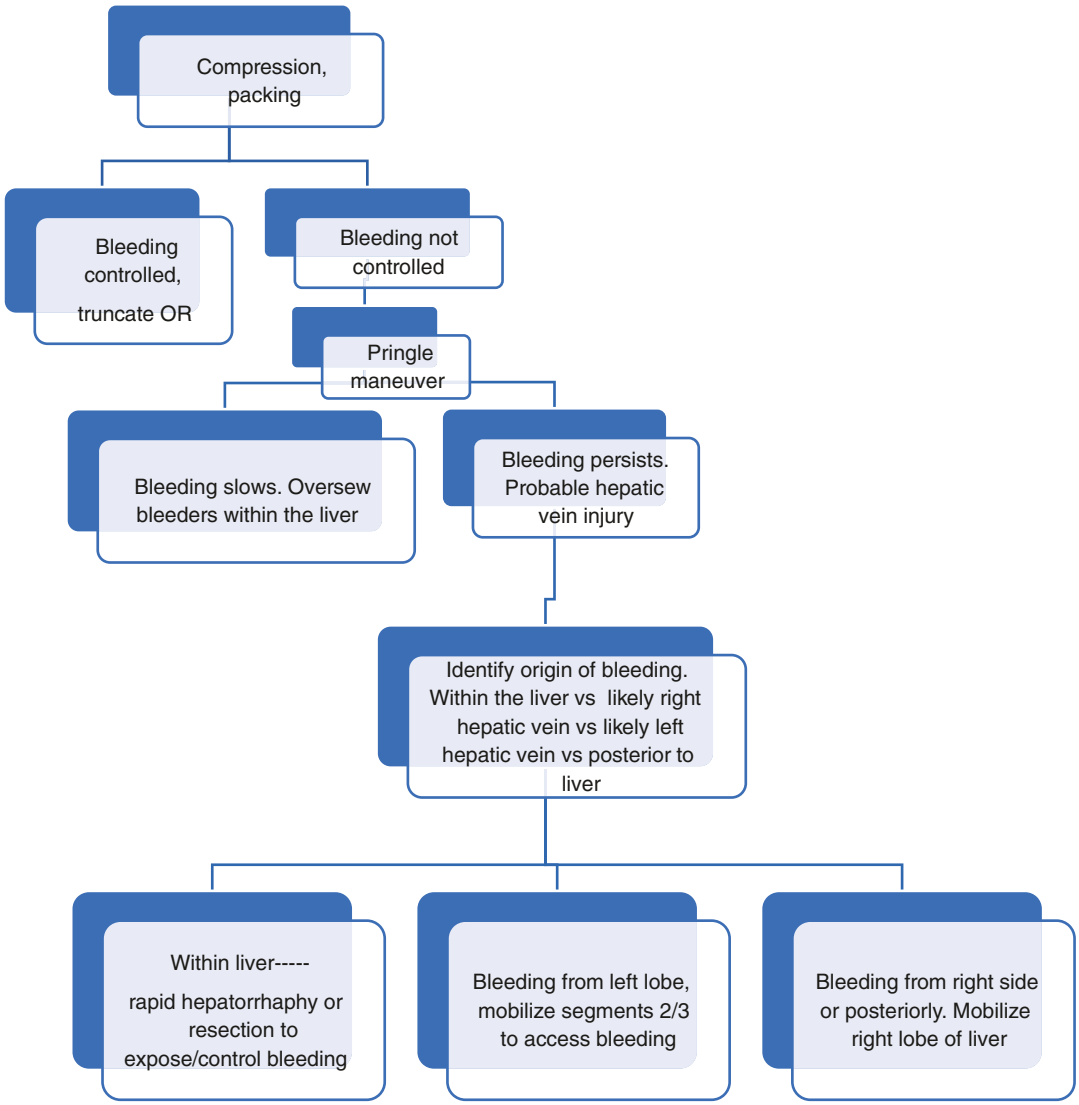


**Fig. 16.10** Flowchart for the operative management of major hepatic injury

debridement of non-viable liver, and drainage, but these operations are most frequently staged.

To begin, temporary tamponade of the bleeding by two-handed manual compression of the entire liver (**push**) immediately after entering the abdomen allows anesthesiology to resuscitate the patient and the surgeon to formulate an operative plan. Next, **pack** the liver to control hemorrhage as blood flow to the liver is largely a low-pressure system. Packing the liver, however, must be performed correctly. Restore normal anatomy by compressing the left lobe back into the right lobe while simultaneously directing the liver posteriorly to tamponade any posterior venous bleeding. Stuffing packs into the liver laceration will distract the injury and exacerbate bleeding. If packing successfully stops the bleeding in a hemodynamically unstable patient, truncate the first operation and plan return to the operating room in 36–48 hours to remove the packs and reassess.

If packing does not control the bleeding, occlude the portal triad within an atraumatic clamp (**Pringle** maneuver); this is both diagnostic and therapeutic. If the Pringle maneuver substantially slows the bleeding, the source is either hepatic artery or portal vein branches; rapid hemorrhage control within the laceration can be accomplished with hepatorrhaphy and individual vessel ligation. Mass parenchymal suturing can lead to tissue necrosis and is discouraged. Incise Glisson's capsule with electrocautery; approach the injury within the liver by the finger fracture technique. With gentle traction on the liver edges, isolate injured vessels and bile ducts between right-angled or tonsil clamps and ligate with 2–0 silk sutures, or even more rapidly with vascular staplers. Intermittent application of the Pringle maneuver (10–15 min on, 5 min off) produces less hepatic ischemia than continuous clamping. Packing the liver defect with viable omentum is not recommended as a reliable hemostatic technique.

If bleeding persists with the porta hepatis occluded, the source is injury to the IVC, a major hepatic vein or the short hepatic veins. If the origin is within the laceration of the liver, a direct approach is preferred. If the bleeding is extrahepatic, the origin can usually be located to either over the dome of the liver, suggesting a middle or left hepatic vein injury, or posterior to the liver, suggesting an IVC, right hepatic vein, or short hepatic vein injury. This determination guides which lobe to mobilize. Remember, the entire liver can be made a midline structure with mobilization.

Liver resections for traumatic injuries are typically non-anatomic and can be performed rapidly with vascular staplers. Often, these are completion resections along injury planes. On occasion, this may be required to expose hepatic vein injuries that can then be ligated or repaired expeditiously. The Aquamantys Bipolar Sealer device is an invaluable adjunct to the Argon Beam Coagulator in managing exposed liver parenchyma following resection or individual vessel ligation.

With major hepatic resection, an intraoperative cholangiogram via the cystic duct (necessitating cholecystectomy) will help define biliary anatomy. Injection of saline through the cystic duct will help identified bile leaks that require ligation to avoid postoperative complications. These maneuvers are often performed at planned returns to the operating room following hemorrhage control rather than the index laparotomy. Closed suction drainage of grade III to V injuries is preferred. Drains are not necessary for grade I and II injuries if bleeding and bile leakage are controlled.

Hepatic vascular isolation with occlusion of the suprahepatic and infrahepatic vena cava, as well as application of the Pringle maneuver, may be required for major retrohepatic venous injuries. Complex retrohepatic vascular injury may require repair in an avascular field on venovenous bypass with total hepatic vascular isolation. Thoracotomy or atrial–caval shunting is rarely helpful. Survival depends on prompt recognition, adequate exposure, and rapid access to a bypass circuit.

Mortality correlates with degree of injury. Although overall mortality for liver injury is 10%, mortality rates for high grade liver injury and retrohepatic caval injury remain well over 50% at most centers. Intrahepatic or perihepatic abscess or biloma occurs in up to 40% of patients

and can usually be managed with percutaneous drainage. Meticulous control of bleeding, ligation of bile ducts, adequate debridement, and closed suction drainage are essential to avoid abscess formation. Biliary fistula (>50 mL/day for more than 2 weeks) usually resolves nonoperatively if external drainage of the leak is adequate and distal obstruction is not present. With a high output bile leak (>300 mL/day), further evaluation with a radionucleotide scan, a fistulogram, ERCP, or a transhepatic cholangiogram may be necessary. Major ductal injury can be stented to facilitate healing of the injury or as a guide if operative repair is required. Endoscopic sphincterotomy or trans-ampullary stenting may facilitate resolution of the biliary leak. Hemobilia is a rare complication that may occur days or weeks after injury. The classic presentation is right upper quadrant pain, jaundice, and hemorrhage with only one-third of patients presenting with all three. Treatment is angioembolization.

## 16.6 Conclusion

Blunt abdominal injury often occurs in the polytrauma patient. As physical examination is unreliable in their diagnosis, adjunctive techniques are vital; FAST, CT, and DPA. Hypotensive patients with blunt abdominal injury require prompt hemorrhage control and at times, invoking damage control approaches.

**Key Concepts**

- Blunt abdominal injury most commonly injures solid organs.
- The majority of solid organ injury is low grade and can be managed nonoperatively. High grade solid organ injury tends to produce hypotension on presentation and operative decision-making is difficult and technically challenging.
- Blunt hollow viscus injury is less common and difficult to diagnose clinically.
- Adjunctive diagnostic techniques are important.

**Take Home Messages**

- Understand injury patterns to suspect blunt abdominal injuries.
- Physical exam is insensitive in the diagnosis of blunt abdominal injury.
- 85% of blunt injuries to the liver and over 65% of splenic injuries can be managed nonoperatively.
- The high grade solid organ injuries produce active bleeding and generally require urgent operation. Damage control is useful in this setting.

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# Penetrating Injuries of the Thorax

# 17

Areg Grigorian and Kenji Inaba

## Abbreviations

| | |
|---|---|
| AAST | American Association for the Surgery of Trauma |
| CT | Computed tomography |
| EAST | Eastern Association for the Surgery of Trauma |
| FAST | Focused Assessment with Sonography in Trauma |
| PMG | Practice Management Guideline |

**Learning Objectives**

- What are the key intrathoracic injuries to be aware of after penetrating thoracic trauma?
- What are the indications for resuscitative thoracotomy and how is it performed safely?
- How do you recognize a tension pneumothorax and/or hemopneumothorax?
- What is an occult pneumothorax?
- How is a tension pneumothorax, hemopneumothorax, and occult pneumothorax managed?
- What is the role of the cardiac box in penetrating thoracic trauma?
- How are suspected penetrating cardiac injuries worked up and managed?
- How are clinically significant lung injuries worked up and managed?
- How are suspected esophageal injuries worked up and managed?

## 17.1 Introduction

In the United States, on average penetrating injuries account for nearly 10% of trauma cases with a relatively equal distribution of patients presenting after gun (47%) or stab wounds (53%). The upper extremity is the most commonly affected region (32%), followed by the chest (29%) [1]. Over the past two decades, we have seen a four and nine-fold increase in the number of prehospital deaths involving gun or stab wounds, respectively, while in-hospital mortality has decreased resulting in a relatively flat rate of mortality after penetrating trauma (2–14%) [1].

All trauma patients should be expeditiously assessed with the primary survey in a systematic fashion including airway, breathing, and circulation. Since penetrating thoracic trauma can affect

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each of the ABCs, the chest needs to be evaluated quickly for life-threatening injuries. The diagnostic approach for penetrating thoracic trauma has undergone several iterations over the past century involving both operative and non-operative algorithms. This is a direct result of alterations in hospital resources, societal guidelines based on clinical trials and advances in diagnostic imaging [2]. One of the most important determinants for patient survival after penetrating trauma is rapid pre-hospital transport as the time interval from injury to control of hemorrhage is an independent predictor of survival [3, 4].

There are several intrathoracic injuries that need to be recognized immediately during the primary survey as there may be a lifesaving intervention that can be performed. These include pneumothorax, hemothorax, cardiac, lung, and esophageal injuries. This chapter will focus on the recognition of these intrathoracic injuries after penetrating trauma as well as the interventions used to treat them.

## 17.2 Resuscitative Thoracotomy

In 1901, the first successful thoracotomy was performed on a trauma patient in cardiac arrest [5]. In subsequent years, Beall et al. advocated for the immediate performance of a thoracotomy in the emergency department for bleeding trauma patients [6]. This should be performed concurrently with airway management. Resuscitative thoracotomy is one of the most polarizing and controversial procedures performed in the emergency department with proponents suggesting it offers patients a possible chance for survival and opponents emphasizing the low survival rate and risks such as the exposure to blood-borne pathogens [7, 8]. While personal protective equipment is paramount and can decrease risk of occupational exposure by 34%, there remains a true risk and cost to this procedure [9]. There are, however, survivors. In the largest analysis of outcomes after resuscitative thoracotomy, the overall survival was 7.4% with patients presenting after penetrating cardiac injury with signs of life having the highest chances of survival, of upwards of 20% [10].

The procedure allows for control of thoracic bleeding, release of pericardial tamponade, and direct cardiac massage. In the case of a polytrauma patient, anterolateral thoracotomy also allows for aortic cross-clamping, providing rapid control of infra-diaphragmatic bleeding in the exsanguinating patient. In cases of suspected right-sided injury, the thoracotomy can be extended in a clamshell fashion to have complete exposure of the thoracic cavity.

### 17.2.1 Indications and Contraindications

In 2011, the Western Trauma Association published a multicenter report detailing the limits of the resuscitative thoracotomy. They deemed resuscitative thoracotomy to be futile in penetrating trauma patients who undergo >15 min of pre-hospital cardiopulmonary resuscitation without response or manifest asystole without pericardial tamponade [11]. The most recent evidence based practice management guideline (PMG) for resuscitative thoracotomy was published in 2015 from Eastern Association for the Surgery of Trauma (EAST) [12]. A strong recommendation is made for patients presenting pulseless to the emergency department with signs of life and a conditional recommendation is made for those presenting without signs of life. The qualifying duration of pre-hospital cardiopulmonary resuscitation was removed due to insufficient evidence. However, they state that thoracotomy after 15 min of arrest time in penetrating trauma is likely futile. It appears that practices and outcomes following resuscitative thoracotomy have not changed significantly since the 2015 EAST PMG publication [13]. Additionally, Focused Assessment Using Sonography for Trauma (FAST) has been demonstrated to have 100% sensitivity in identifying potential survivors after traumatic arrest. The likelihood of survival in patients with absent pericardial fluid and cardiac motion on FAST approaches zero [14]. In summary, for the arresting patient, the treatment is a

resuscitative thoracotomy. Penetrating chest trauma is one of the strongest indications for this procedure.

### 17.2.2 Technique and Staff Safety

The quickest approach to access the essential structures is provided with a left anterolateral incision starting from left of the parasternal border at the fourth or fifth intercostal space and ending at the posterior axillary line . The major muscles divided include the pectoralis major/minor as well as the serratus anterior allowing access to the ribcage. The pleural cavity is then entered by dividing the intercostal muscle with scissors on the superior border of the rib avoiding the neurovascular bundle. A Finochietto retractor spreads the ribs (Fig. 17.1). The inferior pulmonary ligament is then divided, and the lower lung lobe is grasped with forceps and retracted cephalad which exposes the heart and aorta. The goal of this procedure is to evacuate any pericardial blood, control large volume bleeding, cross clamp the aorta, and ultimately restore spontaneous circulation. If this can be achieved, the patient should be taken immediately to the operating room for definitive surgery. Close communication, personal protective equipment, and safely discarding sharps can all help decrease risk of accidental injury to healthcare providers.

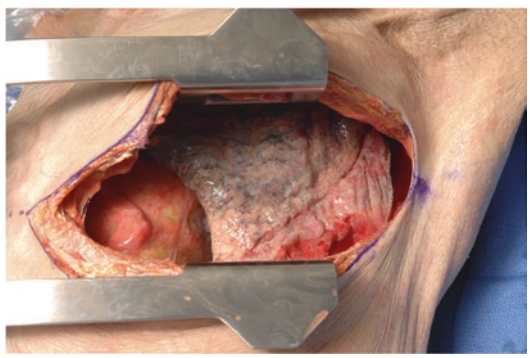

**Fig. 17.1** A Finochietto retractor spreads the ribs. Reproduced with permission from "*Atlas of Surgical Techniques in Trauma, 2nd edition*"; Eds: Demetriades, Inaba, Velmahos; Cambridge University Press; 2020

## 17.3 Tension Pneumothorax

Pneumothorax occurs in 5–10% of penetrating trauma cases while hemothorax occurs in 4–5% of cases [15]. Although hemorrhage needs to be ruled out in all hypotensive trauma patients, tension pneumothorax should be considered as well. Decreased ipsilateral breath sounds are classically described to be associated with a pneumothorax, however it may be difficult to auscultate in the trauma bay, and tracheal deviation may be challenging to detect with a cervical collar in place. A tension pneumothorax can cause functional deformation of the heart, and shift the mediastinum reducing preload, both of which can lead to decreased cardiac output. In a patient with suspected tension pneumothorax, immediate intervention, even without imaging, is required. In equivocal cases, ultrasound can be used at bedside to look for the absence of lung sliding which would support the diagnosis [16].

### 17.3.1 Needle Decompression

Needle decompression is performed to acutely decompress a tension pneumothorax. Using a percutaneous catheter over needle technique, decompression is performed classically in the second intercostal space, mid-clavicular line [17]. This procedure unfortunately is not universally successful, with upwards of half of the catheters not making their way into the pleural cavity due to chest wall thickness [18]. An alternative insertion position, in the fourth or fifth intercostal space, anterior to mid axillary line, has been evaluated and found to be more effective for needle decompression, especially in obese patients and should be considered if initial attempts at decompression fail [19–21].

#### 17.3.1.1 Hemopneumothorax

Hemothorax can be a life-threatening injury with thoracotomy being the procedure of choice in those with massive or persistent bleeding. Indications for immediate operative exploration include: (1) 1000–1500 mL of blood evacuated immediately after tube thoracostomy, (2) 200–300 mL/h for 2–3 h follow-

ing tube insertion, or (3) ongoing blood product resuscitation required to maintain hemodynamic instability [17]. In a polytrauma patient with massive hemorrhage consider autotransfusion with cell-saver technique. This can be performed with most single-chamber chest drainage systems. All efforts to clear a retained hemothorax should be employed as this is associated with high rates of empyema and pneumonia [22, 23].

An occult pneumothorax is defined as a pneumothorax detected on computed tomography (CT) imaging that was not visualized on chest X-ray [24]. The incidence of an occult pneumothorax is up to 15% among trauma patients undergoing CT imaging [25]. For most patients with an occult pneumothorax, observation is the appropriate treatment. In the case of a polytrauma patient with an occult pneumothorax, they may have an extra-thoracic injury (e.g., femur fracture) requiring surgical intervention. This has led some authors to suggest that the positive-pressure ventilation in a mechanically ventilated trauma patient may convert a seemingly benign occult pneumothorax into a clinically significant one [25–27]. However, several evidence based reviews such as the EAST Practice Management Guidelines [28] and the Canadian Association of General Surgeons Evidence Based Reviews [29] recommend continued observation in stable patients with an occult pneumothorax regardless of positive-pressure ventilation.

### 17.3.2 Tube Thoracostomy

While both open and percutaneous methods are available, the standard of care remains the open technique. The ideal incision is at the fourth or fifth intercostal space (level of the nipples in males or inframammary crease in females) at the midaxillary line. After local anesthesia is injected in the skin, a 2–3 cm incision is made and dissected to the ribcage. Using forceps, the thoracic cavity is entered in a controlled manner and the tract is developed using blunt dissection. After confirmation of entry into the chest, a 28–32 Fr tube is then inserted into the pleural cavity and turned towards the chest wall (clockwise on the left and counterclockwise on the right) to help position it posteriorly and cephalad (Fig. 17.2). Smaller tubes (28-Fr) are just as effective as larger ones in evacuating both air and blood [30].

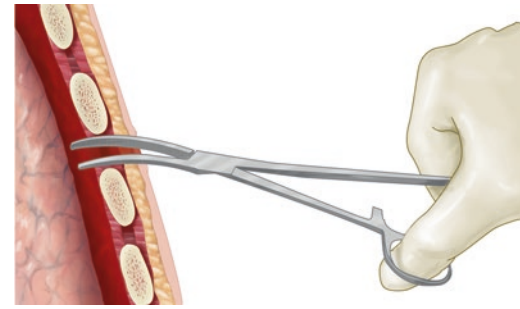

**Fig. 17.2** Chest tube positioned properly posteriorly and cephalad. Reproduced with permission from "*Atlas of Surgical Techniques in Trauma, 2nd edition*"; Eds: Demetriades, Inaba, Velmahos; Cambridge University Press; 2020

## 17.4 Cardiac Injury

Penetrating trauma is far more commonly associated with cardiac injury than blunt trauma. The majority of penetrating thoracic trauma is due to stab wounds (76%) while gunshot wounds comprise 24% [31]. The right ventricle is the most commonly injured chamber of the heart followed by the left ventricle and right atrium [32, 33]. Pericardial tamponade may also be present in upwards of 60% of cases [34]. The clinical presentation is highly variable and patients that arrive hemodynamically stable can deteriorate rapidly. As the distensibility of the heart is reduced due to a shrinking pericardial space, the septum is displaced to the left compromising cardiac output. As such, any delay in decompressing the pericardial space is associated with a poorer prognosis [35].

The "cardiac box" is bordered by the sternal notch, xiphoid process, and nipples. The role of this anatomic location in the clinical evaluation of a penetrating thoracic trauma patient remains unclear. Stab wounds appear to be associated with a higher risk of cardiac injury but not gunshot wounds [31]. However, because cardiac injuries are so time sensitive, all patients sus-

pected of a possible cardiac injury require expeditious workup starting with a FAST exam, regardless of symptoms [10, 36].

### 17.4.1 Identification and Imaging

Patients with cardiac injuries have varied presentations ranging from being completely asymptomatic with normal vital signs to cardiac arrest. More commonly, patients with cardiac injuries may appear restless with weak peripheral pulses, tachycardia, and hypotension. Pulsus paradoxus is identified in less than 10% of patients [37]. All hypotensive patients with penetrating chest trauma should be considered to have a cardiac injury until proven otherwise. All patients with penetrating thoracic trauma (stab wounds or gunshot wounds), regardless of symptoms, need cardiac injury ruled out immediately with a FAST exam.

The primary diagnostic modality readily available to help identify a cardiac injury is the FAST exam [38]. This has replaced the subxiphoid pericardial window. A thin dark anechoic stripe of fluid surrounding the heart has a near perfect sensitivity for cardiac injury [39]. Be aware that chronic pericardial effusion is indistinguishable on FAST from acute hemopericardium and a cardiac injury may occasionally be missed because of associated decompression into the thoracic cavity [38]. For an equivocal FAST exam, consider a formal transthoracic or transesophageal echocardiogram. If the diagnosis remains unclear, the patient may need a pericardial window.

### 17.4.2 Indications to Intervene

In a patient after penetrating chest trauma that appears tremulous or becomes pulseless in the trauma bay, a resuscitative thoracotomy should be performed. This will allow rapid access to the heart to evacuate the hemopericardium. Ideally however, the heart is accessed through a median sternotomy. Hemodynamically stable patients with suspected cardiac injury should be transported to the operating room and placed in the supine position with both arms abducted at 90 degrees. Prepping the patient from their chin to their knees is recommended prior to induction with general anesthesia as this will blunt the patient's sympathetic drive risking cardiac arrest. The goal of the index operation is to confirm the diagnosis and repair the injured external cardiac wall. In the postoperative setting, an echocardiogram can evaluate for septal or valvular injuries and a decision for repair can be made at that time.

### 17.4.3 Operative Exposure

The ideal exposure for injuries to the heart is a median sternotomy. Because of the anterior-lateral location, the right and left ventricles are at greatest risk for injury.

A median sternotomy is performed with an incision extending from the suprasternal notch superiorly to the xiphoid inferiorly. The interclavicular ligament is cleared from its attachment to the underside of the sternum using electrocautery and blunt dissection. A pneumatic saw is then used to divide the sternum after it is scored along the midline with a scalpel or electrocautery. A Finochietto retractor is then used to spread the sternum ensuring the retractor is placed cephalad in the case of a required laparotomy later in the operation.

### 17.4.4 Repair Options

If there is pericardial tamponade, the goal is to relieve the trapped blood as quickly as possible. The pericardium may be quite tense making it difficult to grasp with a hemostat. A small pericardiotomy may be performed which can allow for scissors to open the pericardium longitudinally staying anterior and parallel to the phrenic nerve (Fig. 17.3). In the case of a median sternotomy, the pericardium should be opened along the midline. This maneuver allows for the delivery of the heart.

Penetrating cardiac injuries can range from small linear lacerations to destructive and complex injuries involving the coronary arteries. In the case of exsanguination, temporary techniques

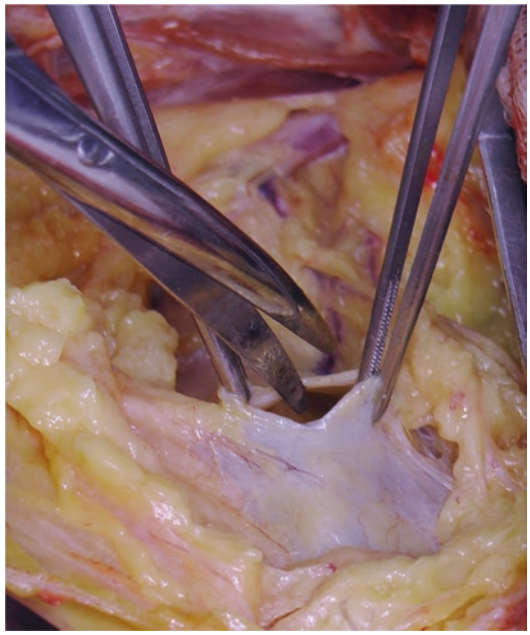

**Fig. 17.3** Sharply opening the pericardium longitudinally staying anterior and parallel to the phrenic nerve. Reproduced with permission from "*Atlas of Surgical Techniques in Trauma, 2nd edition*"; Eds: Demetriades, Inaba, Velmahos; Cambridge University Press; 2020

to control bleeding include finger, balloon and clamp occlusion, or skin staples. These maneuvers must be executed carefully and judiciously as they may convert smaller injuries to larger ones.

Cardiac wounds may be repaired with horizontal mattress or running sutures using polypropylene 2–0 sutures on a large tapered needle. In the case of destructive or blast injuries, the sutures may not hold well without the use of pledgets. However, the routine use of pledgets is not recommended. In the case of cardiac injuries near major coronary vessels, the wound should be repaired with horizontal mattress sutures placed underneath the vessel to avoid ligation and future myocardial ischemia.

### 17.4.5 Complications

In the event of a transected coronary vessel, observation may be appropriate if the injury is distal as this rarely has a clinical impact. In the case of a proximal vessel injury such as to the left anterior descending artery, the vessel should be repaired with interrupted sutures. Cardiopulmonary bypass is rarely needed during the index operation. Evaluation of the posterior heart requires lifting the heart. This can result in cardiac arrest and should ideally be done when the patient is appropriately resuscitated. Lifting the heart sequentially with laparotomy pads may allow for accommodation so the patient can tolerate repair of the posterior aspect of the heart.

## 17.5 Lung Injury

Injury to the lung occurs in 50–70% of patients after penetrating thoracic trauma [40, 41]. The vast majority are treated non-operatively. Due to its unique dual blood supply, pulmonary parenchymal injuries can present with variable bleeding depending on the concurrent vessel injury. The pulmonary artery trunk carries deoxygenated blood from the heart to the lung where gas exchange may occur. The pulmonary trunk and arteries are large diameter vessels under low pressure. Conversely, the bronchial arteries are a high-pressure system arising directly from the thoracic aorta. As such, injury to this vasculature can lead to massive hemorrhage and is the primary indication for operative intervention.

### 17.5.1 Identification and Imaging

Although a pneumothorax may be identified on physical exam, pulmonary parenchymal injuries may be more conspicuous. Stable patients with penetrating chest trauma should always be evaluated with a chest X-ray in the trauma bay, even if it is an anteroposterior portable film. A delayed 1–3-hour chest X-ray in stable patients after a stab wound is warranted [42]. For gunshot wounds, all patients should undergo chest CT [43].

### 17.5.2 Indications to Operate

Most lung injuries can be managed with chest tube drainage and supportive care alone.

However, patients with massive hemorrhage or persistent air-leak may require operative intervention. Generally, non-anatomical lung resections are preferred to anatomic resections. In patients that are hemodynamically stable and will tolerate it, a double-lumen tube is preferred isolating the injured hemithorax.

### 17.5.3 Techniques for Exposure

The ideal incision for most lung injuries is an anterolateral thoracotomy. The incision begins at the sternum in the fourth or fifth intercostal space and ends at the posterior axillary line. The major muscles divided include the pectoralis major/minor as well as the serratus anterior allowing access to the ribcage. The pleural cavity is then entered by dividing the intercostal muscle with scissors on the superior border of the rib avoiding the neurovascular bundle. A Finochietto retractor spreads the ribs to access the chest.

### 17.5.4 Repair Options

There are a variety of options for repair of lung trauma. The site, severity, and concurrent injuries dictate which technique should be employed. The goal for the surgeon should be to remove as little lung as possible as increased mortality is linked with increased lung mass removed [44].

Pneumonorrhaphy or suture repair of the lung is appropriate for small, superficial wounds. Absorbable figure-of-eight suture should be used to control minor air leaks and bleeding (Fig. 17.4). This is generally not the primary problem, as these injuries are most often not clinically significant.

The more significant injury is likely deeper in the lung. Accessing these injuries often requires lung tractotomy or segmental resection. Lung tractotomy can be performed with a stapling device deployed parallel to the vasculature, if possible, with oversewing of any areas concerning for air-leak or significant bleeding. For injuries that are peripheral, a wedge resection may be the more appropriate intervention as this will remove the injured segment, remove any devitalized parenchyma, and allow for ligation of healthy lung tissue underneath the wounded segment.

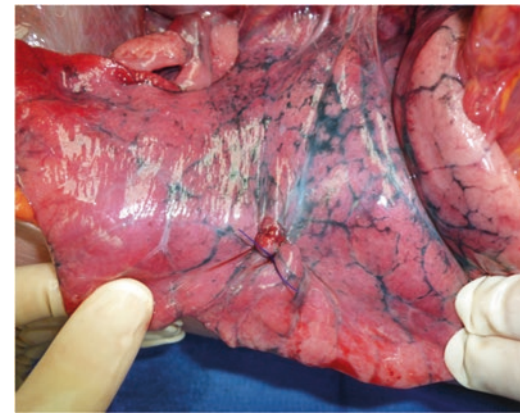

**Fig. 17.4** Pneumonorrhaphy of the lung using absorbable figure-of-eight suture. Reproduced with permission from "*Atlas of Surgical Techniques in Trauma, 2nd edition*"; Eds: Demetriades, Inaba, Velmahos; Cambridge University Press; 2020

In cases of massive or persistent hemorrhage undeterred by the preceding interventions, a large vascular clamp or digital pressure can be applied to the hilum. This needs to be done carefully with close communication with the anesthesia team as this may lead to massive right heart failure. An alternative approach for hilar control is to twist the lung 180-degrees around the hilum constricting both inflow and outflow (Fig. 17.5) although we do not do this routinely.

Finally, a pneumonectomy may be considered in patients as a last-ditch effort. This intervention is associated with a significantly high mortality rate [45]. However, it can be performed rapidly using a stapling device applied across all the hilar structures.

## 17.6 Esophageal Injury

Esophageal trauma occurs in less than 1% of trauma patients but associated with a high mortality rate, particularly if there is a delay in diagnosis

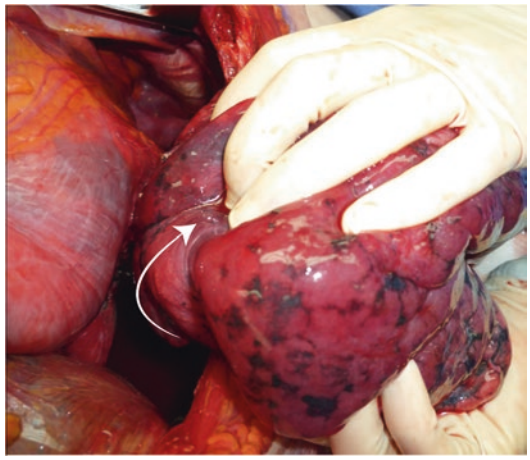

**Fig. 17.5** Hilar control by twisting the lung 180-degrees around the hilum constricting both inflow and outflow. Reproduced with permission from "*Atlas of Surgical Techniques in Trauma, 2nd edition*"; Eds: Demetriades, Inaba, Velmahos; Cambridge University Press; 2020

[46, 47]. More than half of traumatic esophageal injuries occur after penetrating trauma with gunshot wounds being the most common mechanism [48]. The thoracic esophagus is the most common area injured [48]. The esophagus is nested in the neck and chest between the trachea and spine [49]. Although its anatomic position protects it from injury the blood supply to the esophagus is poor and its lack of a serosal layer increases the risk of morbidity when there is an injury [50].

Esophageal injuries are graded based on the American Association for the Surgery of Trauma (AAST) classification system. Patients with a grade-V injury (segmental loss or devascularization >2 cm) have a mortality rate of 66% [51]. The cervical esophagus is generally associated with a lower mortality rate compared to thoracic esophageal injuries. This may be due to the protected anatomical location of the cervical esophagus which may prevent bacterial spillage into the mediastinum. Injury to the thoracic esophagus is associated with more extensive mediastinitis and pleural effusion leading to septic shock [52].

### 17.6.1 Identification and Imaging/ Endoscopy

Thoracic esophageal injury is rarely diagnosed with physical exam alone. Patient's with concurrent hemo- or pneumothoraces requiring chest drainage demonstrating saliva or food particles should be suspected of having an esophageal injury and require additional evaluation [51].

The initial diagnostic modality for a trauma patient with trauma to the chest is a chest X-ray. Pneumomediastinum or free air under the diaphragm can be suggestive of esophageal trauma. Stable patients suspected of thoracic esophageal injury should be worked up with a CT scan which is effective for definitive diagnosis [53]. This can also help define the missile trajectory, and to determine if the other intrathoracic structures were injured. Esophagoscopy or a dedicated contrast swallow study can be used to further evaluate patients with an equivocal CT study. This has been demonstrated to have a negative predictive value approaching 100% but with a poor positive predictive value [54].

### 17.6.2 Indications for Operative Management

Non-operative management is appropriate for hemodynamically stable patients with small and contained leaks with mild or no signs/symptoms. These patients should be managed conservatively with a planned esophagogram within several days to document resolution of the leak before starting an enteral diet. Initial management includes nil-per-os, fluid resuscitation, broad spectrum IV antibiotics, and internal drainage with careful insertion of a nasogastric tube under endoscopic guidance [55]. Patients that are unstable or in septic shock should proceed with surgical intervention.

### 17.6.3 Exposure

The incision depends on which part of the thoracic esophagus is injured. For those with mid-esophageal injuries the preferred incision is a right posterolateral thoracotomy at the fourth or fifth intercostal space. This avoids the aorta which would be in the way with a right-sided exposure. The distal esophagus can be approached with a left posterolateral thoracotomy at the seventh or eighth intercostal space. However, the approach is often dictated by what additional thoracic injuries are present.

### 17.6.4 Repair Options

The general principle in repair of esophageal injury is to first identify the full extent of injury which may require extending the myotomy. All devitalized tissue must be debrided, the defect closed in two layers (mucosa and submucosa) and with the liberal use of buttressed muscle reinforcement. Wide drainage of the injury should also be performed.

### 17.6.5 Complications

The esophagus is unique in the fact that it lacks a serosal layer. This makes it a high-risk organ for postoperative leak. This is particularly a troublesome complication in patients with repaired thoracic esophageal injuries as these patients are at high risk for subsequent mediastinitis, sepsis, and death.

## 17.7 Conclusion

Penetrating thoracic injuries are important to recognize as they may be associated with a high rate of mortality, particularly with a delay in diagnosis. The trauma provider needs to expeditiously assess the patient with the primary survey in a systematic fashion including airway, breathing, and circulation. In some cases (tension pneumothorax), the patient requires intervention before a diagnosis is confirmed. Chest CT and the FAST exam are excellent tools for trauma providers to use when working up a patient with suspected penetrating thoracic trauma.

**Key Concepts**

- Intrathoracic injuries
- Indications for resuscitative thoracotomy
- Tension pneumothorax, hemothorax, pneumothorax, occult pneumothorax
- Interventions for hemopneumothorax
- Cardiac box
- Intervention for penetrating cardiac injury
- Lung injury after penetrating trauma
- Esophageal injury after penetrating trauma

**Take Home Messages/Take Home Points**

- All trauma patients should be expeditiously assessed with the primary survey in a systematic fashion including airway, breathing, and circulation.
- Resuscitative thoracotomy allows for control of thoracic bleeding, release of pericardial tamponade, and direct cardiac massage.
- Although hemorrhage needs to be ruled out in all hypotensive trauma patients, tension pneumothorax should be considered as well and treated with needle decompression initially.
- The clinical presentation of a penetrating cardiac injury is highly variable and patients that arrive hemodynamically stable can deteriorate rapidly.
- The ideal exposure for injuries to the heart is a median sternotomy.
- Most lung injuries can be managed with chest tube drainage and supportive care alone. However, patients with massive hemorrhage or persistent air-leak may require operative intervention.
- Esophageal trauma occurs in less than 1% of trauma patients but associated with a high mortality rate, particularly if there is a delay in diagnosis.

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# Penetrating Abdominal Trauma

# 18

Ning Lu and Walter L. Biffl

**Learning Objectives**

- Immediate LAP is indicated when there is hemodynamic instability, evisceration, peritonitis, or impalement
- SNOM of stable, asymptomatic patients is safe
- Thoracoabdominal injuries require initial evaluation with CXR and pericardial ultrasound
- Back/Flank injuries benefit from CT with intravenous contrast
- Anterior abdominal SWs can be managed with serial clinical assessments

## 18.1 Introduction

Penetrating abdominal trauma has existed throughout history, however the first exploratory laparotomy (LAP) was not performed until the 1800s [1], just prior to the advent of general anesthesia. According to the 2016 National Trauma Data Bank report, stab wounds only represent 4.1% of all trauma incidents, with a case fatality rate of 2.2% [2]. Strategies for management of penetrating abdominal injuries have evolved over time from mandatory LAP to LAP when indicated and selective nonoperative management (SNOM) [3]. It is widely agreed that indications for immediate LAP include hemodynamic compromise, peritonitis, evisceration, or impalement. However, when it comes to the hemodynamically stable, asymptomatic patient, there is great variation in practice patterns. This chapter will focus on the consequences of mandatory LAP and decision-making relating to SNOM of penetrating abdominal trauma. While the majority of literature pertains to stab wounds (SWs), there has also been recent literature on application of SNOM to gunshot wounds (GSWs). Management of stable patients can be performed in a safe, cost-effective, and evidence-based manner.

## 18.2 Mandatory Laparotomy

Up until the 1960s, mandatory LAP was the standard of care for penetrating abdominal injuries. While it is the considered to be the safest method for identifying all injuries in a timely manner, it certainly has consequences. Up to 70% of LAPs for abdominal SWs are nontherapeutic [3]. In a retrospective study of 459 patients who received mandatory LAP, Leppaniemi et al. [4] noted 147 had no associated extra-abdominal injuries or procedures. Of these patients, 17% had complications and mean LOS was 7.6 days. The first prospective study of patients undergoing non-

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therapeutic LAP by Renz and Feliciano [5] demonstrated a 26% complication rate in patients who had nontherapeutic LAP, even in the absence of associated injuries. Mean and median LOS following nontherapeutic LAP for trauma was 5 days, with complications significantly increasing LOS.

In two Western Trauma Association (WTA) prospective multicenter trials, the mean LOS of patient who underwent nontherapeutic LAP was 3.6 days, despite very few LAP-related complications [6, 7]. In the combined data of these studies, 143 of 581 patients were taken for immediate LAP, and 122 (85%) were therapeutic. Ninety percent of immediate LAPs due to hemodynamic compromise and 89% of those due to evisceration were therapeutic. In contrast, 80% of immediate LAPs due to diffuse peritonitis alone—but only 50% of immediate LAPs for local peritonitis—were therapeutic. Thus, it is critical for an experienced clinician to differentiate true peritonitis from tenderness related to the wound itself.

Mitchell et al. [8] presented a review of all patients who underwent LAP in American combat casualties from 2002 to 2011, demonstrating a 32% rate of nontherapeutic LAP in penetrating mechanisms of injury, with an early intra-abdominal complication rate of 1.7% among these patients. Morrison et al. [9] conducted a similar review of UK combat casualties, with a 21% rate of nontherapeutic LAP and with 26% of these patients developing complications. Certainly, both operative and SNOM of penetrating abdominal injuries in such an austere environment have its limitations.

## 18.3 Selective Nonoperative Management

Strategies for evaluation and SNOM of the stable patient with penetrating abdominal trauma vary depending on anatomical location of the injury. Anatomical regions include the thoracoabdomen (from the nipple line to the costal margin), the flank and back (posterior to the anterior axillary lines), and the anterior abdomen (from xiphoid to pubis, between the anterior axillary lines). Hemodynamic compromise, peritonitis, evisceration, and impalement remain indications for LAP, regardless of region.

### 18.3.1 Thoracoabdomen

Penetrating trauma from the nipple line to the costal margin can create injuries in both the chest and abdomen, including the diaphragm. In patients who are unstable, it can be a challenging dilemma deciding which body cavity to enter first [10]. Chest X-ray and pericardial ultrasound will discern presence of blood in the pericardium or thoracic cavity. For patients with GSWs, chest X-ray and abdominal X-rays with radio-opaque markers on the wounds can help ascertain trajectory (transdiaphragmatic or transmediastinal). Patients who are in extremis should undergo resuscitative thoracotomy [11].

Chest X-ray can delineate hemothorax or pneumothorax, which is treated initially with tube thoracostomy. Pneumothorax is typically definitively treated with tube thoracostomy. For hemothorax, large initial volume output (>1500 mL) or continued hemorrhage (>200 mL/h) are indications for thoracotomy. Retained hemothorax is an indication for thoracoscopic drainage.

Hemopericardium on ultrasound in the unstable patient warrants emergent sternotomy. Pericardial ultrasound can be falsely negative in the setting of left hemothorax secondary to decompression via traumatic pericardiotomy [12]. In the stable patient, as demonstrated initially in a retrospective study by Thorson et al. in 2012 [13], and then in a randomized controlled trial by Nicol et al. in 2014 [14], hemopericardium can be managed with intraoperative subxiphoid or transdiaphragmatic pericardial window with pericardial irrigation and drainage, progressing to sternotomy only with continued bleeding. The rate of nontherapeutic sternotomy in these two studies ranged from 38% [13] to 93% [14].

Even stable, asymptomatic patients with potential thoracoabdominal penetrating trauma may have occult injuries. Traumatic diaphragm injury (TDI) occurs more commonly in penetrating rather than blunt trauma, particularly in thoracoabdominal GSWs or SWs [15], with 75% occurring on the left side [16]. Murray et al. [17] found an incidence of TDI in 42% in penetrating abdominal trauma, with a 26% incidence of TDI found on laparoscopy in patients who were completely asymptomatic. A SW can create a small TDI that is difficult to detect on imaging. A prospective study from the University of Maryland Shock-Trauma Center [18] identified 50 of 200 patients with penetrating torso injury as having CT findings of potential diaphragm injury. Twenty (40%) of these patients had specific CT findings of diaphragm injury to include contiguous organ injury on either side of the diaphragm or herniation of abdominal fat through a defect in the diaphragm. Of the 20 patients, 17 had surgical evaluation of the diaphragm, with TDI confirmed in only 12 (71%) of the subgroup. Prior reports of indicated that CT had a sensitivity of 14–61% and specificity of 76–99% [19], improving to 77 and 98%, respectively, with modern multidetector CT. However, as the majority of studies involve blunt TDI, sensitivity decreases to 8–60% in penetrating TDI [20, 21]. Thus, CT evaluation to determine the need for operative intervention for TDI remains questionable.

Other modalities used in diagnosing TDI include diagnostic peritoneal lavage (DPL), laparoscopy, and thoracoscopy. In 1985, Moore and Marx [22] proposed a red blood cell (RBC) threshold of 5000/mm$^3$, as this level was not likely to be attributed to the DPL procedure. As experience with DPL is minimal in modern surgical practice it may have little utility, though it may still have some benefit in austere or resource-constrained environments [23]. Murray et al. [24] and Friese et al. [25] noted a 24% incidence of TDI on laparoscopy for patients with penetrating thoracoabdominal injuries. Uribe et al. [26] diagnosed TDI on 32% of patients with penetrating thoracoabdominal injuries and 89% of these patients had intra-abdominal injuries requiring surgical repair. While laparoscopy and thoracoscopy as diagnostic measures both have the added benefit of ability to surgically treat the TDI, it may not be possible to treat all intra-abdominal injuries via thoracoscopy. As such, thoracoscopic evaluation of the diaphragm is recommended primarily when you have another indication for thoracoscopic exploration (i.e., retained hemothorax).

### 18.3.2 Back/Flank

While penetrating injury to the back and flank (posterior to the anterior axillary lines) has a lower likelihood of significant intra-abdominal injury compared to anterior abdominal or thoracoabdominal wounds, it is difficult to evaluate the retroperitoneum with physical exam and FAST. In the stable patient, CT is reliable for excluding significant injury (Table 18.1) [27, 28]. In the past,

**Table 18.1** Classification and management recommendations for CT scan findings following penetrating flank/back injuries

| Risk | CT Findings | Intervention |
|---|---|---|
| Low | No penetration | Discharge from ED |
| | Penetration into subcutaneous tissue | |
| Medium | Penetration into muscle | Serial clinical assessments |
| | Retroperitoneal hematoma, not near critical structure | |
| High | Contrast extravasation from colon | Laparotomy, laparoscopy, or IR |
| | Major extravasation from kidney | |
| | Hematoma adjacent to major retroperitoneal vessel | |
| | Free air in retroperitoneum, not attributed to wounding object | |
| | Evidence of injury above and below diaphragm | |
| | Free fluid in peritoneal cavity | |

Adapted from Himmelman et al. [27]

triple-contrast CT was recommended for evaluation of retroperitoneal colon and rectal injuries [29–31]. Modern CT imaging seems to provide adequate evaluation of the colon and rectum to determine whether surgical exploration is indicated, without the need for rectal contrast [32].

### 18.3.3 Anterior Abdomen

Penetrating injury to the anterior abdomen includes the area of the torso from xiphoid to pubis, and between the anterior axillary lines. Of all anterior abdominal SWs, only 50–75% enter the peritoneal cavity; and only 50–75% of those that enter the peritoneal cavity cause an injury that requires operative repair. As such, only a minority of initially stable, asymptomatic patients would be expected to require an operation [33]. In 1960, Shaftan [3] challenged the dogma of mandatory LAP for anterior abdominal SWs, and introduced "selective conservatism" based on clinical evaluation. This approach has become accepted due to a desire to avoid nontherapeutic LAP.

The fear of morbidity related to a delay in intervention has resulted in the development of a number of adjuncts to identify significant injuries. Local wound exploration (LWE) can aid in safe discharge of the patients from the emergency department (ED) if the peritoneal cavity is not found to be violated [33]. The WTA prospective observational multicenter trials confirmed that performing LWE would allow 31–40% of the stable patients to be discharged from the ED [6, 7]. However, there remains a 30–50% incidence of nontherapeutic LAP even with a positive LWE. Thus, a positive LWE warrants further evaluation [34, 35]. Selecting patient factors and SW types is not amenable to accurate LWE. These include small puncture wounds (ice pick), long tangential SW tracts, significant obesity, multiple stab wounds, and combative/non-cooperative patients. In these cases, CT imaging can be helpful in assessing the trajectory and estimating the depth of penetration.

In 1964, Mason et al. [36] reduced the nontherapeutic LAP rate from 52% to 12% by utilizing serial clinical assessments (SCAs). In 1987, Demetriades et al. [37] then studied 651 patients with anterior abdominal SWs prospectively. They managed 47% with SCAs, with only 3.6% requiring subsequent LAP, no mortality, no increased length of stay (LOS), and a nontherapeutic LAP rate of 5%. The 2009 and 2011 WTA trials also confirmed that nonoperative observation with SCAs remains safe, with no morbidity related to a potential delay of operative treatment of injuries [6, 7]. These assessments include vital signs and serial abdominal exams, which are ideally performed by the same examiner every 4–6 h. If there is to be a patient handoff, it should take place at the bedside to ensure clear understanding of physical exam findings. In addition, serial complete blood count (CBC) can allow the detection of hemorrhage and trend the white blood count (WBC). This may also be reasonable for patients with short-duration impairment of their examination (i.e., intoxication, short intubation), who have no indication for urgent operation. The recommended period of SCAs is 24 h from the time of injury [6, 7]. The success of SCAs is dependent on close monitoring with the ability to identify changes in the clinical picture that indicates bleeding or peritonitis. This may require a well-resourced setting when the assessments can be performed at frequent intervals by the same practitioners [6, 38, 39].

There has been much debate on the balance of invasiveness, resource utilization, and timely repair of significant injuries in the discussion of additional adjuncts to SCAs. These adjuncts include DPL, ultrasound, or focused assessment with sonography in trauma (FAST) [40], CT [41], and laparoscopy [42, 43]. Per the WTA trials [6, 7], if a stable asymptomatic patient was taken to the OR primarily on the basis of a test result (i.e., FAST, LWE, DPL, or CT), the nontherapeutic LAP rate was high, ranging from 24 to 57%.

DPL was developed for patients with a positive LWE to evaluate for signs of significant

bleeding or perforated viscus [44, 45]. Because significant injuries are commonly manifest by shock, evisceration, or peritonitis, a small amount of bleeding may have come from the abdominal wall, omentum, or a solid organ. Thus, RBC counts are not helpful. The detection of hollow viscus injuries is also unreliable with DPL. Difficulties in interpreting the DPL WBC count have also been widely discussed and to date there is no threshold that offers 100% accuracy [46–48]. In the first WTA series [6], a high lavage WBC count (500 WBCs/mm$^3$) led to two nontherapeutic LAPs, and two patients with hollow viscus injuries had a subthreshold lavage WBC count. Recognizing the problem of equivocal DPL results, measurement of amylase and alkaline phosphatase have been suggested to improve the sensitivity of DPL [49, 50]. These results, like the WBC count, are somewhat dependent on the timing of DPL; furthermore, the enzymes may not reliably diagnose colon injury [47–50]. Based on the reports out of Dallas [45] and Denver [51], false (−) results (i.e., WBC <500/mm$^3$) are found in 3–10% of patients with hollow viscus injuries when DPL is performed relatively soon after injury. On the other hand, waiting 6–7 h may result in a 35% incidence of false (+) studies based on high WBC counts [46]. Standard threshold values for WBCs and enzymes are not reliable enough to overcome physical exam findings. In the experience of the WTA trials, 8 (40%) of 20 patients had nontherapeutic LAP based on DPL results [6, 7].

While ultrasonography (FAST) is critical in managing the unstable patient, or one with potential hemopericardium, its value in AASW management is dubious. In the stable, asymptomatic patient, detectable hemoperitoneum does not necessarily correlate with significant injury requiring operative intervention. In the WTA trials, 10 (50%) of 20 such patients had a nontherapeutic LAP or did not require LAP [6, 7]. The major value of the test is probably in identifying patients who have hemoperitoneum, as it can obviate the need for LWE. On the other hand, the absence of hemoperitoneum does not equate with the absence of injury. In the WTA trials, 30 (17%) of 175 patients with a "normal" FAST ultimately had a therapeutic LAP [6, 7]. Thus, we agree with Udobi and colleagues [52]—who reported 18% sensitivity of FAST in penetrating trauma—that patients should not be discharged from the ED based solely on a (−) FAST.

CT as an adjunct in the management of anterior abdominal SWs remains controversial. Proponents of CT imaging argue that it may help identify tangential wounds in an obese patient allowing for ED discharge, a completely negative CT scan may allow for safe discharge in completely examinable and reliable low-risk patients, and it is both a fast and accurate method to diagnose most abdominal injuries [53–55]. Opponents of CT argue that there is a lack of benefit over SCAs, it is not cost-effective, increases exposure to radiation and intravenous contrast, has low sensitivity for identifying hollow viscus injury, and operative interventions based on CT findings alone lead to a 25% nontherapeutic LAP rate [6, 7, 56, 57]. Both the data and the opinions are mixed.

While laparoscopy is beneficial for evaluation of TDI, it may be difficult to detect a small wound on the posterior wall of the stomach, underneath pericolonic fat, or on the mesenteric border. Leppaniemi and Haapiainen [58] performed a prospective randomized study in 2003 comparing mandatory LAP vs laparoscopy for patients with demonstrated or equivocal peritoneal violation on LWE. The rate of nontherapeutic LAP was 60% for both groups. In addition, laparoscopy compared to SCAs resulted in increased LOS, cost, and time off of work. Finally, O'Malley demonstrated in 2013 a 7% incidence of missed injuries in patients undergoing laparoscopy [59].

### 18.3.4 Gunshot Wounds

Ninety percent of patients with gunshot wounds that violate the peritoneum have an injury that

requires operative management. As such, mandatory LAP has been the standard of care [60]. Recently, however, a number of reports have identified a subset of patients who may be candidates for nonoperative management [61–64]. Stable, asymptomatic patients are candidates for CT scanning. Those who have clear evidence of extracavitary trajectory can be discharged from the ED. Patients with isolated solid organ injuries may be candidates for nonoperative management. However, the setting must be appropriate, as the patient's condition could change abruptly [65].

## 18.4 Conclusion

While the overall management of penetrating abdominal injuries has moved away from mandatory operation, thereby reducing nontherapeutic operations, the precise method of management depends on the patient's condition, the anatomic location of the injury, and the resources available to each institution. The range of acceptable management strategies is best summarized in the 2018 WTA algorithm (Fig. 18.1) [66].

**Key Concepts**

- Indications for immediate LAP for penetrating abdominal trauma
- Indications for SNOM for penetrating abdominal trauma
- Evaluation of thoracoabdominal injuries
- Evaluation of back/flank injuries
- Evaluation and management of anterior abdominal SWs

**Take Home Messages**

- Immediate LAP is indicated when there is hemodynamic instability, evisceration, peritonitis, or impalement
- SNOM of stable, asymptomatic patients is safe
- Thoracoabdominal injuries require initial evaluation with CXR and pericardial ultrasound
- Back/Flank injuries benefit from CT with intravenous contrast
- Anterior abdominal SWs can be managed with serial clinical assessments

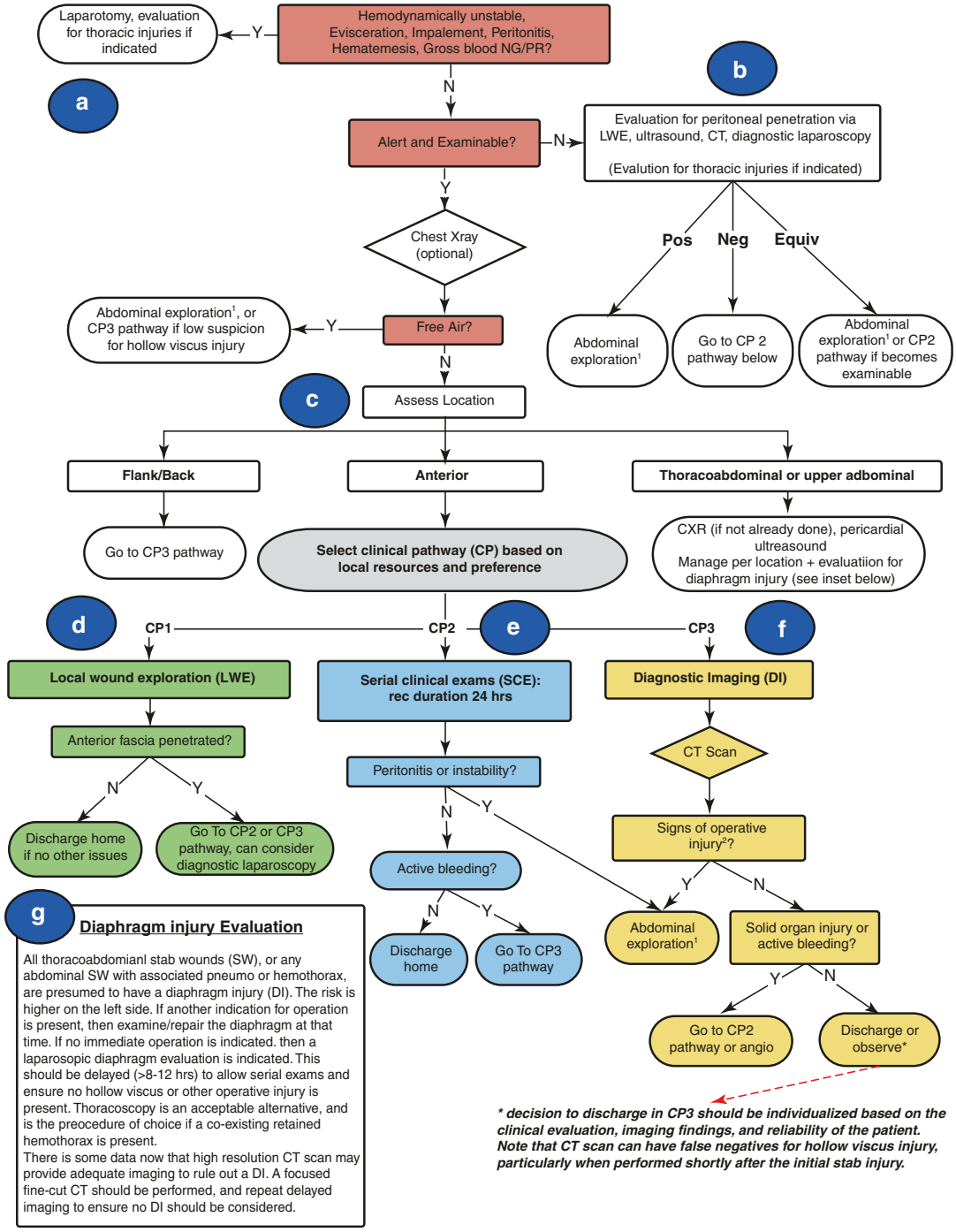


**Fig. 18.1** Western Trauma Association algorithm for the evaluation and management of patients with abdominal stab wounds. Circled letters correspond to sections in the associated manuscript. The "gold standard" for abdominal exploration is via laparotomy. However, diagnostic and/or therapeutic laparoscopy may be performed in select stable patients and by a highly skilled surgeon experienced in minimally invasive surgical techniques. Signs of operative injury include CT scan visualization of bowel injury or secondary signs (unexplained free fluid, free air, bowel wall thickening, mesenteric injury), diaphragm injury, abdominal vascular injury, or contrast extravasation indicating ongoing bleeding. Note that some of these may also be amenable to observation, angioembolization, or endovascular techniques

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# Pelvic Ring Injuries

# 19

Philip F. Stahel and Darryl A. Auston

**Learning Objectives**

- Explain the mechanism-based classification of pelvic ring injuries and its correlation to the risk of hemorrhage and adverse patient outcomes.
- Describe the acute management strategies for patients with bleeding pelvic fractures.
- Recognize patients who are candidates for "damage control" external fixation and pelvic packing.
- Establish the concepts of initial stabilization and resuscitation with delayed scheduled definitive fixation of unstable pelvic ring injuries.
- Discuss novel techniques of pelvic fracture fixation in the twenty-first century.

## 19.1 Introduction

High-energy pelvic ring disruptions represent a major source of life-threatening hemorrhage and potentially preventable post-injury mortality [1]. For patients with hemodynamically unstable pelvic ring injuries, survival depends on the early recognition and control of the associated retroperitoneal hemorrhage [2]. The initial diagnostic workup in the emergency department (ED) is guided by standardized guidelines, including the "Advanced Trauma Life Support "(ATLS®) protocol (see Chap. 6) [3].

About one-third of all patients with complex pelvic ring disruptions are coagulopathic on admission, which is associated with significantly increased post-injury mortality [4]. The early presence of post-injury coagulopathy is best determined with bedside "point-of-care "testing by thrombelastography (TEG) or rotational thrombelastometry (ROTEM) [5]. These real-time diagnostic methods allow for a targeted resuscitation from traumatic-hemorrhagic shock and coagulopathy with blood products and improved post-injury survival rates [6]. In this regard, a recent randomized prospective trial revealed that the use of goal-directed, TEG-guided resuscitation strategies resulted in improved post-injury survival rates compared to standard mass transfusion protocols guided by conventional laboratory testing [7].

Serum lactate and base deficit represent sensitive markers for early recognition of occult hemorrhage and "hidden shock" [8]. The amount of lactate produced by anaerobic glycolysis is an indirect marker of oxygen debt, tissue hypoperfusion, and the severity of hemorrhagic shock, whereas base deficit values derived from arterial blood gas analysis provide an indirect estimation

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of global tissue acidosis from impaired tissue perfusion [8]. A landmark study from the 1990s on multiple injured patients correlated lactate clearance with survival [9]. The study results demonstrated a 100% survival rate in patients whose lactate levels returned to the normal range (≤2 mmol/L) within 24 h, whereas survival decreased to just above 10% in those patients with elevated lactate levels above 2 mmol/L for more than 48 h post-injury [9]. Similar to the predictive value of lactate levels, the initial base deficit has been established as a potent independent predictor of mortality in patients with traumatic-hemorrhagic shock [10]. The extent of base deficit has been stratified into three categories of severity (mild: −3 to −5 mEq/L; moderate: −6 to −9 mEq/L; severe: <−10 mEq/L) and a significant correlation has been demonstrated between the admission base deficit and transfusion requirements within the first 24 h and the risk of post-traumatic organ failure and post-injury death [10].

In patients with exsanguinating hemorrhage in extremis, a resuscitative "ED thoracotomy" (EDT) with cross-clamping of the aorta has been proven effective for bridging the time to the operating room until definitive surgical bleeding control [11]. More recently, bedside endovascular techniques in the ED have provided an alternative to aortic cross-clamping, e.g., with the resurgence of a resuscitative endovascular balloon occlusion of the aorta (REBOA) procedure (see Chap. 8) for temporary hemorrhage control in hypotensive patients with a systolic blood pressure <80 mmHg on presentation [12, 13]. The intuitive advantages of endovascular techniques over resuscitative thoracotomies have to be balanced against a technical learning curve for REBOA with an associated risk of severe iatrogenic complications [14]. Radiologic imaging is used to confirm proper catheter placement in aortic zone III. Patients are then taken to the operating room for surgical bleeding control, including external fixation and pelvic packing, if indicated [15].

## 19.2 Classification of Pelvic Ring Injuries

The first clinically relevant systematic classification of pelvic fractures was described in 1961 by Pennal and Sutherland, based on the mechanism of injury [16, 17]. This system defines three distinct categories of pelvic ring injuries: (1) avulsion fractures, (2) "stable "fractures, and (3) "unstable "fractures, and attempts to correlate injury severity with outcomes. In 1980, Pennal and Tile introduced the aspect of fracture stability to the original Pennal/Sutherland classification and incorporated mechanisms and vectors of injury [17]. The Pennal/Tile classification furthermore served as a basis for therapeutic decision-making and management protocols of pelvic ring injuries. Currently used classification systems are largely based on the seminal publications by Tile, Pennal, and Sutherland [18]. In essence, the AO/OTA classification for pelvic ring injuries is based on Marvin Tile's original classification system [19]. Similarly, the classification by Young & Burgess is reflective of the original Pennal/Sutherland description [20]. Both the Tile and Young & Burgess classification systems are still widely used in the twenty-first century for decision-making and guidance of therapeutic protocols in the acute management of patients with pelvic ring disruptions.

The biomechanical stability of the pelvic ring relies on the integrity of the pubic symphysis and the posterior ligamentous complex. High-energy translational, rotational, and vertical shearing forces are required to disrupt the integrity and stability of the pelvic ring, leading to potentially exsanguinating retroperitoneal hemorrhage from venous presacral and paravesical plexus and cancellous bone from associated sacral fractures [4]. The vector of the impacting force has been shown to drive specific patterns of pelvic ring disruptions and determine their underlying extent of biomechanical instability and risk of associated bleeding [21]. In the twenty-first century, the most widely used classification systems that

serve as a basis for therapeutic decision-making include the alpha-numeric AO/OTA classification (which is historically based on the classification by Marvin Tile) and the mechanistic classification by Young & Burgess (Fig. 19.1).

The mechanistic classification system by Young & Burgess appears to represent the most clinically relevant system in the acute trauma setting by reflecting injury severity and taking into account the three main vectors of impacting forces, as well as any combination of multiple injury vectors [17, 22]. In brief, **antero-posterior compression (APC)** mechanisms induce a gradual disruption of the pubic symphysis with an external rotation deformity of the injured hemipelvis ("open book"), leading to hinging forces on the sacro-iliac (SI) joints and consecutive disruption of the anterior and posterior SI-ligaments. In contrast, **lateral compression (LC)** injuries lead to an internal rotation deformity of the injured hemipelvis and to gradual disruption of the SI-ligament complex by compressing forces, as opposed to the tensile forces resulting from APC injuries. While most high-energy pelvic ring injuries are based on predicted APC- and LC-type mechanisms, a rare yet more lethal

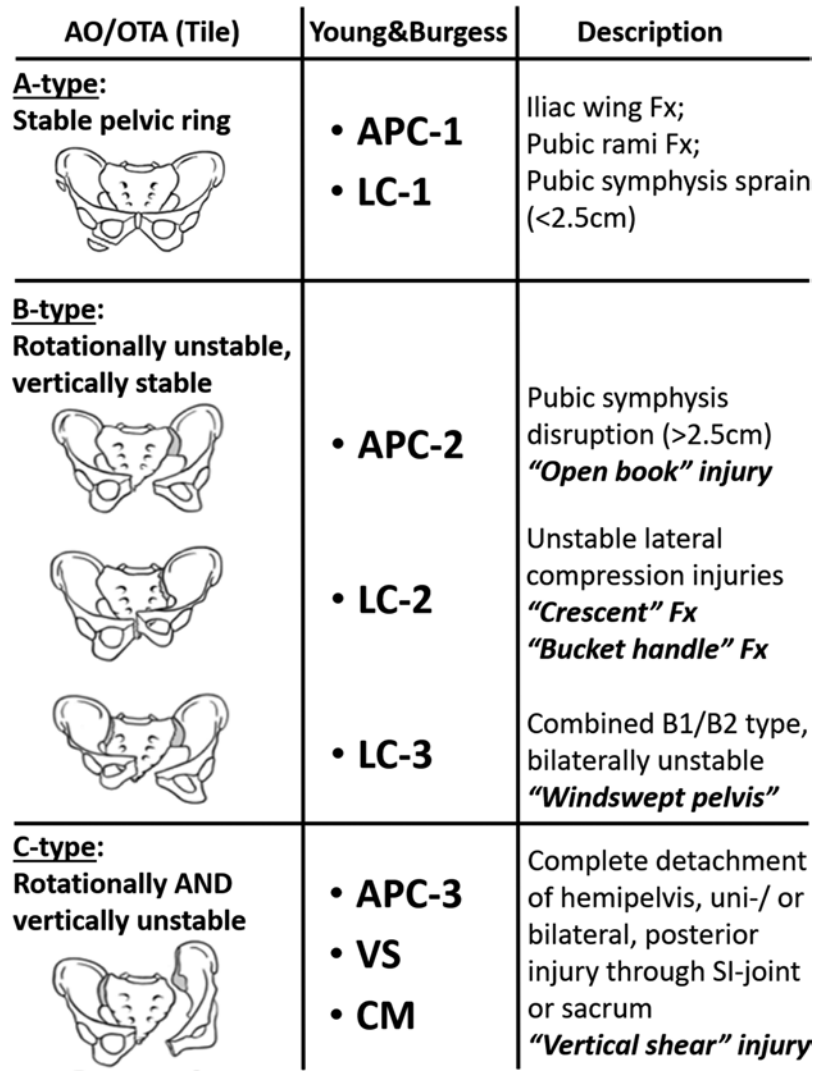


**Fig. 19.1** Comparison of the AO/OTA and Young & Burgess classification systems for pelvic ring injuries, based on injury mechanism and pelvic ring stability

entity is represented by **vertical shear (VS)** injuries due to massive axial loading forces, including high-speed acceleration/deceleration collisions and falls from significant heights. Vertical shear injuries are characterized by a complete unilateral disruption of the anterior and posterior pelvic ring, leading to external rotation and vertical translation of the injured hemipelvis. Any injury mechanism with multiple vectors which do not follow the standard mechanisms of APC, LC, or VS forces can be classified as a **combined mechanism (CM)** injury which is typically highly unstable and associated with major retroperitoneal hemorrhage [1, 23].

## 19.3 The 2017 WSES Classification

A shortcoming of the conventional classification systems discussed above is related to the lack of a predictive correlation between the purely anatomic and mechanistic criteria with the physiologic and hemodynamic response in patients with pelvic ring disruptions. To overcome this limitation, the *World Society of Emergency Surgery* (WSES) recently published a new classification [24] which is based on a combination of the anatomic/mechanistic classification by Young & Burgess in conjunction with hemodynamic stability based on ATLS® guidelines. Based on these combined criteria, the new WSES classification stratifies pelvic ring injuries into three grades of severity:

1. *Minor* pelvic ring injuries (WSES grade 1): Mechanically (APC-1, LC-1) and hemodynamically stable injury patterns.
2. *Moderate* pelvic ring injuries: Mechanically unstable (WSES grade 2: LC-2, LC-3, APC-2, APC-3; WSES grade 3: VS or CM) with hemodynamic stability and/or adequate response to resuscitation ("responders").
3. *Severe* pelvic ring injuries (WSES grade 4): Any hemodynamically unstable injury pattern with patients at risk for acute exsanguinating hemorrhage, independent of the mechanistic fracture classification ("non-responders").

Based on this new anatomic/physiologic classification, the WSES recently published international expert consensus guidelines [24] to provide a classification-based decision-making algorithm for the management of patients with bleeding pelvic fractures (Fig. 19.2).

## 19.4 The Role of Pelvic Binders

The application of pelvic binders or circumferential sheets is a life-saving measure for acute bleeding control in patients with unstable pelvic ring disruptions [25]. Impressively, experimental human cadaveric studies have demonstrated that circumferential sheets are equivalent in providing temporary biomechanical stability in unstable pelvic ring injuries to commercial pelvic binders and external pelvic fixation [26, 27]. In addition, systematic reviews have demonstrated the effectiveness of pelvic binders in the temporary restoration adequate blood pressure in hemodynamically unstable pelvic ring disruptions [28]. In a large database analysis of the German Pelvic Trauma Registry, the application of pelvic binders has been associated with a lower incidence of exsanguinating pelvic hemorrhage compared to the use of sheets. Placement of the pelvic binder at the level of the greater trochanter was shown to improve pelvic ring stability in human cadaveric studies. As the long-term ramifications of pelvic binders remain unclear at present, including the potential risk of soft tissue complications from prolonged compression, the general recommendation is to remove pelvic binders as soon as physiologically justifiable, and to consider replacing binders by early external pelvic fixation [24].

## 19.5 "Damage Control" External Pelvic Fixation

As part of the acute resuscitation strategy, any unstable pelvic ring injury with associated disruption of posterior element instability (WSES grade 2 and 3), particularly in conjunction with hemodynamic instability (WSES grade 4), should

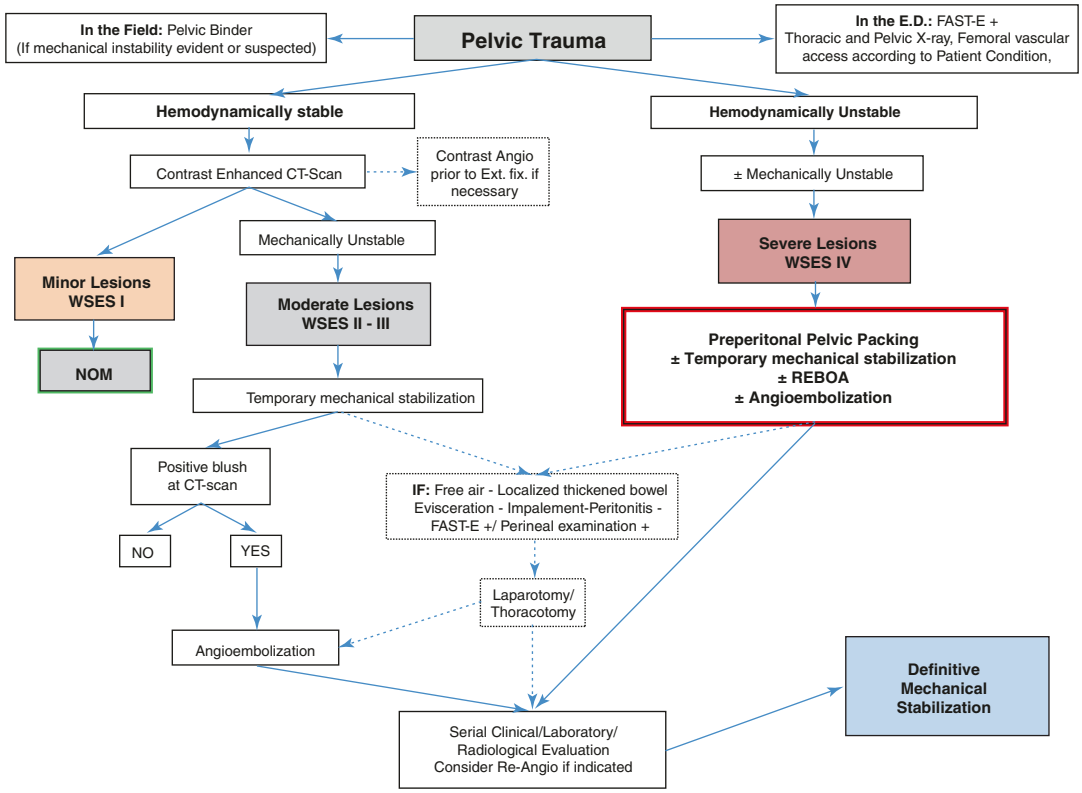


**Fig. 19.2** International consensus guideline by the World Society for Emergency Surgery (WSES) for the acute management of pelvic ring injuries

Adopted with permission from: Coccolini F et al., *World J. Emerg. Surg.* 2017, 12:5.
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be considered for temporary external pelvic fixation [24]. In essence, pelvic external fixation represents a crucial resuscitative tool for acute hemorrhage control, as retroperitoneal bleeding is decreased after closure and reduction of the pelvic ring with adjunctive stability by external fixation [21]. Furthermore, pelvic packing has been shown to be effective only in conjunction with external fixation, in order to provide a counter-pressure from the pelvic ring to the applied lap sponges in the retroperitoneal space [29–31]. From a technical decision-making perspective, most APC- or LC-equivalent injury patterns are preferably stabilized by anterior external fixation, either through the iliac crest route, or through a fluoroscopy-guided supraacetabular route [21]. Either technique has distinct advantages and limitations, as previously described [21]. Anterior pelvic external fixation allows for a closed reduction of the externally malrotated hemipelvis in APC-2 and APC-3 injuries ("close the book"), and for a provisional reduction and retention of the internally malrotated hemipelvis in LC-2 and LC-3 injury patterns. In contrast to the fast application of a "damage control" iliac crest frame, the supraacetabular route for external fixation allows for improved stability of the external fixator frame, however, at the price of requiring strict fluoroscopy-guided pin placement with dedicated views of the supraacetabular corridor. In contrast to APC- and LC-injury patterns, vertical shear (VS) injuries inadequately stabilized by anterior external fixation frames, due to the complete instability of the posterior elements through the iliosacral joint. For these rare injury patterns, the pelvic "C-clamp" has been shown to provide temporary stabilization of the posterior pelvic elements and to effectively control associated retroperitoneal hemorrhage [32–34]. However, the use of a C-clamp should

be restricted to selected indications (VS injuries with exsanguinating hemorrhage) and to adequately trained orthopedic trauma surgeons in order to mitigate the risk of serious intraoperative complications associated with inconsiderate C-clamp application [35]. Skeletal traction represents an additional measure of acute pelvic ring stabilization in VS-type injuries which provides temporary relative stability and restoration of vertical hemipelvis displacement. However, the main downside of skeletal traction relates to patient immobilization in supine position which impedes with appropriate patient positioning for the care of associated injuries [36]. Finally, the proactive modality of acute placement of a percutaneous "antishock" iliosacral screw has been described as a technique to rapidly stabilize the posterior pelvic ring as an adjunct to anterior pelvic external fixation [37].

## 19.6 Pelvic Packing

The concept of direct retroperitoneal pelvic packing as a first-line approach for acute hemorrhage control in unstable pelvic fractures is described in detail in Chap. 9 of this textbook. From a historic perspective, pelvic packing was initially described in the 1980s and 1990s in Hannover, Germany, and Zurich, Switzerland, as a technique of transabdominal open pelvic packing through a "damage control" explorative laparotomy [32, 38]. These early studies demonstrated that severely injured patients with associated pelvic ring injuries have improved outcomes by early surgical "damage control" intervention, including temporary external fixation of unstable pelvic fractures, transabdominal pelvic packing, and surgical bleeding control [33]. The pelvic packing technique was later modified in Denver, Colorado, to a concept of "direct" preperitoneal pelvic packing (PPP) by applying a distinct surgical technique through a suprapubic midline incision that allows packing directly into the space of Retzius, without the necessity of opening the retroperitoneal compartment through a laparotomy [39]. When using the new PPP technique, a midline laparotomy can still be performed through a separate proximal midline incision, if a laparotomy is indicated simultaneously for the management of associated intraabdominal bleeding sources [30]. Importantly, the technique of using two separate midline incisions for pelvic packing and explorative laparotomy appears to be safe with regard to the potential risk of postoperative infections subsequent to pelvic de-packing and delayed definitive orthopedic fracture fixation [40]. Recent studies demonstrated that the pelvic packing protocol incorporated as part of a standardized institutional guidelines led to a significant decrease in blood product utilization and to improved patient outcomes [29, 31, 41]. Indeed, the current literature supports the notion that pelvic packing represents an effective technique for acute hemorrhage control that is associated with a significantly reduced mortality compared to conventional measures without pelvic packing [1, 24]. In addition, we have recently demonstrated that the PPP technique can be performed effectively and fast, within less than 10 min "skin-to-skin" [42]. In patients with ongoing hemorrhage and blood product transfusion requirements subsequent to pelvic packing, delayed angioembolization has been recommended as an adjunct to pelvic packing, which appears indicated in the small selected cohort of patients with ongoing hemorrhage from arterial sources [1]. Very recent data from an 11-years institutional experience with protocolized pelvic packing on a cohort of 138 consecutive patients revealed that the post-injury mortality from acute exsanguinating pelvic hemorrhage was reduced to 2% after resuscitative measures that include PPP and external pelvic fixation [41]. In addition, a recent retrospective analysis demonstrated that there is no increased postoperative infection rate subsequent to open reduction and internal fixation of pelvic ring injuries with preceding pelvic packing and depacking, which corroborates the safety of the PPP protocol [43]. Owing to the proven benefits in improving patients outcomes, pelvic packing was introduced into the recommended management algorithm of the tenth edition of the ATLS® manual [3]. Nevertheless, there

remains residual reluctance and wide variability across level I trauma centers in the United States towards the implementation of the pelvic packing protocol for acute hemorrhage control [44].

## 19.7 Novel Innovative Concepts

### 19.7.1 Examination Under Anesthesia

As outlined above, surgical stabilization of the pelvic ring is essential in controlling ongoing hemorrhage and reducing mortality in severely injured patients [1]. However, selected injury patterns can disrupt the biomechanical stability of the pelvic ring without significant risk of hemorrhage and mortality. These unstable injuries, if left untreated, can lead to significant morbidity due to malunion or nonunion including limb length discrepancy, altered gait mechanics, altered sitting balance, chronic pain, and inability to return to previous career. There is some controversy in surgical management of these unstable pelvic ring injuries among surgeons. Disagreement centers around the definition as to which pelvic ring injury constitutes an "unstable ring" that would require surgical intervention. Gross and occult instability cannot always be predicted by modern fracture classification systems. Additionally, plain film and CT analysis provide only static evaluation of a dynamic problem. Examination under anesthesia (EUA) has been described as a technique for dynamic assessment of the injured pelvis [45]. When pelvic ring instability remains unclear, the patient is placed under anesthesia in the operating room, and a series of maneuvers are performed to test rotational and axial stability [46]. Any detection of dynamic instability will require consideration for surgical pelvic ring fixation. Conversely, a negative stress test showed to be associated with a high negative predictive value in ruling out unstable pelvic fractures [47]. A recent study suggested a high sensitivity in detecting unstable lateral compression (LC)-type injuries by placing the patient in a lateral decubitus position, which allows gravity to support the dynamic exam without the need for patient sedation to distinguish between stable LC-1 patterns from unstable LC-2 type injuries [48]. The advantage of this novel technique is the avoidance of general anesthesia and the downstream associated risks to patients who may not require surgical pelvic fixation.

### 19.7.2 Percutaneous Pelvic Ring Fixation

CT imaging has advanced understanding of the complex osseous pelvic anatomy. Osseous pathways have been described that provide corridors for safe placement of surgical implants that avoid iatrogenic injury to critical neurovascular structures [49, 50]. Improved understanding of safe surgical corridors, in conjunction with the evolution of intraoperative fluoroscopic imaging has allowed for percutaneous screw fixation of pelvic injuries that previously had required surgical exposure and direct reduction and surface fixation of the fracture [37]. Indirect reduction using skeletal traction, percutaneous manipulation of the pelvic ring using external fixation devices, or commercially available surgical table adjuncts allows for indirect reduction of the fractures and percutaneous fixation of the pelvic ring injuries [51]. Understanding of the complex pelvis anatomy, in conjunctions with common variations in pelvic anatomy is critical for successful, safe percutaneous fixation of pelvic ring injuries.

## 19.8 Conclusion

The understanding of injury mechanism and classification allows for appropriate guidance in the management of high-energy pelvic ring disruptions at risk for exsanguinating traumatic-hemorrhagic shock. Current international consensus guidelines are based on classification-driven decision-making algorithms which take into consideration the anatomic/mechanistic aspects of pelvic ring disruptions in conjunction with physiologic/hemodynamic variables and

response to resuscitative measures. A protocolized approach of early pelvic packing and external fixation, followed by delayed angioembolization in case of ongoing hemodynamic instability, has been shown to significantly reduce the historically unacceptably high mortality from severe pelvic ring disruptions. Definitive pelvic fracture fixation is performed subsequent to resuscitation from hemorrhagic shock, coagulopathy, and associated injuries, using standardized surgical approaches and fixation techniques.

**Key Concepts**

- Injury mechanism-based classification systems of pelvic fractures are essential for understanding the severity of injury and to provide a guide for therapeutic decision-making.
- The use of commercially available pelvic binders or circumferential sheet application is recommended as an early measure to stabilize the pelvic ring and decrease the amount of pelvic hemorrhage in the pre-hospital setting.
- Resuscitative endovascular balloon occlusion of the aorta (REBOA) provides a fast and minimally invasive temporary hemorrhage control for hypotensive patients with bleeding pelvic fractures and allows bridging the time to the operating room for hemorrhage control by pelvic packing and external pelvic fixation.
- Serum lactate and base deficit are sensitive tests for early recognition of the extent of traumatic hemorrhage and "hidden shock" in patients with pelvic ring disruptions.
- Definitive pelvic ring fixation is performed subsequently to successful resuscitation using standardized anterior and posterior surgical approaches, or by the use of novel percutaneous techniques.

**Take Home Messages**

- High-energy pelvic ring disruptions represent a global cause of preventable post-injury mortality from exsanguinating retroperitoneal hemorrhage.
- A protocolized approach of early external fixation with direct preperitoneal pelvic packing and delayed angioembolization in case of ongoing hemodynamic instability has been shown to significantly reduce postinjury mortality from acute exsanguinating hemorrhage.

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# Spine Fractures

# 20

Philip F. Stahel and Sebastian Weckbach

**Learning Objectives**

- Describe the new AO/OTA classification system for spine fractures.
- Establish the appropriate sequence of the initial assessment and management of polytrauma patients with unstable spine injuries.
- Recognize the need for early spinal stabilization in polytrauma patients by applying a proactive standardized "spine damage control" approach.

## 20.1 Introduction

The presence of a spine fracture or ligamentous injury must be assumed in any multiple injured patient until proven otherwise. Of note, most spinal injuries do not present with a neurological impairment. On the other hand, the presence of neurological symptoms is presumptive evidence of an unstable spine fracture with associated spinal cord injury (see Chap. 21). Pain or tenderness along the spine, from the occiput to the sacrum, must raise the concern for a spinal injury. The main goal in the initial evaluation of polytrauma patients with associated spine fracture is to determine spinal stability. Biomechanically, spinal instability refers to an abnormal response to applied loads and can be characterized by motion in spinal segments beyond the normal constraints. In general, the definition of "spinal stability" refers to the ability of the spine to maintain its alignment and protect the neural structures during normal activity. This takes into consideration that under physiological loading with the influence of gravity on body mass, the spinal column does not experience increasing deformity, onset of neurological impairment, or increase in pain. Reciprocally, unstable spine injuries are at risk for progressive deformity and neurologic compromise which implies the indication for surgical spine stabilization and decompression of the spinal cord. From a clinical decision-making perspective, it is imperative to take into consideration the mechanism of trauma and to understand the classification of spinal fractures, which corresponds to the level of spinal instability, provides the basis for considering surgical management, and correlates with patient outcomes.

## 20.2 Spine Fracture Classification

Spine fractures, traumatic dislocations, and fracture-dislocations are classified by the alphanumeric AO/OTA classification, which is based

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on the historic classification system developed by the Austrian surgeon Fritz Magerl from 1994 [1]. The previously prevalent spine classification was published in the 2007 version of the AO/OTA compendium [2]. The compendium was completely revised in 2018 and now provides a novel and comprehensive spine classification from occiput to coccyx, which was expanded to include stable ("zero"-type) spinous or transverse process fractures, and specific fracture-dislocation patterns [3].

In essence, the novel AO/OTA classification [3] codes the anatomic spine region by a number: 51 cervical; 52 thoracic; 53 lumbar; 54 sacral fractures. The number of the vertebral body is then added between two dots after the location code (e.g., "52.7." for the seventh thoracic vertebra). For fracture-dislocations, the affected motion segment is placed with a slash between the two respective vertebral bodies (e.g., "52.7/8." for a T7-T8 fracture-dislocation). The spine fracture mechanism and severity of injury are coded by an alpha-numeric combination (A, B, C and 0, 1, 2, 3, 4) in ascending order with the extent of injury severity. The clinical implication of classifying spine fractures by the AO/OTA system is that the classification reflects injury severity and guides the decision-making for treatment (operative vs. non-operative) based on spinal stability. In essence, A-type spine fractures represent *axial-loading* trauma mechanisms that lead to compression fractures or burst fractures. Most A-type fracture patterns are considered stable and are managed non-operatively (Figs. 20.1,

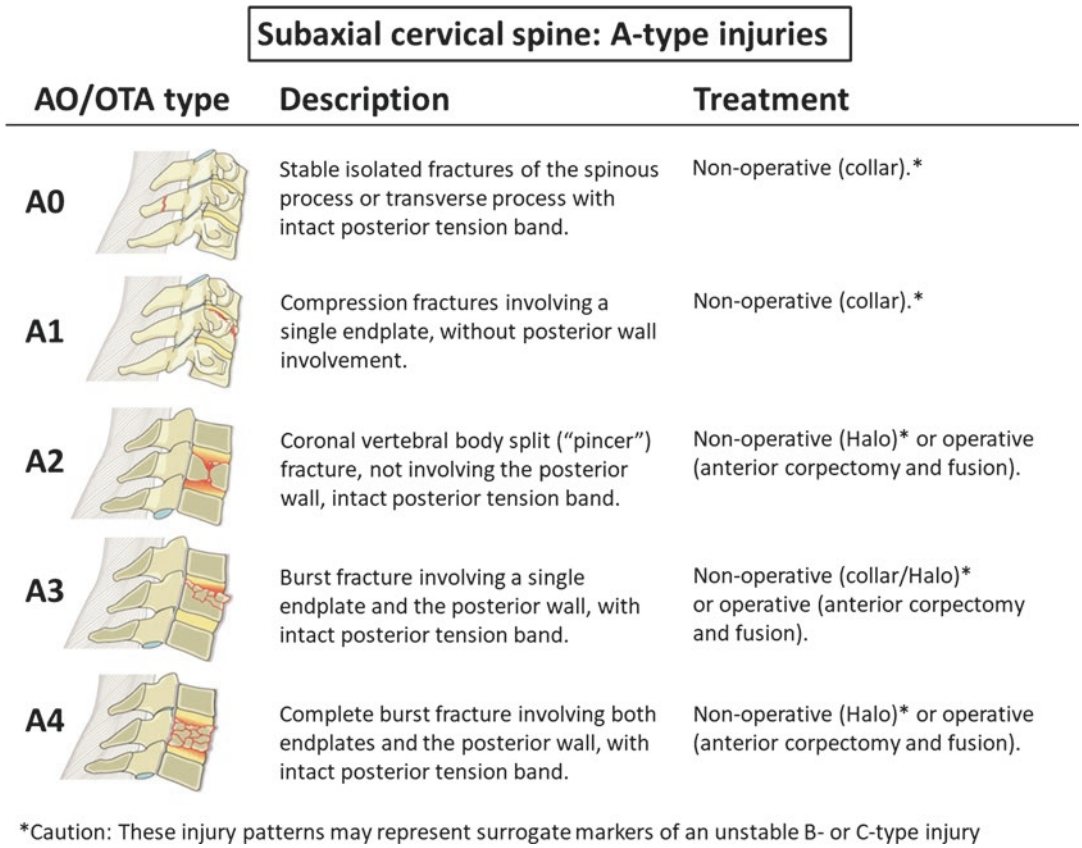


**Fig. 20.1** AO/OTA classification of A-type subaxial cervical spine injuries

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20.3). In contrast, B-type injuries are typically unstable fractures and fracture-dislocations that are inflicted by flexion-distraction or hyperextension trauma mechanisms (Figs. 20.2, 20.4). Finally, C-type injuries represent inherently unstable fracture-dislocations by failure of anterior and posterior elements, associated with rotational instability (Figs. 20.2, 20.4). The incidence of associated neurological (spinal cord) injury increases with the alpha-numeric fracture classification, from essentially 0% risk in stable A0 or A1-type injuries to near 100% in C3-type injuries. The C3-type "Holdsworth" injury (or "slice" fracture) [2] represents the worst spinal injury which is invariably associated with a severe spinal cord injury or spinal cord transection (see Chap. 21).

## 20.3 Spine Fracture-Dislocations

Spine fracture-dislocations are invariable unstable and associated with a high risk of neurological complications. These types of injuries are also termed "traumatic spondylolisthesis" which derives from the Greek words "spondylos" (vertebrae) and "olisthesis" (slip). A traumatic spondylolisthesis is defined by the anterior displacement of a vertebra or the vertebral column in relation to the vertebrae below, which leads to a disruption of the spine's sagittal profile. A "traumatic spondylolisthesis" is commonly related to high-energy trauma from acceleration/deceleration mechanisms [4]. The cervical spine is particularly vulnerable at the cervico-thoracic junction due to its flexible fixation between the

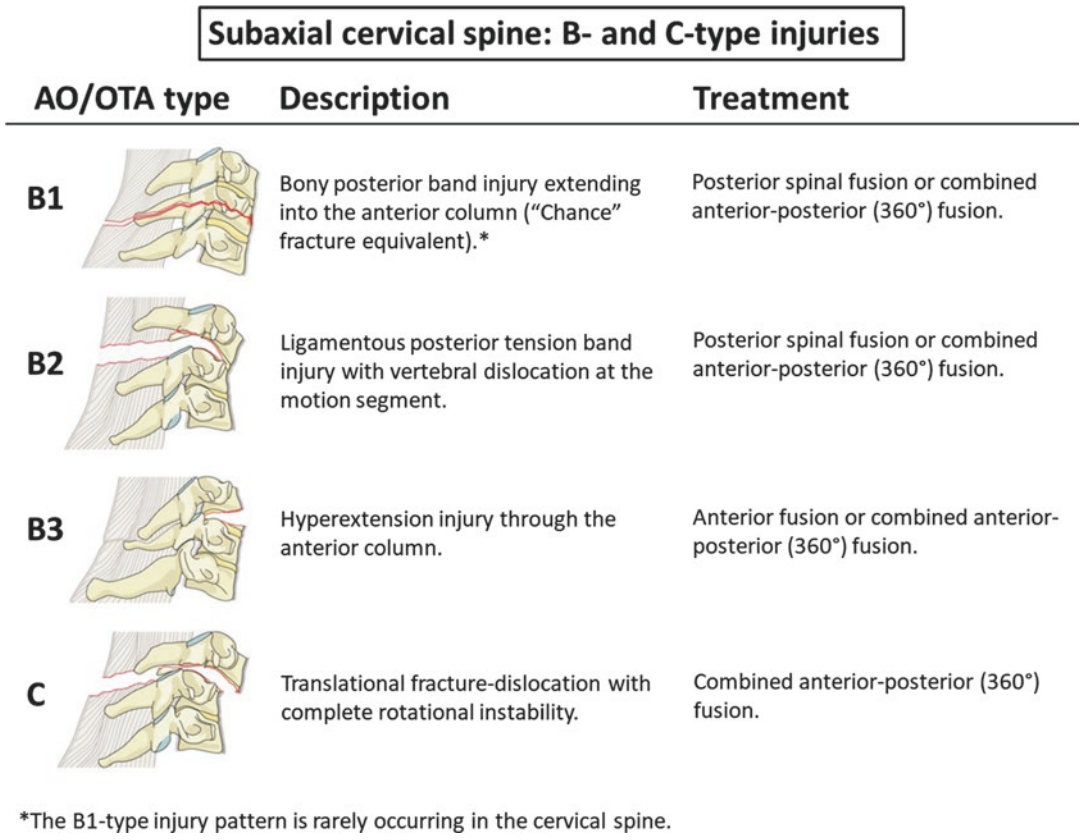


**Fig. 20.2** AO/OTA classification of B-type and C-type subaxial cervical spine injuries

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head and the more rigid thoracic spine which is stabilized by the rib cage. The same biomechanical aspects render the thoracolumbar junction vulnerable to traumatic fracture-dislocations [5].

## 20.4 Diagnostic Workup

The key imperative in the acute management of polytrauma patients with a suspected spine fracture consists of spinal immobilization until a relevant injury has been ruled out by clinical exam and/or radiographic workup (*see spinal clearance protocols below*). A cervical collar is applied to all trauma patients with a high-energy mechanism, and log-roll precautions should be maintained until spinal stability is assured. Per the ATLS® protocol [6], a long spine board must be removed as early as possible once a thorough assessment of the spine has been completed, in order to avoid pressure sores from prolonged immobilization. Under the "E" variable of the A-B-C-D-E mnemonic (see Chap. 6), the entire posterior spine is inspected and palpated for local tenderness and deformities with strict adherence to log-roll precautions. This maneuver requires a team of 4–5 health care personnel to log-roll a patient with simultaneous in-line cervical stabilization [7]. The paraspinal soft tissues are inspected for swelling, bruising, hematomas, open wounds, and spinal asymmetry. The systematic palpation of all spinous processes across the spinal column helps identify localized pain in awake patients and detect a significant gap between spinal processes in flexion-distraction injuries and spinal fracture-dislocations. As part of the inspection and physical exam, it is important to keep in mind that specific injuries can be associated with selected visceral and axial skeletal injuries. For example, facial trauma and head injuries should alert to the possibility of an injury to the cervical spine. An abrasion under the strap of a seat belt can be associated with significant injuries to the cervical spine and cervico-thoracic junction, whereas lap seat belt contusions should heighten suspicion for flexion–distraction injuries to the thoracolumbar spine, e.g., a B1-type "Chance" fracture (see below). These particular fractures are associated with a high risk for visceral abdominal and retroperitoneal injuries. Calcaneal fractures after falls from height are a surrogate marker from significant deceleration trauma and are associated with axial-loading fractures of the thoracic and lumbar spine. Subsequent to inspection, a complete physical exam is performed, including a systematic neurologic assessment. Of note, most spine fractures do not present with an associated neurological impairment. If a patient has signs of numbness, tingling sensation, or paralysis to any extremity, a serious injury to the spinal cord must be suspected. Impairment of bladder and bowel function are frequently missed during the initial exam and may be reflective of a cauda equina syndrome (see Chap. 21) [8].

The diagnostic workup of spinal injuries includes plain radiographs, computerized tomography (CT) scans, and magnetic resonance imaging (MRI). At present, the multislice CT scan (MSCT) has largely replaced the historic necessity for obtaining conventional spinal radiographs. The MSCT is part of the initial trauma workup and provides fast and accurate visualization of the entire spine, including 2-D and 3-D reconstructions. The MRI offers a highly sensitive diagnostic tool for injuries to the soft tissue, ligaments, intervertebral discs, and for detection of epidural hematoma, dural tears, and spinal cord contusions and lacerations [9]. However, in the setting of polytrauma, an MRI should never be obtained in patients who are hemodynamically unstable [10].

## 20.5 Spinal Precautions

An unstable injury to the vertebral column must be suspected in all patients who sustained a high-energy blunt trauma mechanism, independent of the presence of neurological impairment [11]. Pain in the back or neck is the leading symptom of a spinal injury. Spinal precautions are aimed at minimizing the movement of the spine during rescue, transport, and initial assessment and manage-

ment of polytrauma patients with suspected spinal injuries. The main goal is to avoid inflicting preventable secondary damage to the spinal cord by excessive bending or twisting of the spinal column. Spinal precautions are attained by placing the trauma victim in a neutral supine position without rotating or bending the spinal column, in conjunction with in-line immobilization of the cervical, thoracic, and lumbar spine, including the placement of a cervical collar [7]. Strict adherence to log-roll maneuvers is imperative, whenever the patient is moved. The requirement for complete immobilization on a long spinal board (backboard) has recently undergone renewed scrutiny due to associated complications. In addition to spinal immobilization, the exact documentation and timing of the clinical and neurological findings are imperative, since the patients' neurologic status may deteriorate over time [12].

## 20.6 Spinal Clearance

Clearance of the cervical spine has represented a conundrum for many decades. This is mainly due to the risk of complications associated with inconsiderate range of motion of potentially unstable spinal injuries and from prolonged unnecessary spinal immobilization. Last but not least, there is a significant risk of potential medicolegal implications related to missed spinal injuries [11, 12].

Specific risks of prolonged spine immobilization include the following:

- The presence of C-collars interferes with endotracheal intubation, airway management, tracheotomies, and central line placement.
- Staffing requirements for continued log-roll maneuvers.
- Increased risk of skin breakdown, pressure ulcers, risk of aspiration, pulmonary infections, and thromboembolic complications.
- Increased pain and discomfort in awake patients, with impaired ability to provide appropriate nursing care and patient positioning.

Thus, there is an imperative for early appropriate discontinuation of spinal immobilization. The published literature provides a multiplicity of spinal clearance protocols in the trauma patient [5]. In essence, the relevant decision-making algorithms are stratified into three main categories based on the underlying patient condition:

1. Awake & alert patients without neurologic symptoms.
2. Awake & alert patients with presence of neurologic symptoms.
3. Obtunded, intoxicated, or otherwise non-examinable patients.

For patients who are awake, alert, and hemodynamically stable, without any neurologic symptoms, there are standardized guidelines for cervical spine clearance guided exclusively by clinical findings [5]. These include the "National Emergency X-Radiography Utilization Study" (NEXUS) [13] low-risk criteria and the "Canadian Cervical Spine Rule" (CCR) [14] guideline.

The application of these clinical prediction tools allows for a rapid clinical clearance of the cervical spine without the need for radiographic imaging. Multiple validation studies and meta-analyses of the literature revealed a high sensitivity (98.1%) and negative predictive value (99.8%) for the NEXUS low-risk criteria and the CCR guideline to safely clear the cervical spine without radiographic imaging in alert, asymptomatic patients who are hemodynamically stable and are able to complete a functional range of motion examination in absence of distracting injuries or neurologic deficits [15].

Symptomatic patients with neurologic symptoms, or obtunded/intoxicated patients who are not amenable to an awake clinical evaluation, require advanced imaging studies. At present, the use of upright plain radiographs of the lateral C-spine is considered outdated and obsolete, based on a low reported sensitivity in detecting unstable spinal injuries [16]. In contrast, the currently available evidence has unequivocally demonstrated that a normal high-quality CT scan alone is sufficient to allow safe clearance of the cervical spine in the non-examinable patient. The

current guidelines by the Eastern Association for the Surgery of Trauma (EAST) recommend cervical collar removal after a negative high-quality C-spine CT scan result in obtunded adult blunt trauma patients [17]. The EAST study group recommendations are based on a systematic review of the literature that revealed a negative predictive value of 100% for spinal clearance by a normal high-quality CT scan alone. These insights were confirmed by the "Western Trauma" guidelines which are based on prospective multicenter observational study confirming that CT alone was effective for ruling out a clinically relevant C-spine injury with a negative predictive value of 100% [18]. Based on these data, the escalation to further advanced imaging by MRI appears exclusively indicated in patients with an abnormal neurologic examination or equivocal/pathological findings on the initial CT scan.

If spinal stability can be confirmed without the need for surgical intervention, patients should be cleared from log-roll precautions followed by early mobilization with adjunctive bracing for stable A3-type burst fractures, and without a brace for A1-type compression fractures. If spinal injuries are deemed unstable, early surgical treatment should be considered to prevent complications related to prolonged bed rest and immobilization, such as pressure sores or pulmonary and thromboembolic complications [11].

## 20.7 Initial Management

### 20.7.1 General Principles

The primary objective of the initial management of multiple injured patients with suspected traumatic spine injuries is *survival*. During the primary survey, the injured patient is rapidly assessed according to the algorithm of the ATLS® protocol, with life-saving procedures being instituted simultaneously (see Chap. 6) [6]. Spinal injuries are identified during the secondary survey. As outlined above, spinal precautions must be retained until the presence of a spinal injury has been ruled out through clinical or imaging pathways. A spine surgeon (neurosurgery or orthopedics) should be consulted for assessment and treatment recommendation whenever a spine injury is identified, with the exception of isolated A0-type transverse process fractures which do *not* require a specialist consultation.

### 20.7.2 Subaxial Cervical Spine

Subaxial cervical spine injuries (Figs. 20.1, 20.2) and fracture-dislocations represent a significant challenge in polytrauma patients due to the imminent risk of an associated spinal cord injury [19]. Fractures or dislocations of the posterior cervical elements are typically managed by an attempt for initial closed reduction with temporary external fixation in a Halo vest or Gardner-Wells tongs traction, followed by definitive posterior spinal fusion, as indicated [20]. A classic challenge for the management of cervical facet dislocations is represented by the potential of an associated injury to the anterior spinal column with a disc herniation into the anterior spinal canal [21]. In this scenario, a pre-reduction MRI should be obtained in all cases, since the imprudent closed reduction maneuver may lead to the iatrogenic compression of the spinal cord with the potential for subsequent devastating neurological consequences. In absence of access to MRI, the concept of a closed reduction of the cervical spine under close observation in awake and alert patients has been largely proven safe and feasible. Nevertheless, selected cases of catastrophic deterioration of the neurological status after closed reduction maneuvers have been reported. Temporary spinal immobilization is achieved by application of cervical collars, Halo ring fixators, or Gardner-Wells traction. The definitive surgical management of unstable cervical injuries is performed via anterior, posterior, or combined (anterior-posterior or posterior-anterior) approaches, typically as a discectomy or corpectomy in conjunction with spinal fusion above and below the injured level(s) [4]. Unstable 3-column fractures and fracture-dislocations with posterior facet dis-

locations may require a posterior approach and combined 360° fusion [21].

### 20.7.3 Thoracic and Lumbar Spine

Isolated transverse process fractures (A0-type) and stable vertebral compression fractures (A1-type) of the thoracic and lumbar spine (Figs. 20.3, 20.4) are typically treated non-operatively, without the need for bracing [22]. Of note, isolated transverse process fractures do not require spine surgical consultation. Stable burst fractures (A3-type) without neurological deficit can also be treated non-operatively in an external orthosis (so-called TLSO). Indications for surgery include significantly displace posterior wall fractures with spinal canal stenosis >50% and progressive kyphotic deformity >20° [5]. Unstable vertebral fractures of the thoracic or lumbar region, with or without neurological deficits, require early spine specialist consultation (orthopedics or neurosurgery) for consideration of surgical management [23]. As outlined above, patients are kept on log-roll precautions until presence of spinal instability has been ruled out. Unstable thoracic or lumbar fractures (either A4-, B-, or C-types) are managed surgically by spinal canal decompression and spinal fusion [23]. In polytrauma patients with associated thoracic or lumbar fractures, the streamlined proactive approach by a "spine damage control" protocol may be considered in multiple injured patients by initial posterior fracture reduction, fixation, and decompression by laminectomy [24]. This modality allows early mobilization and position-

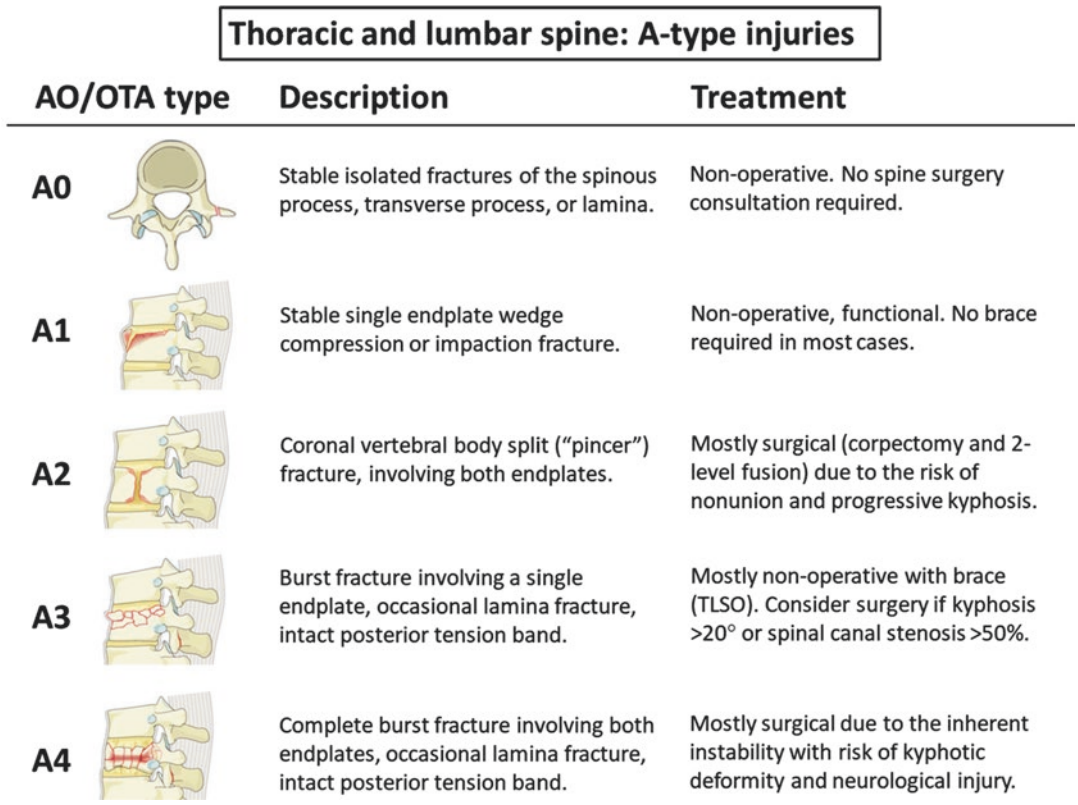


**Fig. 20.3** AO/OTA classification of A-type thoracic and lumbar spine injuries
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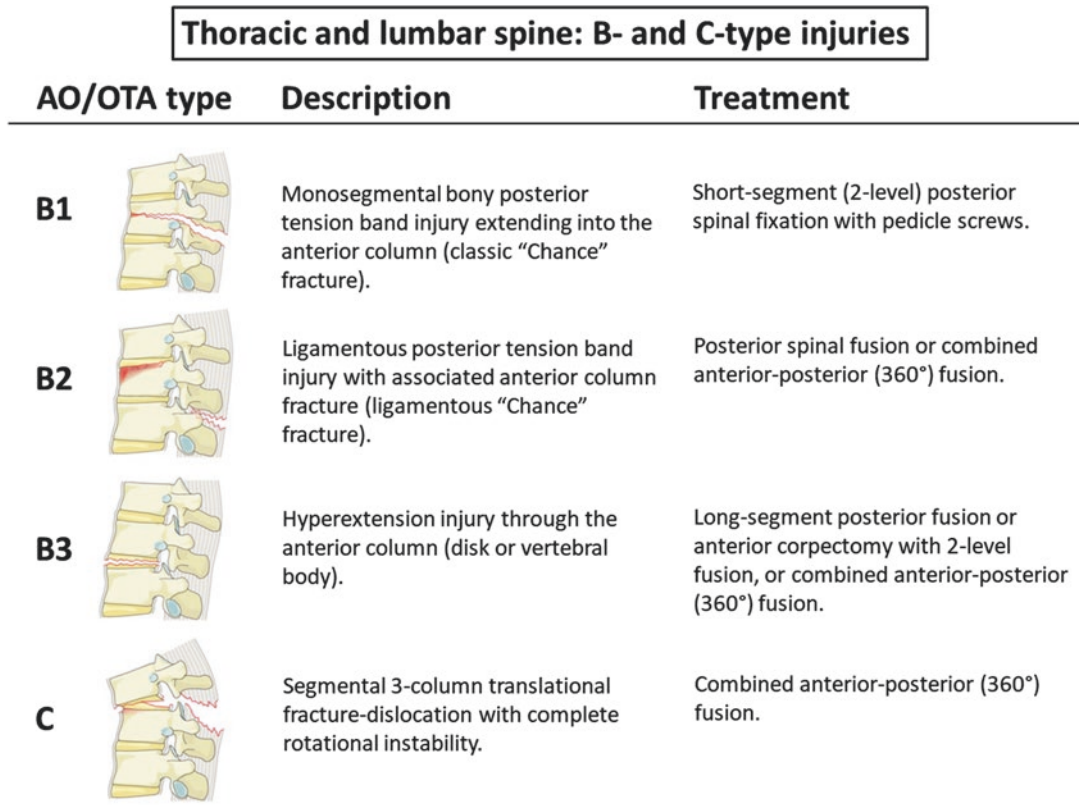


**Fig. 20.4** AO/OTA classification of B-type and C-type thoracic and lumbar spine injuries

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ing of multiple injured patients as needed for intensive care (*see "timing of surgery" below*). Three column injuries frequently require a combined posterior/anterior 360° fusion.

## 20.7.4 Specific Injury Patterns

### 20.7.4.1 Occipital Condyle and Atlas Fractures

Occipital condyle fractures (C0) are rare injuries that are frequently missed, and therefore require a high level of suspicion, particularly in high-energy trauma mechanisms, including motor vehicle accidents and falls from height. The diagnosis is established by initial CT scan and advanced imaging by MRI for determination of ligamentous integrity. Most occipital condyle fractures are considered stable and are managed non-operatively in a Halo vest or cervical collar. Rarely, a surgical occipitocervical fusion is indicated in presence of significant displacement and instability. Atlas fractures (C1) are classified by the Gehweiler classification (Fig. 20.5) [25]. While there is residual inter-observer variability in the assessment of the stability and treatment preference for atlas fractures, most spine surgeons agree that the Gehweiler types I, II, IIIa, and V are typically stable and managed non-operatively, either in a cervical collar or a Halo vest [25, 26].

### 20.7.4.2 Odontoid Fractures

Fractures of the C2 odontoid process ("dens") are classified by the Anderson and D'Alonzo classification (Fig. 20.6) [27]. Type II fractures are the

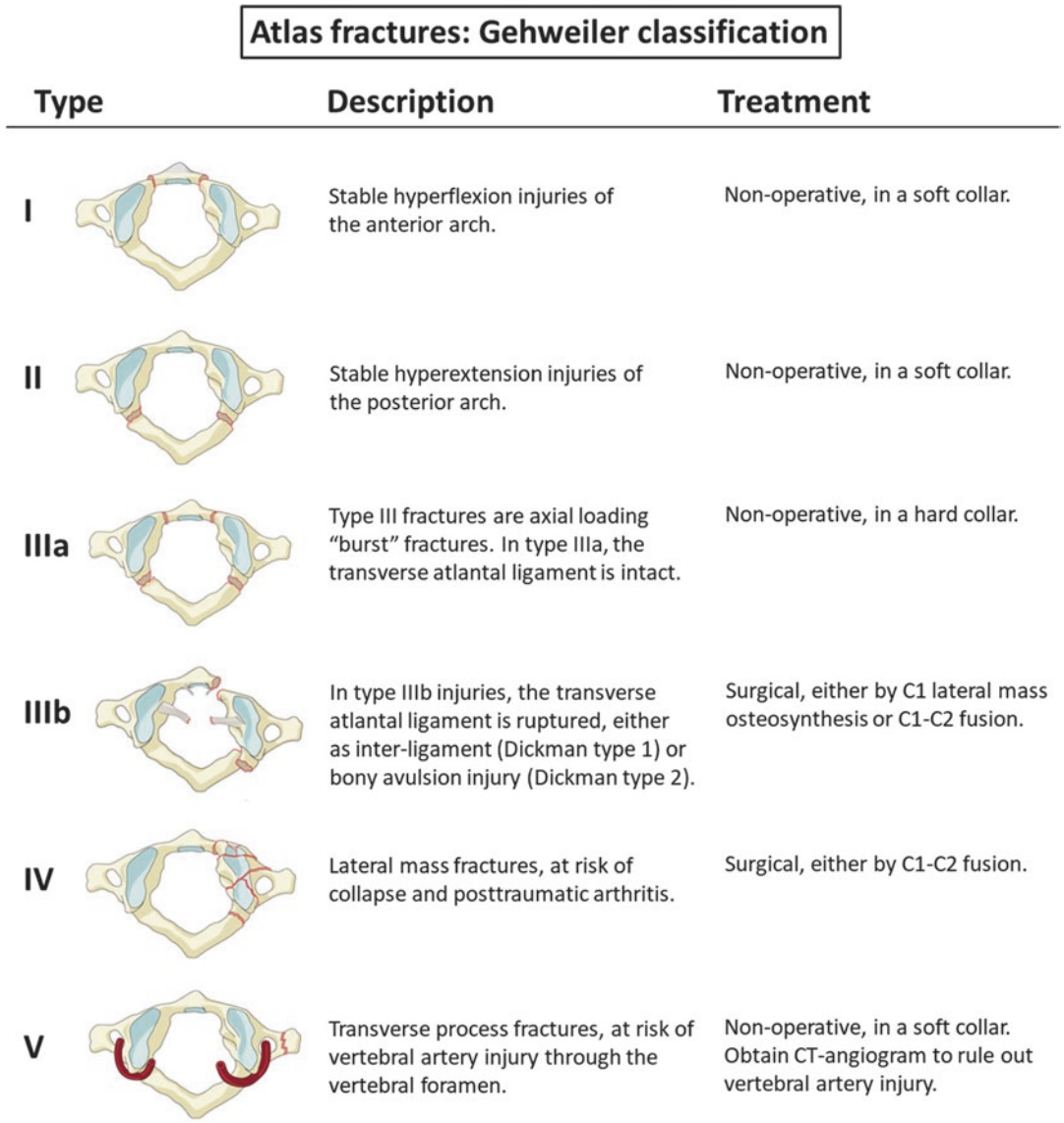


**Fig. 20.5** Gehweiler classification of atlas (C1) fractures
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most common pattern that typically requires consideration for surgical management. In contrast, most type I and type III injuries are managed non-operatively in a cervical collar.

#### 20.7.4.3 "Hangman's Fracture"

A *Hangman's fracture* represents a traumatic spondylolisthesis of the axis, and is defined as bilateral fractures through the C2 pars interarticularis along with a disruption of the C2-C3 intervertebral disc [28]. These fracture-dislocations are usually the result of a combination of extension, flexion, and axial compression. The fracture pattern was first described in the 1860s subsequent to judicial hangings, with the proposed mechanism of hyperextension and distraction at the level of C2-C3 [29]. The classification of Hangman's fracture into 3 types is based on spi-

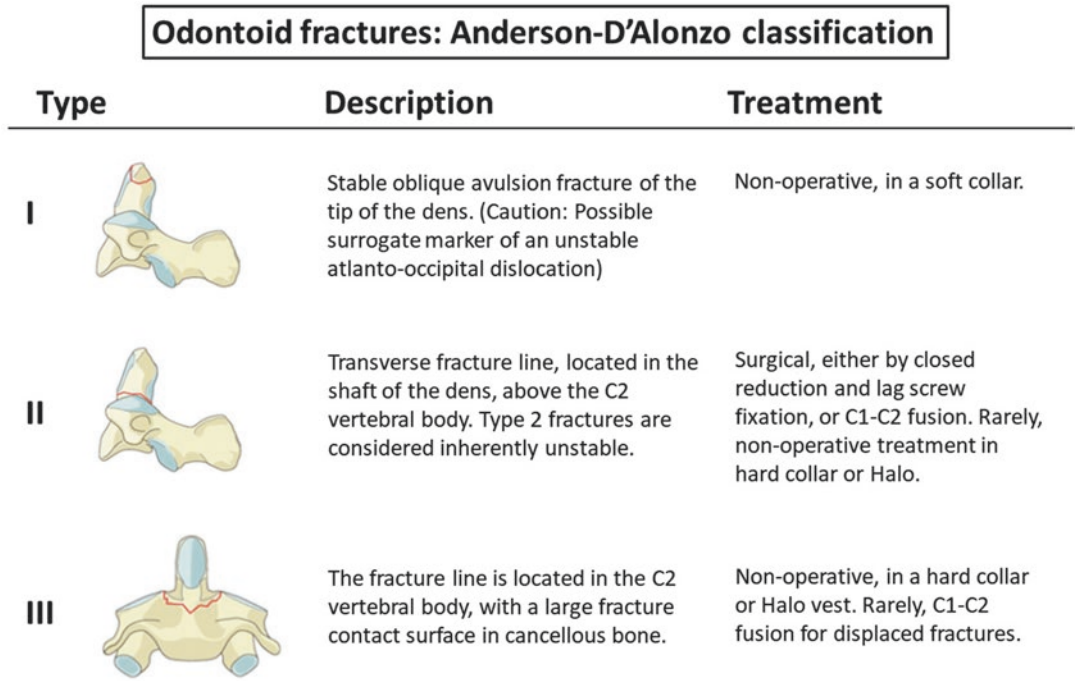


**Fig. 20.6** Anderson-D'Alonzo classification of odontoid (C2) fractures

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nal stability and helps guide the definitive treatment. Most type I and II injuries are managed non-operatively in a hard collar or Halo vets, whereas type III fractures are inherently unstable due to significant translation (>3 mm) and angulation (>11°) with associated C2-C3 facet dislocation. These injuries are managed surgically by C2-C3 fusion.

#### 20.7.4.4 "Chance" Fracture

*Chance fractures* are named after the British radiologist, Dr. George Quentin Chance who first described this injury pattern in 1948 [30]. A Chance fracture, also named "seatbelt injury," is reflective of a classic flexion-distraction injury around the upper lumbar spine (L1, L2) or thoracolumbar junction (T12-L1). These fracture types are unstable by definition and associated with a high risk of associated intraabdominal or retroperitoneal injuries, frequently pancreatic or duodenal contusions. The mechanism leading to a Chance fracture is a deceleration flexion injury of the vertebral body which disrupts the posterior tension banding elements, typically affecting backseat passengers with a lap belt involved in high-speed motor vehicle accidents or falls from heights with a fulcrum of the impacting force anterior to the abdomen.

The B1-Type by AO/OTA classification represents the "classic" Chance fracture reflective of a transosseous tension band disruption through the pedicles and spinal process at a single vertebral level. In contrast, the B-2 type is considered a "ligamentous Chance" injury through the posterior tension band ligaments, with or without involvement of the posterior bony elements ("osseoligamentous" injury), and associated with a compression fracture of the vertebral body (Fig. 20.4) [30].

#### 20.7.4.5 Sacral Fractures

Sacral fractures are typically managed as part of pelvic ring injuries and their classification and managed is described in detail elsewhere in the pertinent literature [31, 32].

## 20.8 Surgical Timing

Unstable spine fractures, dislocations and fracture-dislocations must be recognized early and treated in a timely fashion. This entails early closed reduction and application of Halo fixators for unstable cervical spine injuries, and the early open-reduction and spinal fixation/fusion for unstable thoracic and lumbar injuries and for irreducible cervical spine dislocations [4]. The widely disseminated practice of internally fixating unstable thoracic and lumbar fractures in polytrauma patients consists of either a conservative approach of "delayed spine fixation" (after full resuscitation), or a more proactive approach of "early total care" (ETC). The latter includes invasive anterior approaches, vertebral corpectomy, spinal canal decompression, and anterior spinal column stabilization/fusion. Many spine surgeons are discouraged from early spinal surgery based on the notion that multiple injured patients are frequently "too sick" to safely undergo surgical procedures within the first few days after major trauma [33]. The problem associated with this conservative philosophy is that these vulnerable patients remain bedridden on log-roll precautions, which precludes from a coherent and proactive management of severe associated injuries to the head, chest, abdomen, and pelvis. A landmark article published 20 years ago analyzed 291 consecutive patients that were matched for injury severity and stratified by level of spine injury into two distinct cohorts, depending on the timing of fracture fixation: "early" fixation (within 3 days, $n = 142$) versus "late" fixation (>3 days, $n = 149$) [34]. In this study, the early fixation of thoracic spine fractures resulted in a lower incidence of pneumonia, fewer ventilator-dependent days, a shorter ICU stay, and reduced hospital charges [34].

A proactive approach of "spine damage control" has been described and validated in the recent literature with the intent of mitigating the risk of adverse outcomes in polytrauma patients with associated unstable thoracic or lumbar spine fractures at risk of adverse outcomes [33, 35].The concept of "spine damage control" entails a staged procedure of immediate posterior fracture reduction and instrumentation within 24 h ("day 1 surgery"), followed by scheduled 360° completion corpectomy and fusion during a physiological "time-window of opportunity" (>3 days after trauma) [33]. Proceeding with the second stage is done if an adjunctive anterior decompression and fusion are indicated for neurological or biomechanical reasons (Fig. 20.7). This concept differs from the more common elective strategy of staged spine fixation by initial posterior fixation and delayed anterior completion in two ways. First, by its timeliness (posterior fixation within 24 h) and second, by its expanded applicability to all unstable thoracolumbar fractures, including exclusive anterior column burst fractures.

In a prospective validation study of the "spine damage control"protocol, 112 consecutive patients with unstable thoracic or lumbar spine fractures and Injury Severity Score (ISS) >15 were prospectively enrolled during a three-year time-window [36]. Early "spine damage control" within 24 h was performed in 42 patients, whereas 70 matched patients in the control group underwent definitive operative spine fixation at a delayed time-point. The mean time to initial spine fixation was significantly decreased in the "spine damage control" group (8.9 ± 1.7 h vs. 98.7 ± 22.4 h, $P < 0.01$). The early spine fixation cohort also showed a reduced length of operative time (2.4 ± 0.7 h vs. 3.9 ± 1.3 h), length of hospital stay (14.1 ± 2.9 days vs. 32.6 ± 7.8 days), and number of ventilator-dependent days (2.2 ± 1.5 days vs. 9.1 ± 2.4 days), compared to the delayed spine fixation control group. Most importantly, the post-injury and postoperative complication rate was significantly decreased after "spine damage control," including a reduced incidence of wound complications and surgical

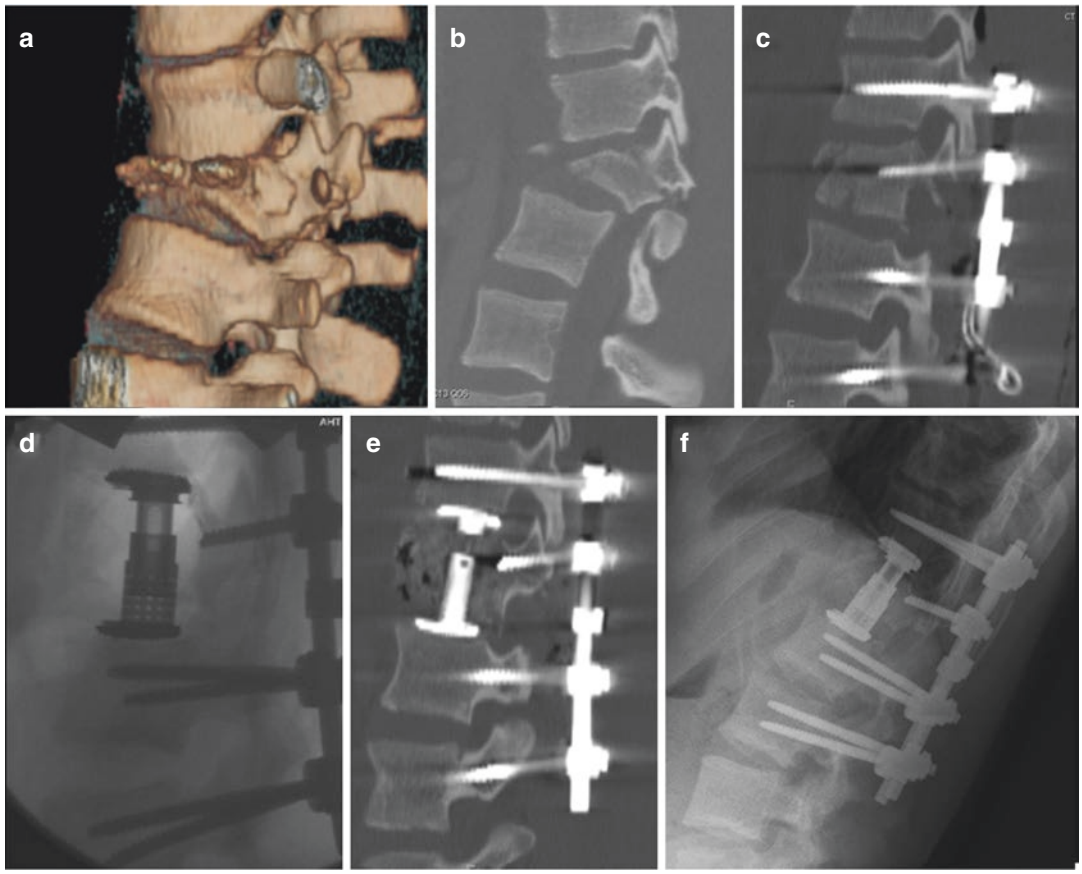


**Fig. 20.7** "Spine damage control" case example of an unstable thoracolumbar fracture-dislocation in a 21-years-old polytrauma patient involved in a high-speed motor vehicle accident

The unstable injury pattern is depicted in spinal CT reconstructions from the initial trauma multislice CT (panels **a**, **b**). A three-level posterior pedicle screw instrumentation, fracture reduction, and spinal canal decompression (panel **c**) was performed on day 1 as part of a standardized institutional "spine damage control "protocol [33, 36] (see text for details). Subsequent to the patient's successful resuscitation and stabilization, a staged anterior vertebral corpectomy and two-level anterior fusion were performed on day 5 post-injury with an expandable cage and bone graft (panels **d**–**f**)

site infections (2.4% vs. 7.1%), urinary tract infections (4.8% vs. 21.4%), pulmonary complications (14.3% vs. 25.7%), and pressure sores (2.4% vs. 8.6%) [36].

This notion is confirmed in systematic reviews of the published literature demonstrating that the early intervention for fracture stabilization in the thoracolumbar spine is safe, advantageous, and associated with a significantly decreased incidence of postoperative complications [37]. However, due to the lack of unequivocal scientific evidence from prospective randomized trials, there is a lack of consensus regarding the "optimal" timing of spine fracture fixation in multiple injured patients [38]. Intuitive advantages of early spine fixation relate to preventing complications associated with prolonged bed rest and the inability to adequately position and mobilize severely injured patients in the intensive care unit (ICU). Unequivocally, multiple injured patients require unrestricted options for mobilization and positioning in the ICU, including the upright seated position for treatment of head injuries and the prone position for respiratory therapy of pulmonary complications, such as the acute respiratory distress syndrome. Finally, unstable and unreduced spinal fractures contribute to adverse

sequelae of major trauma related to stress, pain, ongoing bleeding, and sustained systemic inflammation [10]. This notion provides a strong argument for the early clearance of bed rest and log-roll precautions in multiple injured patients. Current evidence suggests that any unstable thoracic or lumbar spine fracture or dislocation should be reduced and fixated within 24 h of admission [39–41]. This notion is particularly applicable in the care of multiple injured patients at risk of sustaining "second hit" insults and post-injury complications, including pressure sores, pulmonary infections, and thromboembolic complications [24, 42].

## 20.9 Postoperative Rehabilitation

One of the main goals of surgical stabilization of unstable spine fractures is the early unrestricted mobilization of patients with the intent of avoiding preventable complications related to prolonged bed rest [43]. Patients have to be instructed for compliance with "spinal precautions" (i.e., no bending, twisting, lifting for 10–12 weeks) by physical and occupational therapy, to avoid unnecessary strain on the injured/fixated spinal levels with the potential of a delayed failure of fixation, and increased risk of long term adjacent-level degeneration [7]. Patients with spinal cord injury should be transferred to specialized centers for neurorehabilitation as early as possible [8].

## 20.10 Conclusion

The surgical decision-making for multiple injured patients with unstable spine fractures remains a challenging task, due to the multiplicity of confounding variables and conflicting priorities in the initial assessment and management. A protocol-driven standardized approach is therefore imperative, which includes assurance of vital functions by the ATLS® protocol and proactive surgical fixation of unstable spine fractures through a "spine damage control" approach which allows for early unrestricted patient mobilization and appropriate care of associated injuries.

**Key Concepts**

- A standardized "spine damage control" protocol mandates early surgical stabilization of unstable thoracic and lumbar spine fractures in polytrauma patients within 24 h and reduces the risk of post-injury complications.
- Early mobilization of critically injured patients with associated spine injuries is essential and requires a proactive spinal clearance algorithm and early surgical stabilization, if indicated.
- A coordinated multidisciplinary approach is required to assure the timely and appropriate care for the vulnerable cohort of polytrauma patients with associated spine fractures.

**Take Home Messages**

- The presence of an unstable spinal injury is presumed in all polytrauma patients until proven otherwise.
- The novel AO/OTA system from 2018 allows to classify spinal injuries based on mechanism of trauma, injury severity, and spinal stability, and serves as a guide for clinical decision-making.
- Identified spinal injuries in polytrauma patients require a spine specialist consultation, with the exception of stable A0-type isolated transverse process fractures.

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# Spinal Cord Injury

# 21

Philip F. Stahel, Grégoire P. Chatain, and Michael A. Finn

**Learning Objectives**

- Describe the appropriate evaluation of the trauma patient with suspected spinal cord injury.
- Identify the level of sensory and motor impairment based on defined dermatomes and myotomes.
- Understand the ASIA spinal cord injury classification system.
- Establish a plan for timely surgical spine stabilization and decompression, if indicated.
- Recognize the benefit of early patient transfer to neurorehabilitation.

## 21.1 Introduction

Spinal cord injury is a devastating, life-altering event for patients and their families. In spite of decades of innovative research in the field, no pharmacological "silver bullet" has been developed which could mitigate or cure the extent of neurological impairment [1, 2]. Preservation of function by providing early stability to the injured spine followed by neurorehabilitation remains the current standard of care [3, 4]. Surgical decision-making should hinge on the early decompression of neurological elements, if indicated, in conjunction with the surgical restoration of spinal stability and spinal alignment, in order to provide the best baseline opportunity for recovery of the injured spinal cord [5]. A protocol-driven multidisciplinary approach to the management of trauma patients with spinal cord injury is imperative to reduce the risk of preventable complications and to improve long-term patient outcomes [6].

## 21.2 Pathophysiology

The primary traumatic injury to the spinal cord is a result of mechanical forces applied to the bony elements and/or the spinal cord at the time of trauma impact. These forces can induce a translocation of fracture fragments or disk material into the spinal canal, leading to an acute compromise of the spinal canal and compression of the spinal cord. Indirect trauma mechanisms related to shearing and stretching of axons can cause axonal injuries and neuronal tissue disruption. The mechanical damage to axons will consecutively alter the physiological flow of electrical informa-

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tion to target muscles, resulting in motor and sensory deficits below the level of injury [7]. Importantly, the extent of posttraumatic injury to neurons and axons is *not* exclusively related to the severity of the primary trauma and is largely mediated by delayed secondary mechanisms related to the local release of neuroinflammatory and neurotoxic molecules [8, 9]. Furthermore, microvascular neutrophil margination into the spinal cord (Fig. 21.1a) is evident within few hours after injury, and neutrophils contribute to secondary neuronal damage by releasing neurotoxic molecules from the oxidative burst [10–12]. These pathophysiological events lead to a breakdown of the blood-spinal cord barrier [13] which further exacerbates the leakage of neurotoxic molecules from the peripheral circulation into the intrathecal space around the spinal cord, resulting in progressive expansion of the traumatic lesion and perifocal spinal edema [14]. The activation of glial cells leads to reactive microgliosis and astrocytosis (Fig. 21.1b) with release of proinflammatory mediators which further perpetuate the extent of neuroinflammation and neurodegeneration [15, 16]. Within days after trauma, reactive astrocytes form a dense border around the site of injury with the intent to "wall-off" damaged tissue and prevent further spread of injurious molecules and inflammatory cells into adjacent healthy tissue [17]. This inflammatory process further complicates the subsequent neuronal repair [18]. Finally, in addition to the detrimental impact of neuroinflammation, injured neurons undergo apoptotic (programmed) cell death, mediated through signal-transduction pathways that are activated by a variety of host-mediated mechanisms and contribute to the secondary expansion of the spinal cord lesion [19, 20].

## 21.3 Diagnostic Workup

The initial assessment and diagnostic workup of polytrauma patients with suspected spinal injuries, including the fracture classification using the revised 2018 AO/OTA system [21] are described in detail in a separate chapter in this book (see Chap. 20: *Spine Fractures*).

## 21.4 Neurologic Evaluation

A thorough neurologic exam represents a crucial part of the "secondary survey" during the initial assessment of a trauma patient with a suspected spinal injury [22]. Cranial nerve abnormalities indicate a high level of suspicion for injuries at the occipito-cervical junction. Below the subaxial spine, the *bony level of injury* correlates to the level of the vertebral fracture or dislocation, whereas the *neurological level of injury* refers to the most caudal segment of the spinal cord with bilaterally preserved sensory and motor function. Frequently the bony and neurological levels do *not* correlate, since the spinal nerves exit the neural foramina at a different level. The "key" sen-

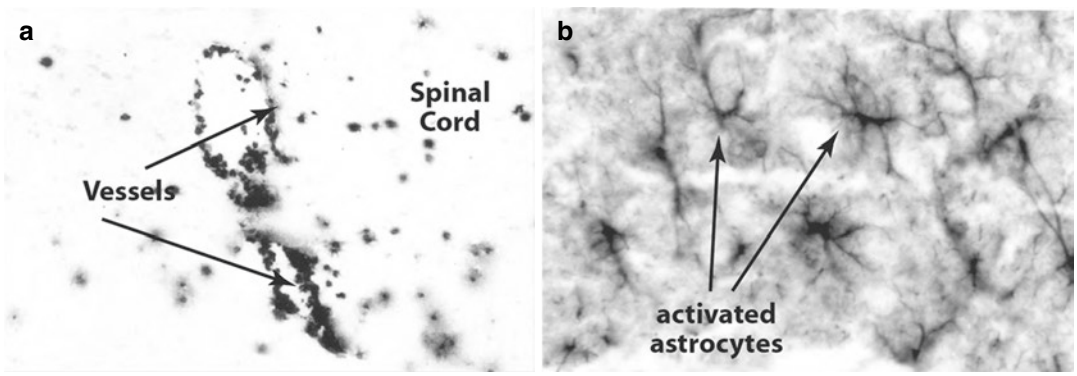



**Fig. 21.1** Immunohistochemical staining of perivascular neutrophil infiltration (**panel a**) and reactive astrocytosis (**panel b**) in the spinal cord in a rodent model of experimental spinal cord injury. (© Phil Stahel, 2010)

**Table 21.1** "Key" spinal nerve segments and areas of innervation (dermatomes)

| Spinal level | Dermatome location |
|---|---|
| C5 | Lateral shoulder/deltoid |
| C6 | Thumb |
| C7 | Middle finger |
| C8 | Little (pinky) finger |
| T4 | Nipple |
| T8 | Lower sternum/xiphoid process |
| T10 | Umbilicus |
| T12 | Pubic symphysis |
| L4 | Medial calf |
| L5 | Web space between first and second toes |
| S1 | Lateral border of the foot |
| S4-S5 | Perianal region |

**Table 21.2** "Key" motor muscles and respective function tests (myotomes)

| Spinal level | Function test |
|---|---|
| C5 | Elbow flexion |
| C6 | Wrist extension |
| C7 | Elbow extension |
| C8 | Finger flexion |
| T1 | Finger abduction |
| L2 | Hip flexion |
| L3 | Knee extension |
| L4 | Ankle dorsiflexion |
| L5 | Toe extension |
| S1 | Ankle plantar flexion |

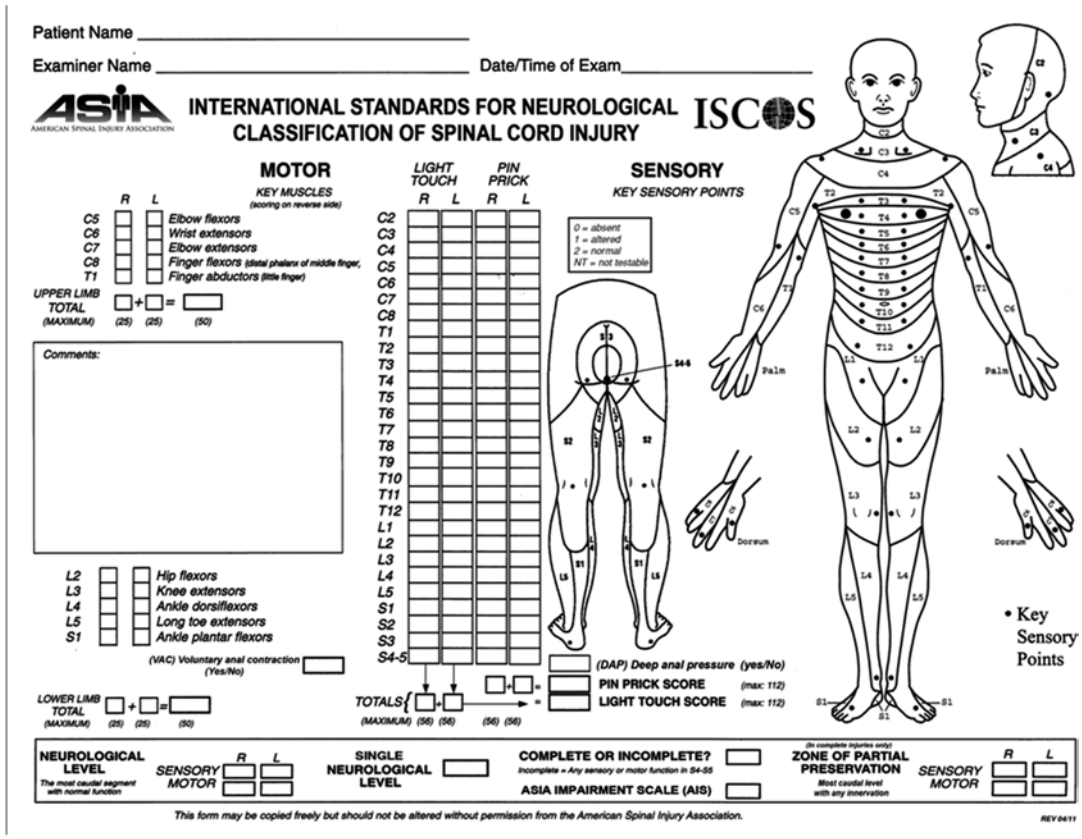
sory dermatomes are outlined in Table 21.1. These include unequivocal truncal and four-extremity sensory points which must be assessed by light-touch and pin-prick sensation and documented in the patient's chart. Importantly, the exact time of the exam must be documented to allow monitoring of neurologic changes over time. The motor examination of the four extremities should focus on the C5-T1 and L2-S1 myotomes, as outlined in Table 21.2. Muscle function grading is performed on a scale from 0-5 points, whereby a score of 5 represents full normal function, and a score of 0 implies complete paralysis (Table 21.3).

The level and severity of a spinal cord injury are determined using the chart by the "American Spinal Injury Association"(ASIA) [5]. The chart is a helpful tool as a rapid mnemonic of the "key sensory points" (dermatomes) and "key muscles" (myotomes) and allows to determine the neurological level of injury (Fig. 21.2). The severity of spinal cord injury is stratified into "complete"(ASIA grade A) versus "incomplete"(ASIA grades B–D), whereby ASIA grade E implies a normal neurologic status. Spinal cord injury is further stratified into paraplegia (paralysis of the lower extremities), resulting from thoracic and lumbar spine injuries, and quadriplegia (paralysis of all four extremities), which originates from cervical spine injuries. With incomplete injuries, the patient has some extent of preserved neurologic function below the level of injury, which is associated with a better outcome prediction compared to complete injuries, where the prognosis is dismal [23].

**Table 21.3** Motor function grading score

| Motor function | Clinical correlate |
|---|---|
| 0 | Complete paralysis |
| 1 | Palpable or visible muscle contraction |
| 2 | Active movement and full ROM with gravity eliminated |
| 3 | Active movement and full ROM against gravity |
| 4 | Active movement and full ROM against gravity and moderate resistance |
| 5 | Normal active function with full ROM against gravity and resistance |
| NT | Not testable (e.g., due to obtunded patient, immobilization, limb amputation, chronic contracture, etc.) |

A full neurologic exam includes reflex testing, with a focus on triceps, brachioradialis, patellar, and Achilles tendons. Hyperreflexivity may be indicative of a spinal cord injury, while areflexia is reflective of spinal shock with temporary absence of all reflexes. Testing for pathological reflexes includes Hoffman's sign, Babinski sign, and presence of clonus in the case of impaired upper motor neuron down-regulation. A rectal examination is part of the mandatory exam and includes assessment and documentation of anal resting, voluntary tone, anal and perianal sensation (light-touch and pin-prick), and spinal reflexes (anal wink and bulbocavernosus reflex; the latter requires a Foley catheter placement in females). Obtunded patients should be observed for voluntary movements and withdrawal activity with objective assessments taken from reflex and




## Muscle Function Grading

**0** = total paralysis

**1** = palpable or visible contraction

**2** = active movement, full range of motion (ROM) with gravity eliminated

**3** = active movement, full ROM against gravity

**4** = active movement, full ROM against gravity and moderate resistance in a muscle specific position.

**5** = (normal) active movement, full ROM against gravity and full resistance in a muscle specific position expected from an otherwise unimpaired peson.

**5*** = (normal) active movement, full ROM against gravity and sufficient resistance to be considered normal if identified inhibiting factors (i.e. pain, disuse) were not present.

**NT** = not testable (i.e. due to immobilization, severe pain such that the patient cannot be graded, amputation of limb, or contracture of >50% of the range of motion).

## ASIA Impairment (AIS) Scale

☐ **A = Complete.** No sensory or motor function is preserved in the sacral segments S4-S5.

☐ **B = Sensory Incomplete.** Sensory but not motor function is preserved below the neurological level and includes the sacral segments S4-S5 (light touch, pin prick at S4-S5; or deep anal pressure (DAP)), AND no motor function is preserved more than three levels below the motor level on either side of the body.

☐ **C = Motor Incomplete.** Motor function is preserved below the neurological level**, and more than half of key muscle functions below the single neurological level of injury (NLI) have a muscle grade less than 3 (Grades 0-2).

☐ **D = Motor Incomplete.** Motor function is preserved below the neurological level**, and at least half (half or more) of key muscle functions below the NLI have a muscle grade ≥ 3.

☐ **E = Normal.** If sensation and motor function as tested with the ISNCSCI are graded as normal in all segments, and the patient had prior deficits, then the AIS grade is E. Someone without an initial SCI does not receive an AIS grade.

**For an individual to receive a grade of C or D, i.e. motor incomplete status, they must have either (1) voluntary anal sphincter contraction or (2) sacral sensory sparing with sparing of motor function more than three levels below the motor level for that side of the body. The Standards at this time allows even non-key muscle function more than 3 levels below the motor level to be used in determining motor incomplete status (AIS B versus C).

NOTE: When assessing the extent of motor sparing below the level for distinguishing between AIS B and C, the *motor level* on each side is used; whereas to differentiate between AIS C and D (based on proportion of key muscle functions with strength grade 3 or greater) the *single neurological level* is used.

## Steps in Classification

The following order is recommended in determining the classification of individuals with SCI.

1. Determine sensory levels for right and left sides.
2. Determine motor levels for right and left sides.
   *Note: in regions where there is no myotome to test, the motor level is presumed to be the same as the sensory level, if testable motor function above that level is also normal.*
3. Determine the single neurological level.
   *This is the lowest segment where motor and sensory function is normal on both sides, and is the most cephalad of the sensory and motor levels determined in steps 1 and 2.*
4. Determine whether the injury is Complete or Incomplete. (i.e. absence or presence of sacral sparing)
   *If voluntary anal contraction* = **No** *AND all S4-5 sensory scores* = **0** *AND deep anal pressure* = **No,** *then injury is COMPLETE. Otherwise, injury is incomplete.*
5. Determine ASIA Impairment Scale (AIS) Grade:

**Is injury Complete?** If **YES,** AIS=A and can record ZPP (lowest dermatome or myotome on each side with some preservation)

NO ↓

**Is injury motor Incomplete?** If **NO,** AIS=B (Yes=voluntary anal contraction OR motor function more than three levels below the motor level on a given side, if the patient has sensory incomplete classification)

YES ↓

**Are at least half of the key muscles below the single neurological level graded 3 or better?**

NO ↓ AIS=C

YES ↓ AIS=D

**If sensation and motor function is normal in all segments, AIS=E**
*Note: AIS E is used in follow-up testing when an individual with a documented SCI has recovered normal function. If at initial testing no deficits are found, the individual is neurologically intact; the ASIA Impairment Scale does not apply.*

**Fig. 21.2** ASIA scoring chart to determine the neurological level and severity of spinal cord injury. (Reprinted with permission from the American Spinal Injury Association)

rectal examinations. Return of the bulbocavernosus reflex is reflective of resolution of spinal shock.

Multiple injured polytrauma patients, particularly in presence of traumatic brain injury (TBI) or major distracting injuries, can be very challenging to undergo a neurologic exam. In addition to the confounding influence of TBI, which may mimic symptoms of spinal cord injury, polytrauma patients are frequently intubated, sedated, and pharmacologically paralyzed. Despite these challenges, it is still possible to obtain relevant information related to the neurological function and potential for presence of a spinal cord injury. When patients cannot be assessed for motor and sensory function, it is important to examine reflexes and to obtain an anal sphincter examination. Spinal cord injured patients frequently have flaccid paralysis with loss of reflexes, which does not occur in isolated TBI. It is important to compare the reflexes of the upper and lower extremities and to check for presence of priapism, which is common in spinal cord injury, but not TBI. This adjunctive information can represent a "clinical window" to the spinal cord, in conjunction with radiographic studies. Aside from the standard diagnostic approach by multislice CT scanning of the polytrauma patient, which allows for 2-D and 3-D reconstructions of the entire spine, magnetic resonance imaging (MRI) of the affected or suspected spinal region (cervical, thoracic, lumbar) represents a highly sensitive tool to classify the neurologic injury and to guide surgical decision-making. The MRI allows investigation of spinal cord compression, contusion, dissection, and to detect intraspinal or epidural hemorrhage and integrity of the intervertebral discs and spinal ligaments. Spine surgeons pay close attention to the integrity of the posterior ligamentous complex (PLC) which includes the ligamentum flavum, the interspinous and supraspinous ligaments, as well as the facet-joint capsules and the intertransverse ligaments. Injury to the PLC represents an important surrogate marker of a mechanically unstable spine injury and relevant for the surgical decision-making process (see below) [23].

## 21.5 Terminology and Specific Injury Patterns

- **Tetraplegia** involves an injury to the cervical spinal cord leading to impairment of function in the upper extremities, trunk, lower extremities, and pelvic organs.
- **Paraplegia** involves an injury to the thoracic, lumbar, or thoracolumbar spinal cord leading to impairment of function in the trunk, lower extremities, and pelvic organs. Upper-extremity function is preserved.
- **Pentaplegia** reflects a spinal cord injury at or above the C4 level which results in complete loss of motor, sensory, and reflexive functions below the injured level. Importantly, this also includes paralysis of respiratory muscles. Patients with pentaplegia often remain ventilator-dependent in the long term.
- **Complete spinal cord injury** may result from transection, shearing, or contusion of the spinal cord. All functions (motor, sensory, and reflexes) below the level of the injury are lost. Complete spinal cord injury is associated with a dismal prognosis.
- **Incomplete spinal cord injury** involves some extent of preservation of motor or sensory function below the neurological injury level. One frequent symptom is "sacral sparing" with preserved sensation in the sacral dermatomes.
- **Anterior Cord Syndrome** results from an injury of the anterior two-thirds of the spinal cord (the distribution of the anterior spinal artery), which carries motor, pain, and temperature tracts. Vibration sense and proprioception are left intact because the posterior columns are typically preserved. This injury usually stems from a vascular insult, with poor long-term prognosis.
- **Posterior Cord Syndrome** results from an injury to the posterior third of the spinal cord within the distribution of the posterior spinal artery, which carries proprioceptive and sensory tracts. Motor function and interpretation of painful and temperature stimuli are preserved. This injury pattern typically results from vascular hypoperfusion and the prognosis is variable.

- **Traumatic Central Cord Syndrome** (TCCS) results from injury to the central area of the spinal cord. This entity is often found in patients with pre-existing cervical stenosis resulting from spondylophytes. The prevalent injury mechanism is a hyperextension of the neck with buckling of the thickened posterior ligamentum flavum into the spinal canal. Characteristic deficits are more severe in the upper extremities than in the lower extremities owing to the axial arrangement of the neuronal tracts. The prognosis is variable, and some patients show spontaneous recovery, with residual long-term sensory dysfunction in the upper extremities ("burning hands syndrome").
- **Brown-Séquard Syndrome** typically results from penetrating injuries that affect one side of the spinal cord through a unilateral hemitransection. This entity is rarely also seen in blunt trauma mechanisms in the presence of unilateral herniated discs. The syndrome results from injury to half of the spinal cord where clinical manifestations result in motor, position, and vibration deficits on the ipsilateral side of the injury, whereas the contralateral side shows deficits in pain and temperature sensation. The prognosis is variable depending on the root cause and severity of the injury.

## 21.6 Neurogenic Versus Spinal Shock

Neurogenic shock is a "hemodynamic entity" that reflects hypotension resulting from loss of vasomotor tone and sympathetic innervation of the heart [22]. Cervical spine injuries and injuries in the upper thoracic spinal cord (above T7) can cause impairment of the descending sympathetic pathways and result in bradycardia and shock by pooling of peripheral blood which results in hypotension from relative hypovolemia. The management of neurogenic shock includes the use of vasopressors since fluid management alone may result in fluid overload and pulmonary edema. In contrast to neurogenic shock, spinal shock represents a neurological syndrome that refers to the transient loss of muscle tone (flaccidity), complete loss of sensation, and loss of reflexes during the early posttraumatic phase after spinal cord injury [6]. Recovery from spinal shock occurs in phases, typically starting with return of the bulbocavernosus reflex around 48–72 h post-injury. Deep tendon reflexes may take several days or weeks to return. Of note, the term "shock" in spinal shock does not relate to hypotension with end-organ hypoperfusion [22].

## 21.7 Decision-Making and Treatment Options

Presence of an unstable spinal injury must be suspected in any patient who sustains a high-energy trauma mechanism, independent of a neurological impairment [23]. A suggested decision-making algorithm for the diagnostic workup and treatment of polytrauma patients with suspected spinal cord injuries is shown in Fig. 21.3. The cervical collar is kept in place until spinal clearance, which frequently requires radiographic studies [22]. Clearance is the process by which the treating physician (trauma surgeon or spine surgeon) confirms that a spinal injury is absent. Patients should be removed from the back-board as soon as possible, using a team-based log-rolling maneuver. The principles of spine immobilization and spinal clearance are described in detail in a separate chapter in this book (see Chap. 20: *Spine Fractures*).

Patients with spinal cord injuries above the level of C5 are more likely to require intubation and mechanical ventilation, since the spinal C4 level innervates the diaphragm which is a crucial muscle for breathing. When securing the airway, care is required during intubation to prevent hyperextension of the neck that might cause an iatrogenic injury to the spinal cord. Per ATLS® principles, endotracheal intubation is performed with in-line cervical traction or by fiber-optic assistance. Maintenance of oxygenation and normotension are "key" variables to prevent or minimize the potential for second hit insults to the vulnerable spinal cord. In a selected subset of bradycardic patients, hypotension may result

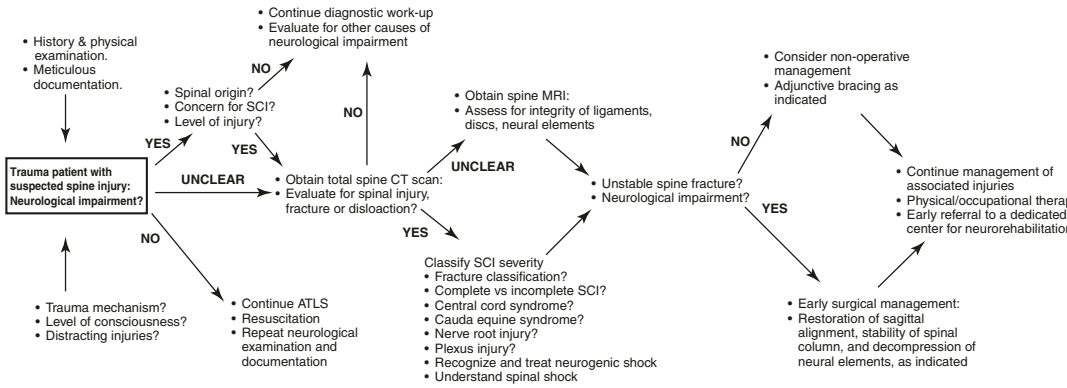



**Fig. 21.3** Decision-making algorithm for the diagnostic workup and management of polytrauma patients with suspected spinal cord injury

from neurogenic shock due to disruption of sympathetic output to the cardiovascular system, as described above. These patients typically require the use of inotropic and chronotropic support to maintain adequate systolic blood pressures.

## 21.8 Surgical Considerations

In general, surgery for unstable spinal injuries attempts to accomplish three main goals:

1. To decompress neurological structures (spinal cord, spinal nerve roots, cauda equina, conus medullaris), as indicated.
2. To restore and maintain the sagittal alignment of the spine.
3. To restore and maintain the stability of the spine.

Cervical and thoracolumbar spine injuries represent a heterogenous spectrum of injury and pathology type which can be difficult to categorize and classify. Advanced imaging techniques, including multi-slice CT and MRI, allow to quantify the degree and instability of the injury. The "Subaxial Cervical Spine Injury Classification" (SLIC; Table 21.4) and the "Thoracolumbar Injury Classification and Severity Score" (TLICS; Table 21.5) were both introduced to assist in clinical decision-making based on the ease of application and reproducibility of those scoring systems [5]. Both SLIC and TLICS incorporate the morphology of injury, ligamentous complex stability, and neurological status and allow to stratify the treatment options. In general, a score of ≤3 is deemed non-surgical, while a score ≥ 5 indicates the necessity of surgical spine stabilization with or without neural element decompression. A combined score of =4

**Table 21.4** "Subaxial Cervical Spine Injury Classification" (SLIC)

| Injury characteristic | Points |
|---|---|
| *Injury morphology* | |
| No abnormality | 0 |
| Compression | 1 |
| Burst | +1 |
| Distraction (e.g., facet perch, hyperextension) | 3 |
| Rotation/translation (e.g., facet dislocation, unstable "tear-drop," or advanced staged flexion compression injury) | 4 |
| *Discoligamentous complex (MRI)* | |
| Intact | 0 |
| Indeterminate (e.g., isolated interspinous widening, MRI signal change only) | 1 |
| Disrupted (e.g., widening of anterior disc space, perched facet/dislocation, kyphotic deformity) | 2 |
| *Neurological status* | |
| Intact | 0 |
| Root injury | 1 |
| Complete cord injury | 2 |
| Incomplete cord injury | 3 |
| Ongoing cord compression in setting of neurological deficit | +1 |

**Table 21.5** Thoracolumbar injury classification and severity score (TLICS)

| Injury characteristic | Qualifier | Points |
|---|---|---|
| *Injury morphology* | | |
| Compression | | 1 |
| Burst | | +1 |
| Rotation/translation | | 3 |
| Distraction | | 4 |
| *Neurologic status* | | |
| Intact | | 0 |
| Nerve root | | 2 |
| Spinal cord/conus medullaris | (Incomplete) | 3 |
| Spinal cord/conus medullaris | (Complete) | 2 |
| Cauda equina | | 3 |
| *Posterior ligamentous complex (MRI)* | | |
| Intact | | 0 |
| Suspected/indeterminate | | 2 |
| Disrupted | | 3 |

falls into a "grey zone" whereby the preferred management strategy should be determined on a case-by-case basis. It is important to highlight that in both scoring systems, the presence of *incomplete* spinal cord injury scores the highest number, which frequently provides the main deciding factor in guiding surgical versus conservative management [23].

The specific management strategies for spinal fractures, traumatic dislocations, and fracture-dislocations are described in detail in a separate chapter in this book (see Chap. 20*: Spine Fractures*). A case example of a young patient with a high-energy fracture-dislocation at T9-T10 and associated flexion-distraction injury at T6 managed by "spine damage control" long-segment posterior fusion and decompression within 12 h of injury is shown as a representative case illustration in Fig. 21.4.

## 21.9 Surgical Timing

The classification of the neurological level and extent of spinal cord injury drives the decision-making related to the surgical indication and surgical timing [23]. *Incomplete SCI* is a surgical "spinal emergency" with the goal of preserving the remaining function of the spinal cord and providing as stable baseline for neurological recovery. Incomplete injury to the spinal cord involves the preservation of some motor or sensory function below the level of injury. Typically, there is also variable sparing of sacral nerve roots which is manifested by retained perianal sensation and a certain extent of sphincter control. *Cauda Equina Syndrome (CES)* is a surgical urgency that requires decompression of the lumbar nerve rootlets. CES reflects a diverse spectrum of injury ranging from subtle bowel and bladder dysfunction to full-blown flaccid paralysis of the lower extremities with loss of sensation, areflexia, and complete sphincter incompetence. *Complete SCI* is a less urgent clinical scenario given the extremely limited potential for neurological recovery in these patients. Nevertheless, the consideration for early surgical management (<24 h) by spinal canal decompression and restoration of sagittal alignment and spinal stability will set the best prerequisite for early mobilization and neurorehabilitation, in conjunction with a decreased risk of post-injury complications, including pressure sores, venous thromboembolisms, and pulmonary complications.

Although the technical aspects in the surgical management of patients with spinal cord injuries are highly variable in the pertinent literature, the basic considerations remain invariably aligned to restore spinal alignment and stability, and to provide decompression of neural elements, if indicated. To achieve this goal, spine surgeons may employ anterior approaches, posterior approaches, lateral approaches, or a combination of approaches to ensure that the basic principles of spinal surgery are upheld (see Chap. 20: *Spine Fractures*). One of the "key" aspects for spine surgery in patients with spinal cord injuries relates to the notion that spinal precautions should be cleared after surgery, since patients with neurological impairment are typically unable to comply with restrictions related to bending, twisting, and lifting. This notion implies the imperative of providing "rock-solid" spine fixation, e.g., by 360° antero-posterior spinal fusion, in order to allow the best possible baseline for the early postoperative transfer to neurorehabilitation.

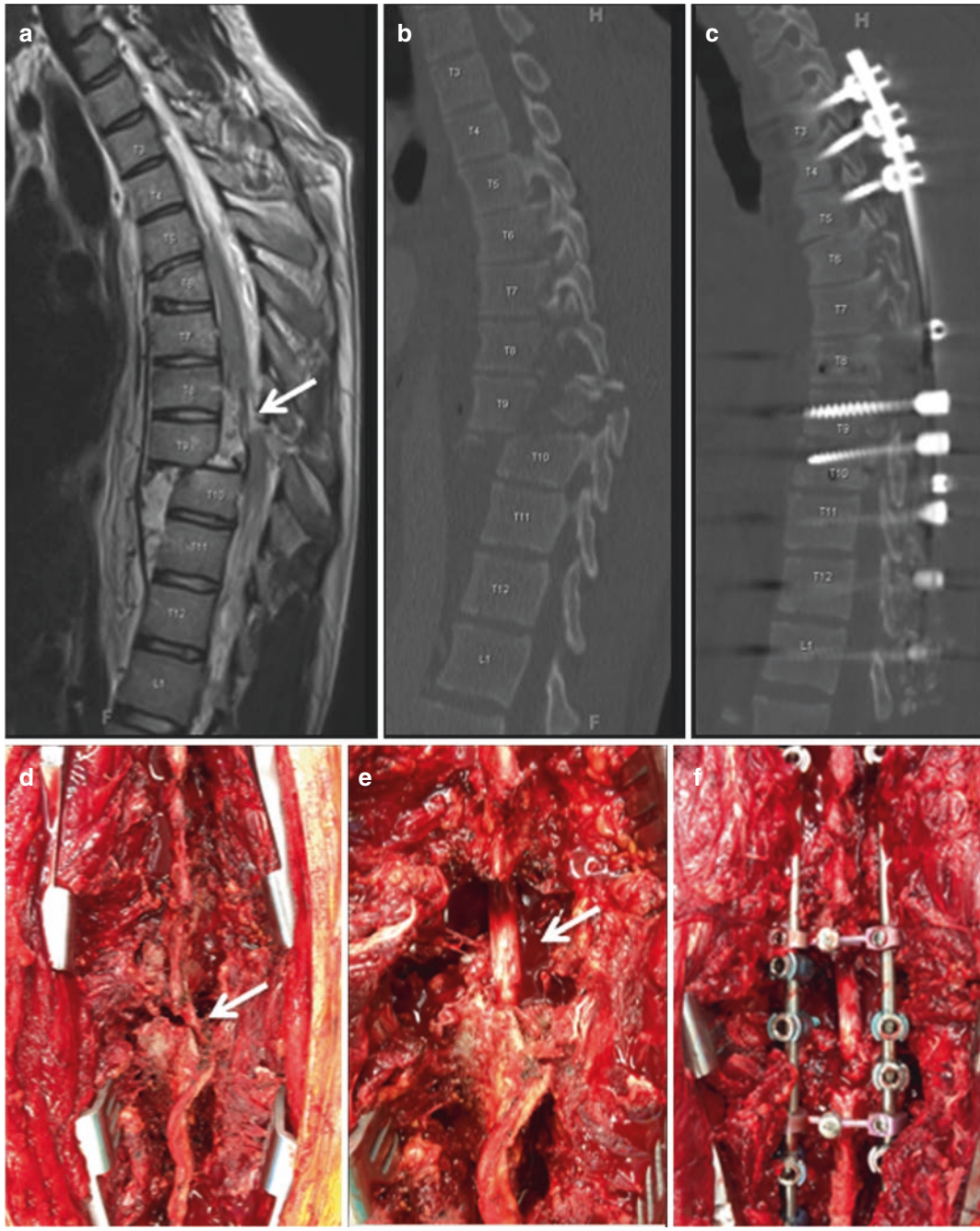



**Fig. 21.4** Case example of a T9–T10 "slice" fracture-dislocation with complete spinal cord transection

This 27-year-old patient sustained a high-energy twisting injury to the thoracic spine subsequent to a fall from height, leading to a rotationally and translationally unstable fracture-dislocation at the T9–T10 level. The patient was paraplegic at the accident site, with a complete spinal cord injury (ASIA grade A). The initial MRI shows the extent of displacement at T9–T10 and the associated spinal cord transection at the level above (arrow in **panel a**). The sagittal CT reconstruction demonstrates the amount of translational displacement at T9–T10 (**panel b**), and the surgical restoration of the sagittal profile after posterior spinal instrumentation from T3 to L1 (**panel c**). The posterior ligamentous injury and laminar fracture (arrow in **panel d**) and the exposed spinal cord after surgical decompression (arrow in **panel e**) and posterior instrumentation (**panel f**) illustrate the intraoperative findings during the early surgical management ("spine damage control") on day 1 of injury.

## 21.10 Principles of Postoperative Care

After spine surgery, patients should be placed on an evidence-based multidisciplinary spinal cord injury protocol ("SCI protocol"). These guidelines include proven best practices for prevention of hospital-acquired complications, including blood clots, pressure sores, as well as pulmonary and urinary tract infections. A dedicated "SCI Team" should be involved very early in the care process, including intensivists, respiratory therapists, physiatrists, physical and occupational therapists, behavioral health and spiritual care specialists, and social workers. In essence, the coordinated postoperative care following surgery is equally important as a well-executed surgical plan. The ultimate goal for patients with spinal cord injuries is the referral to a designated neurorehabilitation facility at the earliest time-point once all associated injuries have been definitely managed and stabilized [5, 6].

## 21.11 Special Considerations

### 21.11.1 The Role of Steroids Revisited

Despite current science unequivocally demonstrating a lack of effectiveness of high-dose methylprednisolone in the acute management of patients with spinal cord injuries, the issue remains a topic of daily debate and uncertainty among the involved care providers in the trauma bay. From a historic perspective, the consideration of high-dose steroids originated from presumed benefits in patients with brain tumors and head injuries in the 1960s and 1970s. After publication of the 2nd "National Acute Spinal Cord Injury Study" (NASCIS-2) in 1990, the application of high-dose methylprednisolone for patients with acute SCI became a globally accepted standard of care for more than a decade. [24] A critical analysis of the NASCIS data, however, placed the use of high-dose steroids under scrutiny due to questionable benefits and the potential for inflicting unintentional harm, such as placing the patients at increased risk for pulmonary infections [25]. The large-scale prospective randomized multicenter "CRASH" trial (**C**orticosteroid **ra**ndomization **a**fter **s**ignificant **h**ead injury) confirmed the notion of the unjustified experimental nature of high-dose steroids in the acute management of neurological injuries. The CRASH trial was unexpectedly aborted after enrollment of about 10,000 patients, based on the unexpected finding of a drastically increased mortality in patients treated with methylprednisolone, compared to the placebo control group [26]. The extrapolation of the negative results from this large-scale trial implied that the uncritical administration of corticosteroids in the 1980s and earlier may have been the cause of preventable post-injury mortality [27]. In absence of new prospective randomized trials on the role of steroids in spinal cord injury, current guidelines and clinical recommendations consider the routine use of steroids for patients with acute spinal cord injury obsolete [22, 28]. Selected neurologic injuries patterns, including spinal contusions or traumatic central cord syndrome (TCCS) allow consideration for a short course of steroids at the individual treating spine surgeon's discretion.

### 21.11.2 Riluzole

Riluzole is a glutaminergic modulator with neuroprotective properties which may improve functional and neurological outcomes after SCI [29]. Extensive preclinical animal models have corroborated its promising effects in improving motor function while also ameliorating a plethora of underlying pathophysiological events described above (see "pathophysiology") [30, 31]. In early clinical trials, riluzole was found to decrease the severity of SCI and neuropathic pain and to increase motor function. Further large-scale validation studies are needed to determine with scientific accuracy whether riluzole may represent a new "silver bullet" in the pharmacological treatment of patients with SCI [32].

### 21.11.3 Blood Pressure Augmentation

Current clinical guidelines advocate for elevating the mean arterial pressure (MAP) to increase spinal cord perfusion in SCI patients. Early MAP augmentation has been shown to improve neurological outcomes by reducing ischemia/reperfusion-related secondary neuronal injuries. The general goal for MAP threshold in SCI patients above 85 mmHg for 5–7 days is positively correlated with improvement in neurological recovery. This is typically achieved in the neurocritical care setting with administration of vasopressors, such as norepinephrine or phenylephrine. Blood pressure augmentation remains one of the main cornerstones of SCI management in a setting of limited available pharmacological treatment options.

### 21.11.4 Thromboembolic Prophylaxis

Prophylaxis against venous thromboembolism (VTE) is a crucial consideration in patients with unstable spine fractures and spinal cord injuries. The most recent and updated CHEST guidelines for VTE prophylaxis were published in 2016. All trauma patients with associated spinal injuries should have mechanical prophylaxis instituted as soon as possible with graduated compression stockings and/or sequential compression devices. Pharmacologic prophylaxis with unfractionated heparin or low-molecular-weight heparin (LMWH) should be initiated as soon as the acute risk for additional bleeding in the trauma patient is adequately controlled. LMWH appears to be more effective for the VTE prevention and associated with fewer bleeding complications than unfractionated heparin in patients with spine injuries. The duration of pharmacologic VTE prophylaxis is determined by the patient's mobility status and should be typically continued for two weeks in patients without neurological injuries, and for 6–12 weeks in presence of spinal cord injury. If patients are poor candidates or have a contraindication to pharmacological VTE prophylaxis due to increased risk of bleeding complications, then the early placement of a removable inferior vena cava (IVC) filter should be considered as an alternative option. Pharmacologic VTE prophylaxis is not indicated in low-risk situations, e.g., for ambulatory patients with isolated stable thoracolumbar compression fractures.

### 21.11.5 Timing of Tracheostomy

One of the unresolved challenges in the management of ventilator-dependent trauma patients with associated unstable spine fractures and spinal cord injuries consists in defining the ideal timing of conversion to a tracheostomy. The conundrum consists of coordinating the timing of early tracheostomy (the intent of which is to reduce the inherent risk of ventilator-associated pneumonia) and the timing of cervical spine fixation (if indicated for the management of unstable cervical injuries) [33]. Spine surgeons are generally worried that a preceding tracheostomy may increase the risk of a surgical site infection for a delayed anterior cervical spine fusion (ACDF). This concern appears unjustified based on the existing literature which demonstrates that ACDF surgery is safely performed in presence of a prior tracheostomy, without an increased risk of a postoperative infection. As the dual incisions are typically located several centimeters apart, the tracheostomy wound can be safely draped off during the preparation for the ACDF procedure and does not appear to pose a risk of cross-contamination. In fact, these two procedures can be safely performed during the same operating-room visit under the same anesthetic. At our own institution, the requirement for prolonged mechanical ventilation in patients is discussed as part of the overall surgical plan in the management of patients with spine fractures and spinal cord injuries. Our protocol attempts to coordinate the early timing of tracheostomy with the timing for the spinal fusion. This proactive approach, tailored at decreasing the risk of preventable pulmonary infections and adverse outcomes in a highly vulnerable patient population, requires

close cooperation between spine surgeons and the general surgery trauma team [34].

### 21.11.6 Gunshot Injuries

Gunshot injuries to the spine are typically managed conservatively, with very few selected indications for surgery [35]. The kinetics of civilian low-velocity gunshot wounds do not lead to unstable spine injuries, and surgical decompression is rarely indicated [36]. Spinal gunshot wounds with retained bullet or bony fragments within the spinal canal causing ongoing neurological compression may require surgical management. Shrapnel within the thecal sac can lead to persistent cerebrospinal fluid (CSF) leak or concern for lead poisoning. Figure 21.5 illustrates the intraoperative findings in a young patient who sustained a gunshot wound with a retained bullet in spinal canal at the level of L1. The pattern of injury was found to be unstable, as the pedicle and facet joints were severely disrupted, requiring posterior instrumentation. A large dural laceration was found at time of surgery which was repaired to prevent persistent CSF leak. When missiles traverse the abdomen preceding to the spine, a surgical debridement in conjunction with antibiotic prophylaxis may be indicated due to the risk of intestinal contamination.

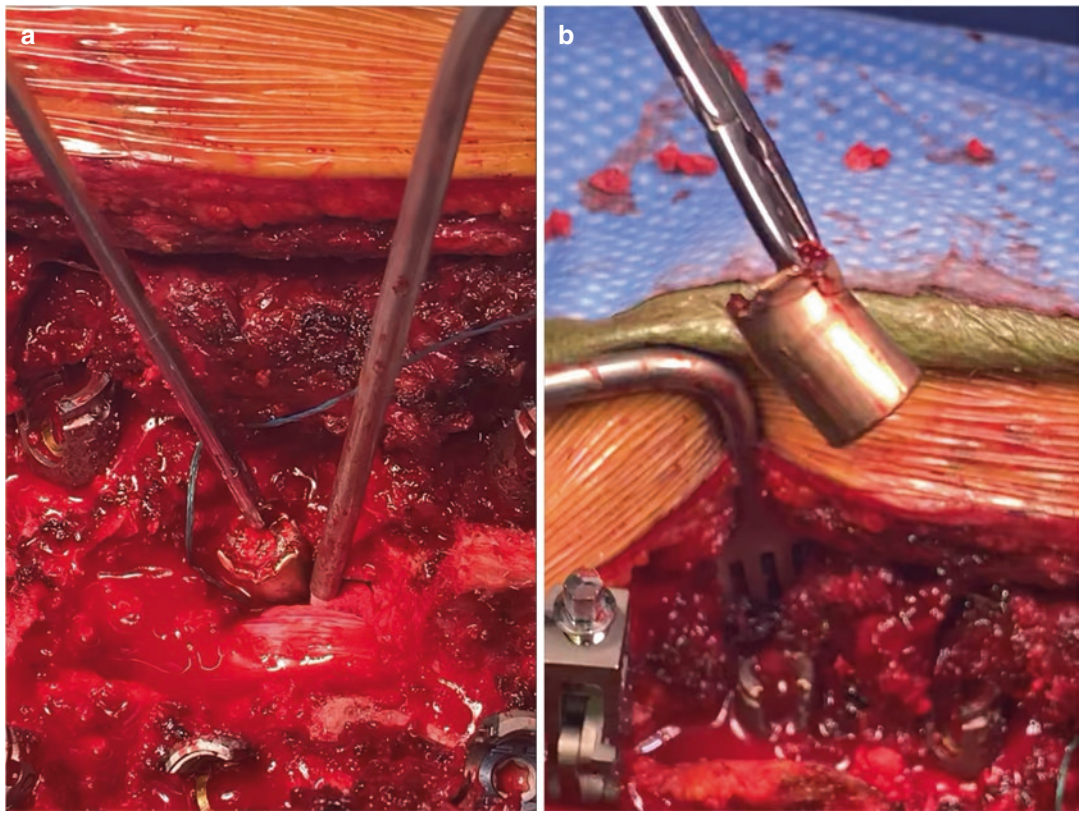



**Fig. 21.5** Case example of a T9–T10 "slice" fracture-dislocation with complete spinal cord transection

This 33-year-old patient sustained a low-velocity gunshot injury with a dural tear and cerebrospinal fluid leak at the L1 level. The bullet was retained next to the spinal cord, as demonstrated in **panel a**. The disruption of the posterior elements required pedicle screw instrumentation. **Panel b** demonstrates the intraoperative bullet removal

## 21.12 Conclusion

Surgical decision-making for polytrauma patients with spinal cord injuries is a challenging task, due to the heterogenic patient population and multiple confounding variables. After stabilizing vital functions from associated life-threatening injuries, a standardized protocol-driven approach to the assessment and management is imperative, as exemplified in the algorithm provided in Fig. 21.3. The goal of surgical treatment is to restore spinal alignment and stability, and to decompress the spinal cord, if indicated. Once the surgical goals are accomplished, patients with spinal cord injury require a standardized multidisciplinary approach with coordinated care to improve post-injury outcomes. Unfortunately, even with optimal timely care provided, these highly vulnerable patients often experience life-long functional impairment and post-injury sequelae.

**Take-Home Messages**

- The presence of an unstable spinal injury is presumed in all trauma patients until proven otherwise.
- The trauma team must ensure spinal immobilization during the initial assessment and during transport of patients with proven or suspected spinal injuries.
- A complete neurological evaluation is mandatory in all trauma patients and includes a physical examination and advanced imaging studies. Computed tomography is performed as part of the initial diagnostic trauma workup. Magnetic resonance imaging is indicated on a case-by-case basis after spine surgeon consultation.
- The adult central nervous system is inherently incapable of regeneration, and there are currently no pharmacological strategies available to heal the injured spinal cord.
- The routine use of corticosteroids has been abandoned as a "harmful "standard of care for patients with acute spinal cord injuries and should be reserved for selected specific injury patterns.
- The timing of tracheostomy in patients requiring prolonged mechanical ventilation should be considered early and coordinated with the timing of cervical spine fixation, if indicated.

**Key Concepts**

- The patient's history and initial physical examination must be documented early to establish a baseline for subsequent changes in the neurologic status.
- Spinal cold injury may be complete and incomplete, and should be classified according to the ASIA scale, including the exact spinal cord level.
- A multidisciplinary approach is required to ensure proper care of critically injured patients with associated spinal cord injuries.
- The early transfer to a designated facility capable of providing definitive care to patients with spinal cord injuries should be considered during the initial diagnostic workup.

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# 22 Urological Injuries in Polytraumatized Patients

Patricia John, David Pfister, and Axel Heidenreich

## 22.1 Introduction

In patients with multiple traumas, urological components are regularly involved approximately in 10% of the cases [1, 2]. Genitourinary injuries can result in significant morbidity and mortality [1–4]. In general, one has to distinguish between blunt and penetrating injuries to the urogenital organs necessitating an individualized therapeutic approach. According to the exposition of the different organs, the incidence lowers from cranial to caudal with the kidney being the most common injured organ with 1–5% of trauma cases. In most cases, ureteral injuries are iatrogenic, whereas about 18% result in blunt and 7% in penetrating trauma. In the following chapter, current classifications, symptoms, diagnostics, and treatment of urological injuries in polytrauma patients will be addressed in a cranial to caudal order of urogenital organs.

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## 22.2 Renal Trauma

Renal trauma occurs in about 1–5% of all traumas with blunt trauma accounting for the most common mechanisms of renal injury in about 90% of the cases [1–8]. While penetrating injuries are less frequent, they tend to be more severe. These result in a higher rate of nephrectomies and are associated with a higher rate of associated organ injuries [9]. Possible indicators for renal trauma are falls, blunt trauma to the flank region, or high speed motor-vehicle accidents [1, 2, 6, 7]. The Committee on the Organ Injury Scaling of the American Association for Surgery of Trauma (AAST) classified renal injuries as shown in Table 22.1 [10, 11].

### 22.2.1 Clinical Symptoms

Gross hematuria might be present but it does not correlate with the degree of injury since major injuries such as renal pedicle lacerations or disruption of the ureteropelvic junction may occur without hematuria [12]. Blood transfusion requirements are an indirect indication of the rate of blood loss.

### 22.2.2 Imaging Studies

Patients with blunt renal, microscopic hematuria, stable vital signs in the absence of deceleration


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**Table 22.1** Renal trauma classification by the American Association for the Surgery of Trauma (AAST)

| Grade[a] | Type of injury | Description of injury |
|---|---|---|
| I | Contusion | Microscopic or gross hematuria, urologic studies normal |
| | Hematoma | Subcapsular, nonexpanding without parenchymal laceration |
| II | Hematoma | Nonexpanding perirenal hematoma confirmed to renal retroperitoneum |
| | Laceration | <1.0 cm parenchymal depth of renal cortex without urinary extravagation |
| III | Laceration | >1.0 cm parenchymal depth of renal cortex without collecting system rupture or urinary extravagation |
| IV | Laceration | Parenchymal laceration extending through renal cortex, medulla, and collection system |
| | Vascular | Main renal artery or vein injury with contained hemorrhage |
| V | Laceration | Completely shattered kidney |
| | Vascular | Avulsion of renal hilum which devascularizes kidney |

[a]Advance one grade for bilateral injuries up to grade III

trauma usually do not have to undergo any specific imaging studies [1, 5, 12].

Indications for immediate renal CT imaging studies are instable vital signs, gross hematuria, non-visible hematuria and one episode of hypotension, penetrating injuries, a history of rapid deceleration trauma or clinical signs suggesting renal trauma like fractured rips or abdominal distension (Fig. 22.1) [1–3, 6]. CT imaging represents the gold standard for radiographic assessment in suspected renal injury because (1) it defines the location and the extent of injuries, (2) detects contusions and devitalized segments, (3) allows for visualizsation of the entire retroperitoneum, (4) allows for assessment of the renal pedicle, and (5) detects urinary extravasations, (6) quickly establishes the presence of the contralateral kidney, and (7) demonstrates concurrent injuries of other organs [1, 6, 12, 13]. Spiral CT scans are advantageous due to shorter scanning times, but do not allow the identification of injuries to the renal collecting system, thereby necessitating the use of delayed CT scans. Angiography is important only for superselective embolization in the management of persisting or delayed hemorrhage.

### 22.2.3 Treatment

In general, there are several guidelines addressing renal trauma. The management of renal trauma was described in detail by the European Association of Urology (EAU) (11). In most renal injuries, organ preservation can be obtained without the need of a surgical approach. The majority of AAST grade I-IV injuries are managed non-operatively [1, 2].

Persistent bleeding, injuries to the renal collecting system, the renal pelvis, or the ureter with urinary extravasation are relative indications for surgery [1]. Urinary extravasation may be treated by endoluminal stenting and/or placement of a percutaneous nephrostomy. However, surgical reconstruction is advised in the presence of devitalized fragments and associated enteric and pancreatic injuries [14]. Aggressive surgical management for renal lacerations is associated with a 23% morbidity rate, whereas initial nonoperative treatment resulted in a 85% morbidity rate.

Haemodynamically stable patients with AAST grade I and II injuries can be managed non-operatively with supportive care, bed-rest, hydration, and prophylactic antibiotics [5–7].

Stable patients with renal gunshot injuries or stab wounds must be explored if the renal hilum and the collecting system are involved or if persistent bleeding exists.

In patients with significant renal injuries, postoperative observation is extremely important because a variety of delayed complications may occur within the first 30 days of injury. This includes but is not limited to hemorrhage, urinary fistula, arteriovenous fistula, pseudoaneurysms [3, 15]. Patients must undergo imaging studies if they develop clinical symptoms such as fever, increasing flank pain, persistent bleeding, and arterial hypertension. Repeat imaging within two to four days after trauma is recommended in > grade III AAST trauma to minimize the risk of missed complications [1]. As for the primary

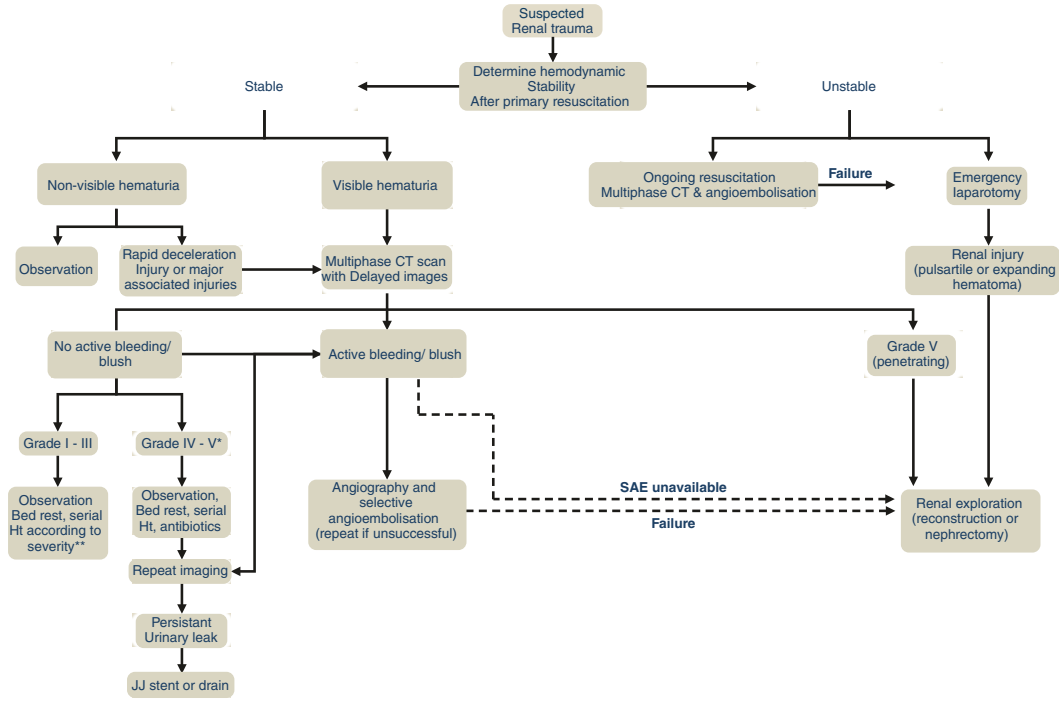


**Fig. 22.1** Algorithm renal trauma

diagnosis, CT scan of the abdomen is the preferred imaging modality.

A summary of the various therapeutic approaches is presented in Fig. 22.1. Life-threatening haemodynamic instability or an expanding or pulsatile retroperitoneal hematoma during explorative laparotomy usually represents AAST grade V injury and requires immediate surgery [1, 4]. A transperitoneal approach with early occlusion of the pedicle prior to opening of Gerota's fascia is strongly recommended. In patients with avulsion of the renal pedicle close to the aorta or the inferior vena cava, it might be necessary to clamp the major vessels just above and below the renal pedicle to control bleeding and to explore the retroperitoneum. In patients with significant injuries to the vascular pedicle, nephrectomy is the treatment of choice, unless the kidney can be preserved in cases of solitary organ or bilateral injuries. In patients with bleeding from the renal parenchyma due to penetrating injuries, embolization is advised [5, 7, 16, 17].

### 22.2.4 Selective Angioembolizsation

The use of selective angioembolizsation (AE) in renal trauma remains heterogenous. Indications for AE are active extravasation of contrast, pseudo-aneurysm, and arteriovenous fistula [1]. The best predictor of the need for AE is a combination of active extravasation of contrast and large hematoma [18]. AE is most beneficial in patients with > grade III AAST traumas [19]. Usually an open surgery approach mostly leading to nephrectomy is indicated after repeat failed embolization [20].

## 22.3 Ureteral Trauma

Trauma to the ureter is rare and it accounts for only about 1% of all genitourinary injuries. Most commonly, ureteral lesion results from iatrogenic injuries (approx. 80%), and only 18% and 7% result from blunt and penetrating trauma, respectively [1, 21].

**Table 22.2** Ureteral trauma classification by the American Association for the Surgery of Trauma (AAST)

| Grade | Description of injury |
|---|---|
| I | Hematoma |
| II | Laceration <50% of circumference |
| III | Laceration >50% of circumference |
| IV | Complete tear <2 cm of devascularization |
| V | Complete tear >2 cm of devascularization |

As with all other genitourinary organs, the AAST has classified ureteral injuries according to their severity as indicated in Table 22.2 [22].

### 22.3.1 Clinical Symptoms

There are no specific clinical symptoms; unspecific symptoms such as meteorism, abdominal distension, and flank pain caused by retroperitoneal urinoma can occur, while hematuria is an unreliable indicator of ureteral injury [21]. Ureteral injury should always be suspected in patients with penetrating abdominal or retroperitoneal injuries, and in patients with blunt deceleration traumas [1].

### 22.3.2 Imaging

The gold standard of diagnostic imaging for suspected ureteral trauma is a multi-phase CT scan [1]. Intravenous pyelography due to high false negative rates of up to 60% is no longer used to detect ureteral injuries [21]. In unclear cases, retrograde or antegrade urography can be performed to verify the location and the extent of the ureteral injury. In very rare cases, the suspicion of an ureteral injury is based on ultrasound findings of a retroperitoneal fluid collection (urinoma) or a hydronephrosis (Fig. 22.2).

### 22.3.3 Management

In patients with partial tears of the ureter or small ureteral lesions, the most common, simple and effective measure is placement of a ureteral stent and/or a percutaneous nephrostomy tube.

If iatrogenic ureteral injuries are detected intraoperatively, an endoluminal DJ stent should be placed with the ureteral laceration being closed by interrupted sutures with a monofil suture. Postoperatively, no drain or suction should be placed in order to prevent the development of an urinary fistula.

Reconstruction of grade III–V injuries depends on the anatomic localization of the injury. Usually, grade III and IV injuries can be treated by an end-to-end anastomosis. The anastomosis is reconstructed with absorbable sutures after placement of a ureteral catheter, which can stay in place for about 3–4 weeks. Other surgical options are listed in Table 22.3.

## 22.4 Bladder Trauma

Bladder injuries are one of the most frequent urological injuries in trauma patients. Among abdominal injuries requiring surgical repair, about 2% involve the bladder [1, 23, 24]. The categorization of bladder traumas can be devided into an aetiological classification or, in the light of the subsequent management, according to the localization of the trauma. Blunt traumas accounts for about 65–85% of bladder ruptures, whereas penetrating traumas accounts for only about 14–33% of all bladder injuries. Bladder ruptures are primarily classified as extra- or intraperitoneal triggering the choice between a conservative approach and a surgical correction. Most commonly, extraperitoneal bladder ruptures occur in up to 61% of the cases, followed by intraperitoneal bladder ruptures in about 40% of all cases. Combined injuries are rare (5–8% of cases). Motor- vehicle accidents contribute significantly to bladder rupture by blunt trauma. Seventy to ninety-seven percent of patients with bladder trauma have accompanied pelvic fractures, whereas only 5–30% of the pelvic fractures are associated with bladder injuries [13–29].

The Committee on the Organ Injury Scaling of the American Association for Surgery of Trauma (AAST) classified bladder injuries as shown in Table 22.4 [30].

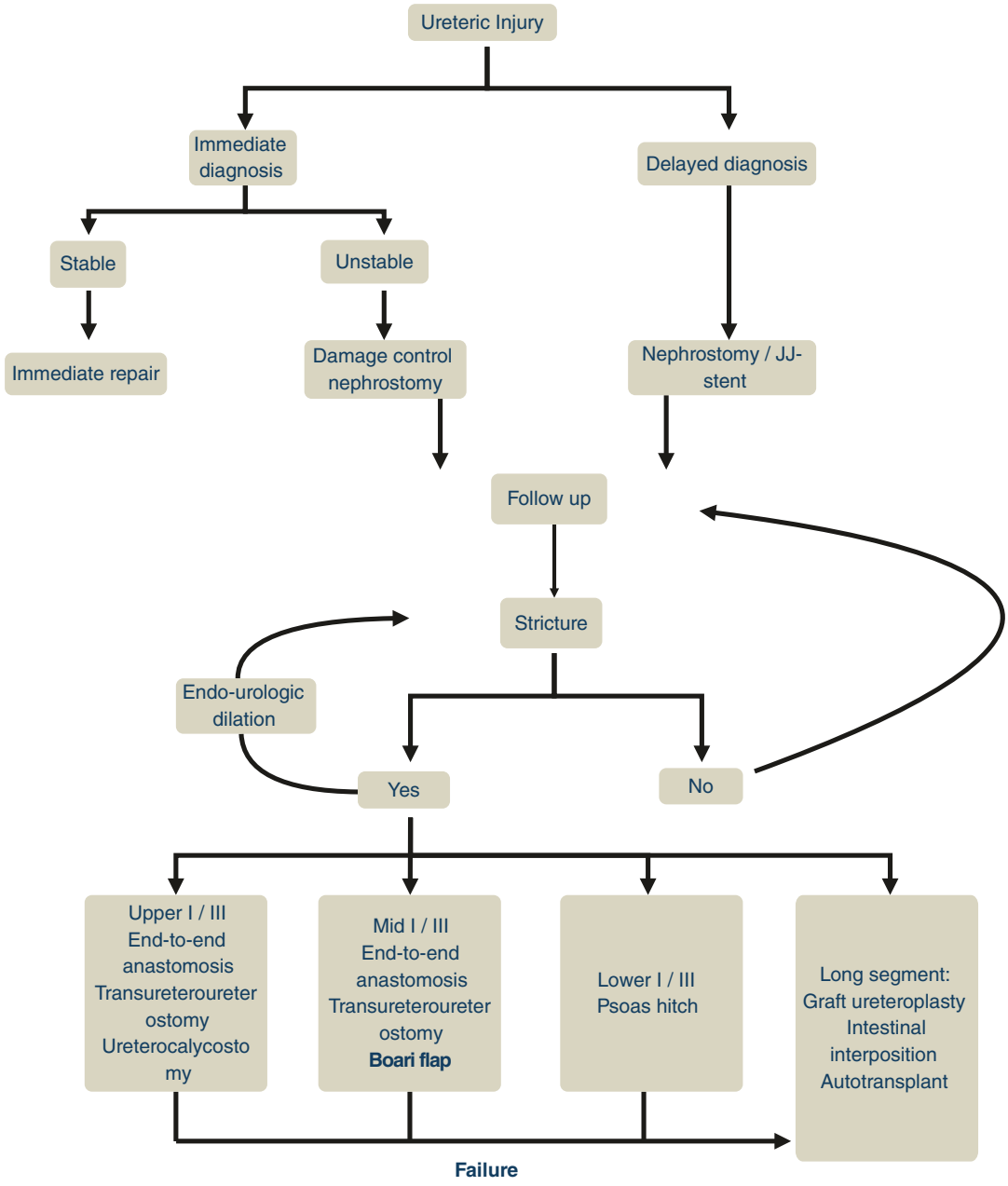


**Fig. 22.2** Algorithm ureteral trauma

### 22.4.1 Clinical Symptoms

The two most common signs and symptoms for bladder injuries are gross hematuria (80–100%) and abdominal tenderness (60–70%) [23]. Other findings may include the inability to void (rule out: intrapelvic urethral rupture!), bruises over the suprapubic region, and abdominal distension. Depending on the type and extent of associated injuries to the pelvic floor extravasation of urine may result in swelling of the perineum, scrotum, thighs, and the anterior abdominal wall.

**Table 22.3** Surgical management of ureteral trauma

| Type of injury | Management |
|---|---|
| Proximal and mid-ureteral injury | |
| – Shorter than 2–3 cm | Primary uretero-ureterostomy<br>Uretero-calycostomy |
| – Extensive ureteral loss | Transutero-ureterostomy |
| Distal ureteral injury | Uretero-neocystostomy<br>– Psoas hitch to bridge small gaps<br>– Boari flap to bridge large gaps |
| Long segment ureteral injury | Ileal interposition graft<br>Buccal mucosa ureteroplasty<br>Auto-transplantation |

**Table 22.4** Bladder injury classification by the American Association for the Surgery of Trauma (AAST)

| Grade | Injury | Description |
|---|---|---|
| I | Hematoma | Contusion, intramural hematoma |
| | Laceration | Partial thickness |
| II | Laceration | Extraperitoneal bladder wall laceration <2 cm |
| III | Laceration | Extraperitoneal ≥2 cm or intraperitoneal <2 cm bladder wall laceration |
| IV | Laceration | Intraperitoneal bladder wall laceration ≥2 cm |
| V | Laceration | Laceration extending into bladder neck or ureteral orifice (trigone) |

### 22.4.2 Imaging

The classic combination of pelvic fracture and gross hematuria requires immediate cystourethrography to rule out urethral and/or bladder ruptures [23, 25, 31, 32]. All patients with pelvic ring fractures and gross hematuria should undergo immediate cystography (Figs. 22.3, 22.4, and 22.5). Since microscopic hematuria is a relative indicator for significant injury, recommendations for the most appropriate imaging studies are sparse in the literature and in the existing guidelines. Imaging of the bladder may be reserved for those with anterior rami fractures (straddle fractures) or Malgaigne type severe ring disruption.

Retrograde cystography in the evaluation of bladder trauma represents the imaging procedure of choice [13, 25, 27–29, 31]. With an adequate filling and post-void images taken, cystography has great accuracy in the identification of bladder ruptures (90–95% sensitivity and 100% specificity). For the highest degree of diagnostic accuracy, the bladder should be filled with at least 350 cc. Bladder rupture may be identified only on the post-drainage film in only about 10% of patients. Thus, images must always have to include X-rays upon maximal distension and a completely emptied bladder (Fig. 22.6).

As CT scan is performed in most patients who present with multiple trauma, CT cystography is an excellent substitute for standard cystography. The bladder should be filled with at least 350 cc of dilute (2%) contrast dye [32].

Associated urethral lesions occur in 10–30% of the cases and can be detected by retrograde urography [1, 25].

Other imaging studies such as ultrasonography, intravenous pyelography, standard CT scans, or magnetic resonance imaging are inadequate for the evaluation of the bladder and the urethra after trauma [1, 23, 25].

### 22.4.3 Treatment

The therapeutic approach to treat any bladder rupture depends on the type of injury, the coexisting injuries, and the condition of the patient. (Fig. 22.3). Figure 22.7.

Most patients with extraperitoneal bladder ruptures may be treated nonoperatively by drainage even in the presence of large extravasations [1, 27–28, 33]. More than two-thirds of the ruptures resolve within 2 days and almost all within 3 weeks. From the day of catheterization until 3 days after removal of the catheter, antibiotic prophylaxis is recommended.

Despite the in the majority of cases successful conservative approach for extraperitoneal bladder ruptures, in a few cases there is a need for surgical management.

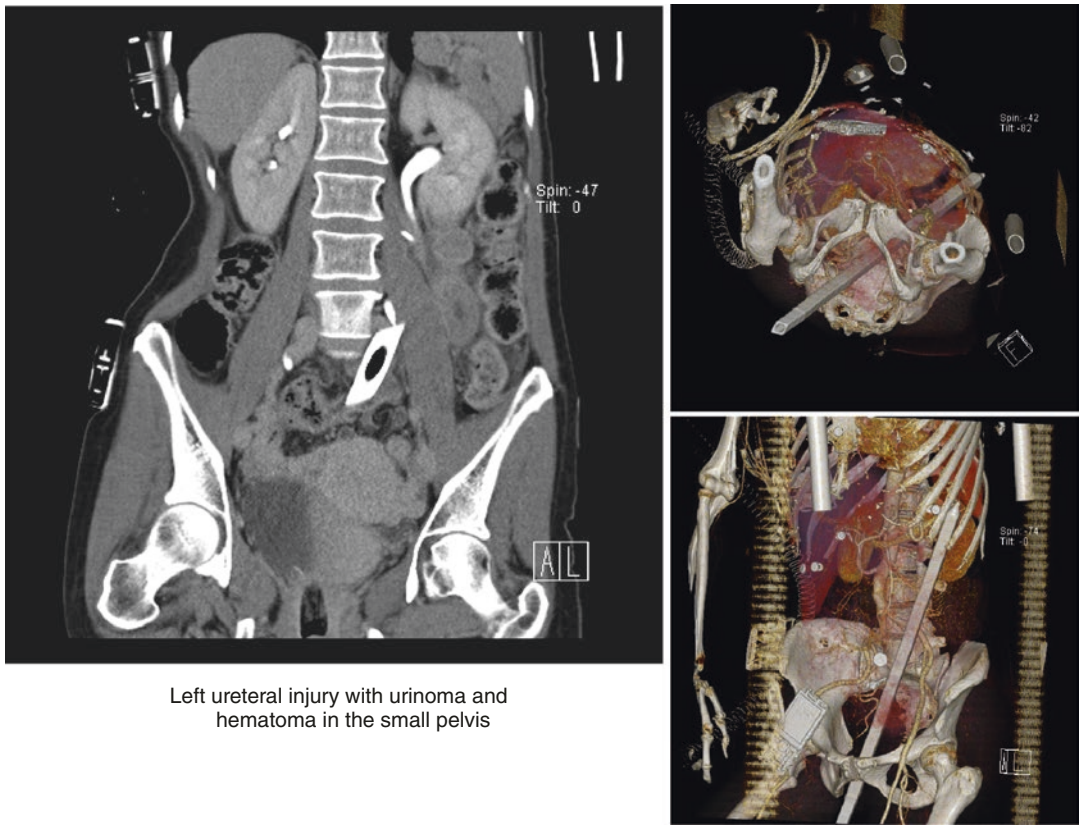


**Fig. 22.3** CT Ureteral trauma

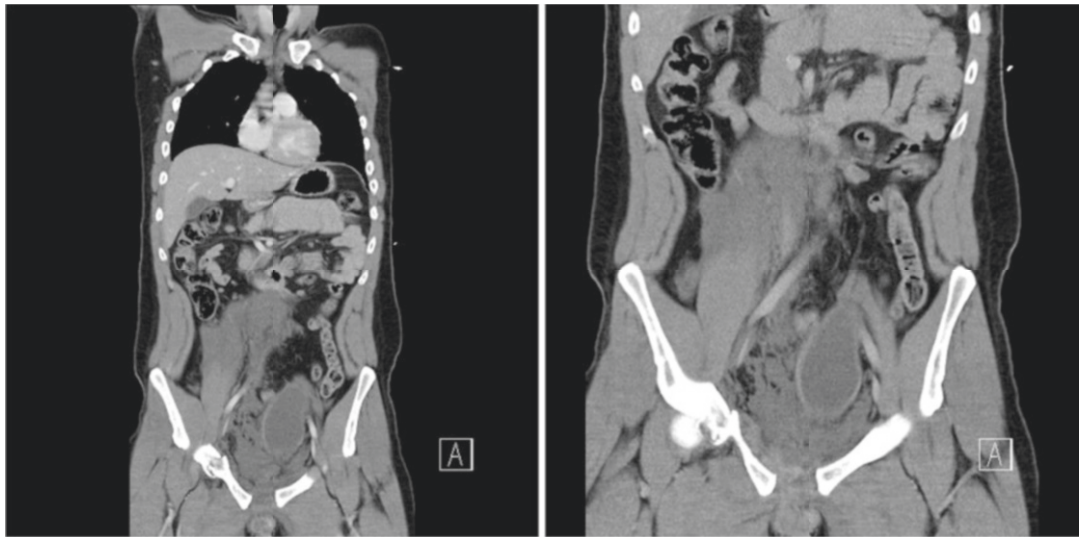


**Fig. 22.4** CT Pelvic fracture

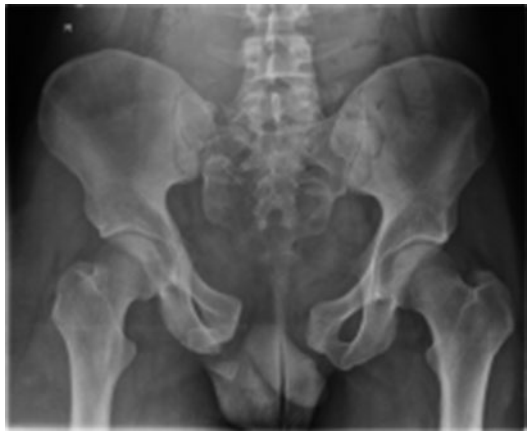

**Fig. 22.5** X Ray pelvic fracture

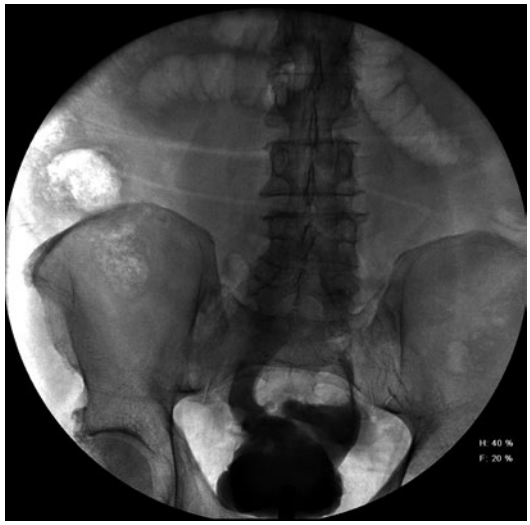

**Fig. 22.6** Cystography intraperitoneal bladder rupture

If a laparotomy is performed for any other reason, extraperitoneal bladder ruptures should be closed by a single layer running suture of 2-0 or 3-0; the bladder is usually drained by a 20F transurethral catheter before a cystography is performed postoperatively on day 5. Following internal fixation of the pelvic fracture, a direct repair of the extraperitoneal rupture is advised. Concomitant rectal and/or vaginal injuries, open pelvic fractures, the presence of bone fragments in the bladder wall, and entrapment of the bladder wall between bone fragments necessitate immediate surgical repair even in extraperitoneal bladder rupture [1, 23–24]. Involvement of the bladder neck or the ureteral orifices also requires immediate surgical repair. Bladder neck reconstruction, transurethral placement of an endoluminal catheter, or even ureteral reimplantation (Psoas-Hitch technique) may be required in cases of severe ureteral orifice damage.

In contrast to an extraperitoneal bladder ruptures, all penetrating and intraperitoneal injuries should undergo immediate surgical repair [1, 23–24]. In most cases, intraperitoneal bladder perforations are accompanied by other intra-abdominal injuries. Peritonitis might develop because of the urinary leackage. In this scenario, an overlooked bladder perforation may be mimicked by a significant rise in serum creatinine levels due to peritoneal reabsorbtion. Antibiotic prophylaxis is administered for 3 days. Standard cystography is feasible on postoperative day 7–10 [25]. A suprapubic catheter is superior to a transurethral catheter for urinary drainage. In case of concomitant rectal or vaginal injuries, the ruptured organs are closed separately in a two-layer technique and a peritoneal flap of a vascularized omentum flap is interposed between bladder, vagina, or rectum.

## 22.5 Urethral Trauma

Urethral injuries occur most commonly in association with pelvic fractures [1, 25, 34, 35]. Unstable diametric pelvic fractures and bilateral ischiopubic rami fractures carry the highest risk of injury to the posterior urethra. In particular, the combination of straddle injuries with diastasis of the sacroiliac joint poses a risk about seven times higher for urethral injuries. Due to differences in pelvic anatomy, pathophysiology and symptoms of urethral traumas differ in male and female patients.

In men, the bulbomembranous junction is more vulnerable, as the posterior urethra is fixed at the urogenital diaphragm as well as the puboprostatic ligaments. In male children, these are more frequently localized proximally and interfere with the bladder neck, as the prostate still is rudimentary [1].

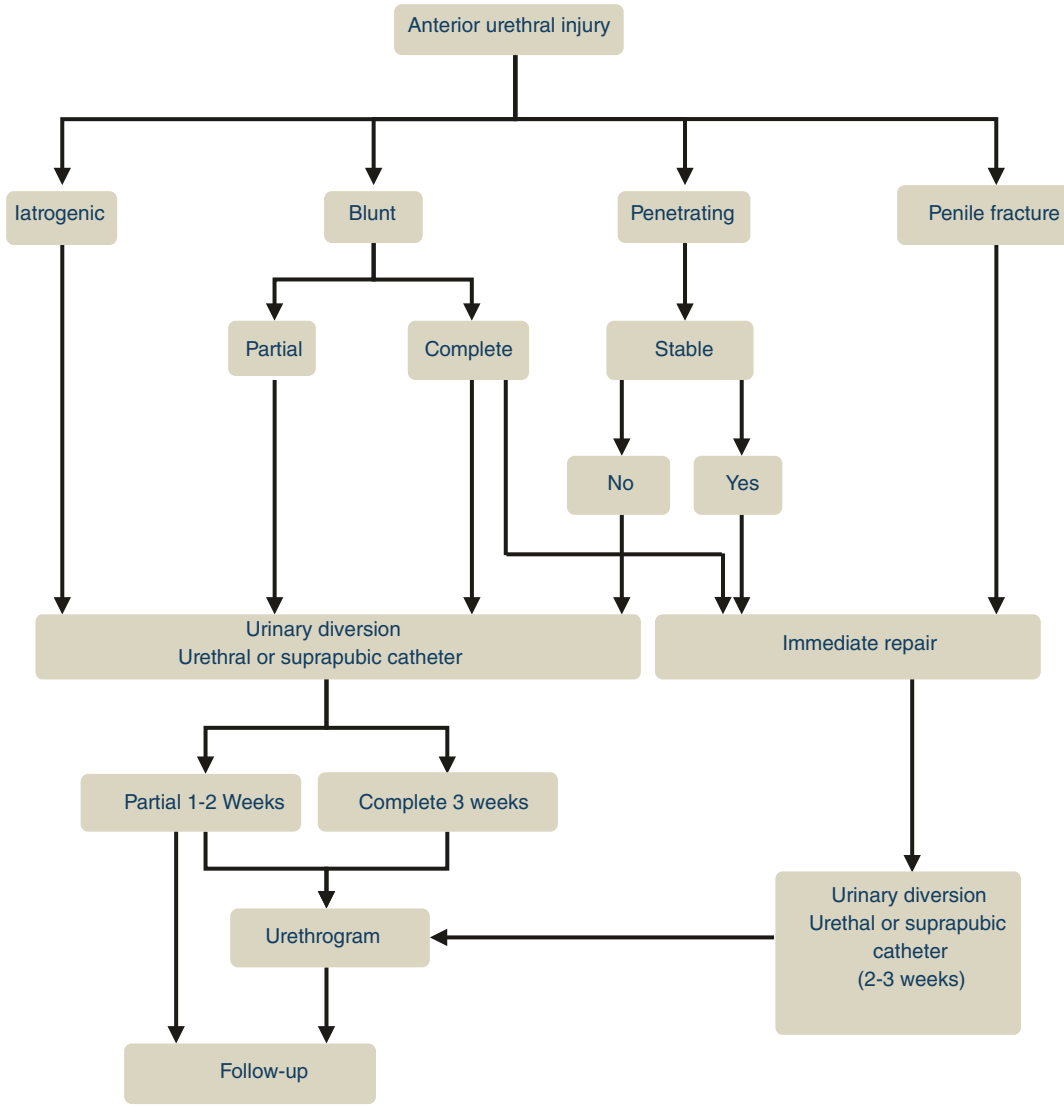


**Fig. 22.7** Algorihythm anterior urethral trauma

Additional symptoms may include perineal hematoma and inability to palpate the prostate. In cases of a large pelvic hematoma, the symptom of an impalpable prostate may be misdiagnosed, as the contour of the prostate is smudged.

In female patients with urethral injuries, vulvar edema and blood at the vaginal entrance are among the signs of urethral disorders.

In rare cases, a urethral disruption is diagnosed by the existence of the triad: of blood at the external urethral meatus, inability to void, and palpable full bladder. It is usually detected by false catheterization or by the inability to place a transurethral catheter in the emergency department.

Blood at the urethral meatus may be a sign for significant urethral injury. In these cases, retrograde urethrography should be performed prior to catheterization of the bladder to exclude urethral lesions.

The Committee on Organ Injury Scaling of the American Association for the Surgery of Trauma (AAST) has developed a reliable urethral- injury scaling system (Table 22.5) [36].

**Table 22.5** Urethral injury classification by the American Association for the Surgery of Trauma (AAST)

| Grade | Injury type | Appearance |
|---|---|---|
| I | Contusion | Blood at the urethral meatus, normal urethrogram |
| II | Stretch injury | Elongation of the urethra without extravasation on the urethrography |
| III | Partial disruption | Extravasation of contrast at injury site with contrast visualized in the bladder |
| IV | Complete disruption | Extravasation of contrast at injury site without vizualization in the bladder; <2 cm of urethral separation |
| V | Complete disruption | Complete transection with >2 cm urethral separation, or extension into the prostate or vagina |

No treatment is required for type I and II injuries [1, 34, 35, 37–42]. Usually, types II and III can be managed nonoperatively. A transurethral and a suprapubic catheter are placed. Types IV and V will require either endoscopic realignment or delayed urethroplasty.

Penetrating injuries to the anterior urethra most commonly derive from gunshots and involve the pendulous and bulbar urethral segments [1].

### 22.5.1 Clinical Symptoms

Blood at the meatus is present in about 40–95% of male patients with posterior urethral injuries and in about 75% of patients with anterior urethral trauma. Blood at the external urethral meatus is present in more than 80% of female patients with pelvic fractures and urethral injuries.

In men, presence of blood at the meatus Its presence should preclude any attempts of urethral manipulation until the entire urethra is adequately imaged. Partial urethral disruption can be very easily transformed into complete urethral disruption due to several attempts of forced transurethral catheterisation. In unstable patients one attempt of transurethral catheterization is justified; if there is any difficulty, a suprapubic tube should be inserted instead. If a urethral injury is suspected, a retrograde urethrogram should be performed.

Gross or microscopic hematuria is a nonspecific clinical sign and the amount of bleeding does not correlate with the extent of injury [1, 35]. Pain during urination or acute urinary retention suggests urethral intrapelvic disruption or temporary spasm of the internal bladder sphincter. Any of the above-mentioned symptoms necessitates immediate radiographic evaluation [42], precludes transurethral manipulation, and prompts placement of a suprapubic catheter for urinary drainage.

### 22.5.2 Radiographic Examination

When a urethral injury is suspected, immediate retrograde urethrography (RUG) should be performed/Fig.22.6 [1, 35, 42]. Any type of contrast extravasation proves urethral damage. In females, direct urethroscopy can be performed. Furthermore, flexible cysto-urethroscopy can deliver information on the extend of urethral damage (complete vs. partial rupture) [1]. In cases of subsequent urethral strictures a combined urethrography and cystography can be performed to delineate the pelvic anatomy. Also, magnetic resonance tomography or antegrade cystourethroscopy via the suprapubic tract can be performed to visualize the anatomy of the urethra.

### 22.5.3 Treatment

Treatment differs with regard to the involvement of the anterior vs. posterior urethra and differs between male and females.

#### 22.5.3.1 Treatment for Urethral Injuries in Males

Type I and II injuries of the anterior urethra can be easily managed by the placement of a transurethral catheter [1]. Type III injuries of the anterior urethra can be managed by the placement of a suprapubic catheter or a transurethral catheter with the advantage of the suprapubic

tube avoiding urethral manipulation and diverts urine from the place of injury [34, 35]. In more than 50% of the cases, spontaneous recanalization occurs; in all other cases, strictures can be managed by internal urethrotomy. Alternatively, delayed urethral reconstructive surgery may be performed with anastomotic urethroplasty in strictures <1 cm or buccal mucosa grafts in strictures longer than 1 cm.

Type IV injuries can be repaired by an end-to-end anastomosis, whereas type V injuries should be reconstructed by flap urethroplasty of by buccal mucosa grafts.

Proximal urethral injuries are best approached transvesically with an optimal view of the bladder neck, the ureteral orifices, and the proximal urethra.

A treatment algorithm for the management of anterior and posterior male urethral injuries is present in Figs. 22.7 and 22.8.

Partial tears or short disruptions of the posterior urethra can be managed in most cases with a

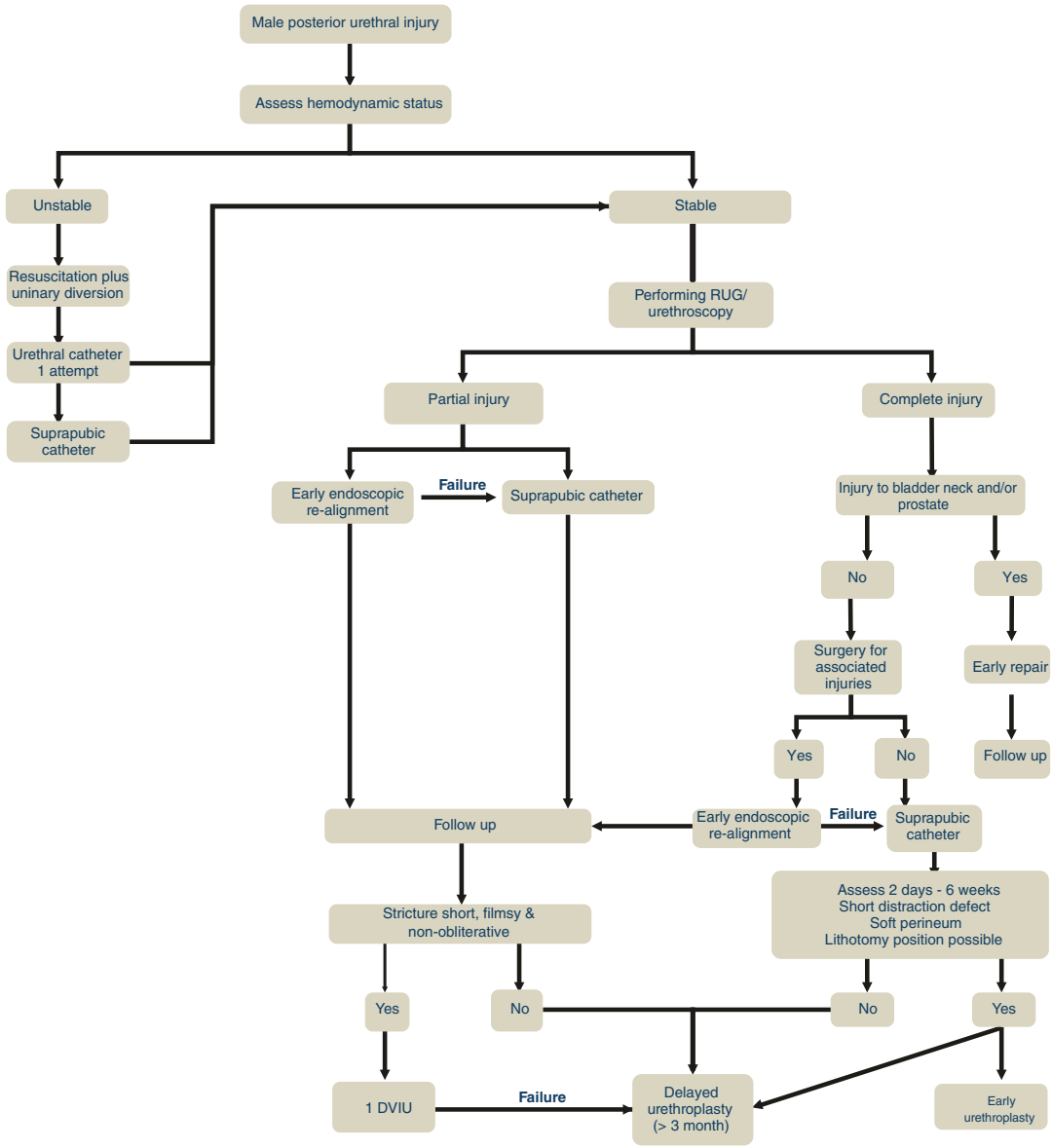


**Fig. 22.8** Algorithm posterior urethral trauma

suprapubic catheter or a transurethral catheter for about 2 weeks. The majority of injuries heal and the risk of urethral strictures is low [43].

The management for complete disruption of the posterior urethra is variable [37–44]:

- immediate open repair in case of any associated injury to the rectum double-layer closure of urethral and rectal lesion and interposition of a flap from the greater omentum,
- primary endoscopic realignment by antegrade (using the canal of the suprapubic catheter) or retrograde approach [43],
- primary open realignment with evacuation of the pelvic hematoma is not recommended; it is associated with frequent postoperative incontinence and impotence [45].

The most common result of posterior urethral disruption is the development of a short prostatobulbar urethral gap filled with dense fibrotic tissue. Delayed surgical repair of a posterior urethral disrupture remains the standard treatment and should be performed after 3 months. Surgery requires proper positioning of the patient in the lithotomy position [1]. Preoperatively, a retrograde urethrogram and a simultaneous cystogram should be performed to determine the length of the stricture or fibrotic discontinuation of the urethra. If involvement of the bladder neck is suspected, a flexible or rigid urethroscopy is helpful for examining anatomy. In patients who did not undergo primary realignment, the urethral dislocation as well as the length of the defect can be accurately described by MRI. In selected patients with short urethral strictures after realignment of the urethra an endoscopic strategy may follow. In case of complete urethral obstructions, some have favoured endoscopic interventions. However, there is a high risk of undermining the urethra and bladder neck and the restructure rate is 80%. Furthermore, the endoscopic procedure often requires several interventions and long-term repetitive dilatations with recurrent strictures and obliterations [45].

Usually, long posterior urethral strictures are best managed by an open surgical repair via a perineal approach. The urethra is accessed by a midline or lambda incision. The urethra is then mobilized starting from the beginning of the fibrotic defect to the mid-scrotum allowing a tension free anastomosis. The scar tissue as well as the fibrotic tissue of the proximal urethra must be excised completely to prevent restrictures. For long strictures, a flap urethroplasty of buccal mucosa grafts is used. Adjunctive manoeuvres are infrequently needed. In rare cases, pubectomy can be helpful for cases with extended fibrosis, failed former urethroplasty, or accompanied bladder neck involvement.

Erectile dysfunction is a complication of urethral distraction injuries described in 30–60% of the patients with pelvic fracture [44]. It is questionable as to whether posttraumatic erectile dysfunction is a result of the injury itself or because of the surgical management. The frequency of posttreatment erectile dysfunction remains the same independent of initial therapy (early realignment, open surgery, or no treatment) [46]. The overall rate of incontinence, anejaculation, and areflexic bladder is low (2–4%). Another problem is recurrent urethral strictures, which arise in 15–23% of patients. Minimally invasive treatment by endoscopic incision of the stricture is often sufficient.

#### 22.5.3.2 Treatment of Urethral Injuries in Females

Vaginal inspection should be performed in every single female patient to assess the extent and localization of the urethral injury and the presence, localization, and extent of potentially associated vaginal injuries. Vaginal injuries are further evaluated with an abdominal CT scan to screen for associated intrapelvic or intraabdominal injuries.

In complete urethral ruptures, immediate surgical repair is recommended to avoid urethrovaginal fistulas and complete urethral obliteration. In females, most anterior urethral injuries can be sutured primarily from a transvaginal approach [34, 35]. Early repair (<7d) of ruptures is preferred if the patient is hemodynamically stable to avoid complications like urinary incontinence, fistulas, and vaginal stenosis [47]. A complete obliteration with an embedded

urethra in scar tissue results in a significantly more complicated surgery with an increased frequency of severe complications. Injuries of the distal urethra can bee easily repaired via a transvaginal approach. Injuries of the proximal urethra or the bladder neck are best reconstructed via a retropubic approach. Only in unstable patients should a suprapubic catheter be used and delayed primary reconstruction is justified [34–35, 47].

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# Gyn. Injuries/Pregnant Patient in Polytrauma

# 23

Axel Gänsslen and Annelie Weinberg

## 23.1 The Pregnant Polytrauma Patient

Trauma in pregnancy for long time was a relatively uncommon problem but was complicated due to the alterations of the maternal anatomy and physiology as well as the presence of the fetus in the gravid uterus.

In contrast during the last decades, the numbers of trauma in pregnancy dramatically increased and trauma in pregnancy is now the leading course of non-obstetrical maternal death [1].

Between 4% and 8% of all pregnant women have an accident resulting in an injury [2–5] but only 0.3–0.4% require admission to hospital [6].

> Trauma is the leading non-obstetric cause of maternal mortality accounting for 46% of maternal deaths [1, 7].

This translates to approximately one million deaths per year worldwide. Pregnancy itself is not a risk factor for mortality following trauma, this has been shown to be a function of the severity of the injury [8, 9]. The risk of trauma to both the fetus and the mother increases as the pregnancy progresses with approximately 15% of injuries occurring in the first trimester and up to 55% in the third trimester. The pregnant patient seems to be more vulnerable to abdominal trauma and less prone to head or thoracic injury. It is not clear however whether the severity of the head injury is less or the potential for recovery greater [9]. The increase in the relative incidence of abdominal trauma with increasing gestation is most likely due to change in the shape of the patient as well as inappropriate positioning of seatbelts in motor vehicles. The leading cause for trauma are road traffic accidents, followed by falls [7]. Other important causes such as domestic violence should not be overlooked and some studies suggest this to be the leading cause for maternal mortality [10]. These injury patterns are described in reports from western countries.

The leading cause in fetal death are road traffic accidents predominantly due to maternal death and placental abruption. A combination of a non-viable pregnancy (less than 23 weeks of gestation) and an injury severity score of >8 has been associated with a fivefold increase of fetal mortality [11].

Several risk factors have been identified for the occurrence of injuries and trauma in the pregnant patient including young age, history of

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domestic violence, and drug abuse [12]. It is interesting that some racial risk factors have been identified in the occurrence of trauma in pregnancy in the USA. It has been shown that African-American and Hispanic pregnant women are at higher risk for trauma in pregnancy [13]. This is more likely to be a function of the patient's socio-economic status. As well as the high-energy injuries described above, pregnant women sustain low energy fractures associated with falls. Osteoporosis of pregnancy has been implicated in these injuries [14, 15].

The complication rate is reported to be significant. Ali et al. described an incidence of abruptio placentae in 40–60%, compared with 1–5% in the general population [16]. In a multiple regression analysis an increased incidence of complications was observed [17]. Prospectively, abruptio placentae represented the most common complication [18].

## 23.2 Anatomic and Physiologic Changes During Pregnancy

The most obvious and dramatic change during pregnancy is the enlargement of the uterus brought about by the growth of the fetus. The uterus becomes an intra-abdominal organ at approximately 12 weeks of gestation. At 20 weeks the vertex of the uterus can be palpated at the level of the umbilicus, and by the 36th week the uterus reaches the costal margin. In the last few weeks of pregnancy, fundal height decreases as the fetal head engages into the pelvis in preparation for the birth.

The changes of relevant organ function is well described in the literature [19, 20].

The changes of the cardiovascular system are numerous and begin from the eighth week of gestation. Progesterone induces relaxation of the smooth-muscle in walls of the peripheral vasculature. There is a gradual decline in blood pressure from week 10 reaching its lowest point by week 28 of gestation. In the third trimester the blood pressure gradually returns to pre-pregnancy levels. The heart rate also shows an increase by 10–15 beats per minute driving an increase in the cardiac output of 30–50%. This gradually returns to normal over the first two postpartum weeks. There is a 50% increase in the blood volume which is mostly due to an expansion of the plasma volume with only 30% increase in the volume of red cells. This brings about a dilutional anemia referred to as physiological anemia of pregnancy. The hypervolemic and hyperdynamic circulation allows the mother to tolerate blood loss of 500–1000 mL with little change in blood pressure and pulse rate. This however is achieved to the detriment of the fetus following trauma. Vasoconstriction of uterine and splanchnic blood vessels and diversion of circulatory volume masks maternal blood loss although signs of fetal distress will be apparent prior to the mother showing the expected signs of shock [21].

Hemorrhagic shock due to maternal blood loss becomes later relevant due to physiological hypervolemia during pregnancy with detrimental effect for the fetus (Table 23.1).

Almost all of the coagulation factors increase in pregnancy. This along with the expansion of blood volume and cardiac output are important adaptations for the expected blood loss at the time of delivery [12]. This hypercoagulable state predisposes the mother to thromboembolic disease.

The respiratory system also undergoes some changes. There is engorgement of the respiratory mucosa that leads to difficulties in intubation and mucosal bleeding [22, 23]. This may result in severe airway compromise. There are also adaptations related to the increased metabolic demands. The presence of the fetus necessitates an increase in oxygen consumption of 15–20%. Progesterone stimulates the respiratory center leading to hyperventilation which brings about a compensated respiratory alkalosis with a concomitant drop in the $PCO_2$. There is a 4 cm elevation of the diaphragm with a 2 cm increase in the thoracic anteroposterior diameter. This results in a 20–25%

**Table 23.1** Adaptive physiological changes during pregnancy, influencing ATLS B (breathing and ventilation) and C (circulation and coagulation) concepts

| Relevant physiological changes during pregnancy | | | |
|---|---|---|---|
| ATLS | Parameter | Change | Implication |
| B | Gastrointestinal mobility | Decreased | Increased aspiration risk |
| B | Functional lung residual volume | Decreased | Hypoxia from atelectasis |
| B | Minute ventilation | Increased | Respiratory alkalosis |
| C | Maternal blood volume | Increased | Delayed clinical response to hemorrhage |
| C | Heart rate | Increased | Advanced clinical response to hemorrhage |
| C | MEAN arterial blood pressure | Decreased | Advanced clinical response to hemorrhage |
| C | Cardiac output | Increased | Increased metabolic demands |
| C | Uterus size | Enlarged | Hypotension in supine position—caval compression |
| Coag | Factors I, II, V, VII–X, XII | Increased | Hypercoagulable state—delayed signs of TIC |
| Coag | Fibrinogen | Increased | Hypercoagulable state—delayed signs of TIC |

*Coag* coagulation, *TIC* trauma induced coagulopathy

decrease in the functional residual capacity [24]. The pregnant patient is therefore much less tolerant to hypoxia and the associated acidosis. Fetal oxygenation remains constant of maternal $PaO_2$ kept above 60 mmHg as below this level there is a profound drop in fetal oxygenation [12].

> Respiratory changes include up to 40% increase of the tidal volume and minute ventilation, a 15–20% decrease of the expiratory reserve volume, a 20–25% decrease of the functional residual capacity, and a 15–20% increase of oxygen consumption at rest [12, 24].

Progesterone reduces gastrointestinal motility and the gravid uterus displaces the stomach cephalad. This results in the incompetence of the gastroesophageal pinchcock mechanism placing the pregnant patient at greater risk of regurgitation and aspiration [25]. Therefore, all pregnant patients should be assumed to have a full stomach and the threshold for insertion of a gastric tube lowered.

In the genitourinary system there is gradual ascent of the uterus from the pelvis where it is well protected into the abdomen from the 12th week of gestation. Once the uterus becomes intra-abdominal it is at greater risk of injury from blunt and penetrating trauma. The bladder is displaced anteriorly and superiorly. The renal pelves and ureters become dilated due to the compressive effect of the uterus as well as the effect of circulating progesterone. The increased cardiac output and blood volume increases renal perfusion by up to 60% with a concomitant increase in the glomerular filtration rate. This leads to a significant reduction in the serum urea and creatinine levels [24].

A summary of clinically relevant changes during pregnancy while treating polytraumatized patients is presented in Table 23.1 adapted from [12, 24, 26].

Anatomical changes during pregnancy should be borne in mind when interpreting initial radiological assessment of the patient.

The elevation of the diaphragm by approximately 4 cm and its widening by 2 cm during late pregnancy should be appreciated on the chest radiograph. This may mimic a widening of the mediastinum and an enlarged heart.

Increased levels of circulating progesterone lead to the softening of the sacroiliac ligaments, hence widening of the joint space. The symphysis pubis may also be widened by 4–8 mm [27].

## 23.3 The Right Patient to the Right Hospital

According to guideline recommendations, in suspected pregnant trauma, alle women should be transported to a maternity facility, especially

when injuries are neither life- nor limb-threatening and the fetus is viable (≥23 weeks), and to the emergency room when the fetus is under 23 weeks' gestational age or considered to be non-viable [28]. In patients with significant hemodynamic instability, transport to a Level 1 trauma unit or emergency room is advocated, regardless of gestational age [28].

## 23.4 General Assessment of the Injured Pregnant Patient

The initial assessment and management of the injured pregnant patient follow well established routines of the Advanced Trauma Life Support [19].

### 23.4.1 Primary Survey

Optimal resuscitation of the mother is the best treatment of the fetus [19, 29].

The safe and judicious assessment of the pregnant patient should be a multidisciplinary exercise with the early involvement of an obstetrician, neonatologist, radiologist, and trauma surgeon [12, 24, 27, 30, 31].

The Canadian Board of the Society of Obstetricians and Gynecologists recommends, that in cases of major trauma, the assessment, stabilization, and care of the pregnant women are the first priority [28].

Availability of an obstetrical surgeon is recommended for detailed fetal analysis with fetal heart rate auscultation and extended fetal monitoring in viable fetuses (≥ 23 weeks) or signs of uterine contractions, placental abruption, or traumatic uterine rupture, as soon as feasible [28]. Vaginal bleeding should be evaluated by speculum or digital vaginal examination after ultrasound-based exclusion of a placenta previa [28].

Pregnant trauma patients can be divided into four groups [27]:

- women, who are not aware that they are pregnant; therefore all female trauma patients of reproductive age should have a pregnancy test performed [19, 32]; identification of these patients is especially important because routine radiographic studies, performed in the trauma assessment, have the greatest teratogenic potential in early pregnancy although this consideration should not interfere with life-saving investigations or interventions for the patient.
- injured women of less than 26 weeks of gestation: in these patients, resuscitation is aimed primarily at the mother since the fetus is not yet independently viable.
- the most challenging group consists of women with pregnancies >26 weeks gestation: at this stage there are two patients to consider during the assessment and resuscitation.

After 20 weeks of gestation nursing the pregnant patient supine may induce supine hypotension syndrome as the gravid uterus compresses the cava vein reducing the venous return and embarrassing maternal cardiac output by up to 30%. This can be alleviated by either displacing the uterus to the left side or, if possible to nursing, the patient tilted left side down by 15°. Due to reduction in the mother's respiratory reserve supplemental oxygen should be provided.

Loss of up to 2000 mL of blood is well tolerated, but this is at the expense of uterine blood supply. The use of vasopressors further compromises uterine blood flow and their use should be avoided unless it is a life-saving intervention.

Monitoring of uterine activity and the assessment of the fetus are imperative and should continue for 2–6 h after an injury even with relatively minor trauma [33, 34]. Signs of fetal distress may be the first signs of maternal hypovolemia and hemodynamic compromise. The use of vasopressors should be avoided as they further embarrass uteroplacental perfusion. It is preferable to manage cardiac output and blood pressure by replacing volume.

Whenever possible, the use of vasopressors should be avoided.

An urgent obstetrical ultrasound scan should be undertaken when the gestational age is undetermined and need for delivery is anticipated [28].

In case of a positive Kleihauer–Betke test, indicating fetal blood in the maternal circulation, the rhesus-negative patients should receive anti-D antibody to prevent isoimmunization [19, 28].

Anti-D immunoglobulin should be given to all rhesus D-negative pregnant trauma patients [28].

In patients "in extremis" (the dying patient), especially in the third trimester, early perimortem cesarean section should be considered, as this may facilitate maternal resuscitation and preserve the life of the fetus [35, 36].

It should start not later than 4 min (when possible) following maternal cardiac arrest [28].

The physiological changes during each trimester of pregnancy result in changes of hemodynamic and laboratory values, which have to be addressed during initial evaluation of pregnant women (Table 23.2).

### 23.4.2 Guideline Recommendation During Primary Survey [28]

1. Every female of reproductive age with significant injuries should be considered pregnant until proven otherwise by a definitive pregnancy test or ultrasound scan.
2. A nasogastric tube should be inserted in a semiconscious or unconscious injured pregnant woman to prevent aspiration of acidic gastric content.
3. Oxygen supplementation should be given to maintain maternal oxygen saturation > 95% to ensure adequate fetal oxygenation.
4. If a thoracostomy tube is needed, it should be inserted in an injured pregnant woman 1 or 2 intercostal spaces higher than usual.
5. Two large bore (14 to 16 gauge) intravenous lines should be placed in a seriously injured pregnant woman.
6. Vasopressors in pregnant women should be used only for intractable hypotension that is unresponsive to fluid resuscitation.
7. After mid-pregnancy, the gravid uterus should be moved off the inferior vena cava to increase venous return and cardiac output in the acutely injured pregnant woman. This may be achieved by manual displacement of the uterus or left lateral tilt. Care should be taken to secure the spinal cord when using left lateral tilt.
8. To avoid rhesus D (Rh) alloimmunization in Rh-negative mothers, O-negative blood should be transfused when needed until cross-matched blood becomes available.

Fetal assessment should include electronic fetal monitoring for at least 4 h [28].

### 23.4.3 Secondary Survey

As part of the secondary survey, a complete medical and obstetric history should be obtained, particularly details relating to pre-existing hypertension, eclampsia, and diabetes.

**Table 23.2** Physiological changes during pregnancy (adapted and modified from [37])

| Parameter | Pre-pregnancy | 1st Trimester | 2nd Trimester | 3rd Trimester |
|---|---|---|---|---|
| Heart rate (/min) | Normal | On-going increase, but <90 mmHg | | |
| Systolic BP (mmHg) | Undulating change between 112–125 mmHg | | | |
| CVP (mmHg) | Continuous decrease | | | |
| Cardiac output (L/min) | Normal: approx. 4.5 l/min | | Increase to 6 L/min | |

*BP* blood pressure, *CVP* central venous pressure

Information about the mechanism of injury, use of drugs and alcohol should be sought. Otherwise all limbs and body system should be examined in the usual manner [19]. Radiological examination of all suspected fracture should be carried out with the involvement of a radiologist as a close check needs to be kept on the cumulative dose of radiation received by the patient [26, 31, 38–40].

An early vaginal examination must be conducted. Ideally this should be performed with an obstetrician in attendance to assess cervical effacement and dilation, fetal position, and the presence of amniotic fluid or blood. In the presence of vaginal bleeding it is prudent to rule out a placenta previa prior to the formal examination of the cervix [39]. The bleeding may be due to placental abruption, labor or placenta previa. Other more traumatic causes such as uterine rupture and an open pelvic fracture must also be considered.

The Canadian Board of the Society of Obstetricians and Gynecologists recommends that pregnant trauma patients (≥23 weeks) with adverse factors including uterine tenderness, significant abdominal pain, vaginal bleeding, sustained contractions (>1/10 min), rupture of the membranes, atypical or abnormal fetal heart rate pattern, high risk mechanism of injury, or serum fibrinogen <200 mg/dL should be admitted for observation for at least 24 h [28].

A focus assessment sonographic trauma (FAST) scan is important to assess presence of intra-abdominal hemorrhage [41]. An ultrasound examination of the fetus and placenta can be performed after the FAST scan or incorporated as part of the trauma scan. If a chest tube thoracostomy is needed, it has to be placed one or two intercostal spaces higher than usual to avoid diaphragmatic injury.

Tetanus prophylaxis is not contraindicated and should be administered according to standard protocols [19].

## 23.5 Radiological Assessment

Trauma in pregnancy represents a special situation as two patients are involved—the mother and the child. Radiographic and CT examinations of the pregnant patient irradiate the unborn and can cause severe harm. Intrauterine development consists of three phases and radiation sensitivity is related to gestational age.

As a general guideline the "ALARA Principle" should be mentioned here—meaning, that radiation should be used "as low as reasonably achievable" [42].

**Basics of Radiation Protection**

The following types of radiation have to be differentiated: α, β, γ, and x-rays. For medical imaging only γ-radiation (Nuclear Medicine) and x-rays are used.

Important Units for radiation benchmarking:

- ion dose: measures radiation by the amount of the induced ionization—the SI unit is R.
- absorbed dose: defines the absorbed dose per kg mass, the SI unit is Gray (Gy) = 1 J/kg.
- dose output: is dose/time, Gy/s represents the SI unit.
- due to the inherent different properties of α-, β-, γ-, and x-rays they are converted into units that are representative of their varying biologic activity; this is achieved by multiplying the absorbed dose by a dimensionless radiation weighting factor (WR, prior Q—relative biological effectiveness); the result is the dose equivalent, which is measured in Sievert (Sv):
  Sievert (Sv) = Gy * WR—the corresponding values can be found in Table 23.3.
  organ dose: represents the absorbed dose output of an organ, tissue, or body part, which is multiplied by the radiation weighting factor—SI unit is again Sv.
  effective dose equivalent: consider the different radiation sensitivity for various

human tissues by the so-called tissue/organ weighting factor (WT—Table 23.4); the effective dose equivalent is calculated by first multiplying the organ dose with the tissue/organ weighting factor, followed by adding all individual doses.

- natural background radiation: the source of natural background radiation falls into two broad categories—natural (from ground and space) and artificial (medicine, radioactive fallout, nuclear waste, consumer products, etc.); the cumulative dose is approximately 4 mSv; it is interesting to note that medical diagnostic imaging and nuclear medicine are responsible for about 79% of manmade radiation [43]; typical radiation doses for medical imaging are shown in Table 23.5.
- deterministic vs stochastic radiation effects:
  in deterministic effects, there is a classical dose–effect relationship such as the LD50/30 (the dose of whole body irradiation where 50% of subjects die within 30 days) [55] of ~4.0Sv, or after a 3.0Sv there are severe skin burns, after 3.0–4.0 Sv cataracts occur—just to name some examples.

  stochastic effects are those that occur in a random manner, including cancer and genetic defects. These events cannot be related to a single dose but the cumulative effect of multiple exposures may result in damage and for this reason the concept of the excess lifetime risk was introduced. The risk is higher for younger people, which can be partly explained by the higher sensitivity of dividing cells to radiation. The "International Commission on Radiation Protection (ICRP)" suggest an excess rate of 5% per Sv for lower doses and 10% for higher ones.
- an excess lifetime risk factor of 10% means after exposing 10,000 individuals to 10 mSv dose of radiation, there will be about 10 additional deaths due to leukemia or cancer, but it is important to note that even without this radiation there would be 2500 cancer related deaths [44].

**Table 23.3** Weighting Factor by radiation type [45]

| Radiation type | | Radiation weighting factor |
|---|---|---|
| Photons | | 1 |
| Electrons, Muons | | 1 |
| Neutrons | <10 KeV | 5 |
| | 10–100 KeV | 10 |
| | >100 KeV–2 MeV | 20 |
| | >2–20 MeV | 10 |
| | >20 MeV | 5 |
| Protons (Energy >2 MeV) | | 5 |
| α-Radiation | | 20 |

### 23.5.1 Radiation Effects During Intrauterine LIFE

The following facts are based on the report of "German Society for Medical Physics" and the "German X-Ray Society" [47]. A summary of all effects is presented in Table 23.6.

The period of intrauterine life can be divided into three phases, where exposure to radiation has characteristic effects (Tables 23.7 and 23.8):

- the pre-implantation phase (until 10 days post-conception): high doses (>100 mSv)

**Table 23.4** Tissue/organ weighting factor due to consideration of the different sensitivity of tissues/organs to radiation [46]

| Tissue/organ | Weighting factor $W_t$ | Tissue/organ | Weighting factor $W_t$ |
|---|---|---|---|
| Gonads | 0.20 | Chest | 0.05 |
| Red bone marrow | 0.12 | Liver | 0.05 |
| Colon | 0.12 | Esophagus | 0.05 |
| Lung | 0.12 | Thyroid | 0.05 |
| Stomach | 0.12 | Skin | 0.01 |
| Urinary bladder | 0.05 | Bone surface | 0.01 |

**Table 23.5** Typical effective doses in potential trauma imaging (modified according to [44])

| Examination | Typical effective dose (mSv) | Number of chest X-rays leading to the comparable exposure |
|---|---|---|
| Chest (p.a.) | 0.02 | 1.0 |
| Extremities/joints | 0.01 | 0.5 |
| Skull | 0.07 | 3.5 |
| Pelvis | 0.70 | 35.0 |
| Head CT | 2.30 | 115.0 |
| Chest CT | 8.00 | 400.0 |
| trunk CT | 10.00 | 500.0 |

**Table 23.6** Effects of irradiation during intrauterine life [43]

| Effect | Gestational age | Lower threshold | Risk coefficient |
|---|---|---|---|
| Death during pre-implantation phase | 0–10 days | 100 mSv | 0.1%/mSv* |
| Malformation | 10 d–8 weeks | 100 mSv | 0.05%/mSv* |
| Severe mental retardation | 8–15 weeks<br>16–25 weeks | 300 mSv<br>300 mSv | 0.04%/mSv*<br>0.01%/mSv* |
| IQ-reduction | 8–15 weeks<br>16–25 weeks | | 0.03 IQ/mSv<br>0.01 IQ/mSv |
| Cancer/leukemia | | | 0.006%/mSv |
| Genetic defects | | | 0.0003%/mSv male<br>0.0001%/mSv female |

**Table 23.7** Estimated doses to the fetus during typical conventional trauma imaging (modified and adapted from [48])

| Examination | Typical fetal dose (mGy) |
|---|---|
| Extremities | 0.001 |
| Chest (PA, lat) | 2 |
| 21-cm patient thickness | 1 |
| 33-cm patient thickness | 3 |
| Lumbar spine (AP, lat) | 1 |

*AP* antero-posterior projection, *lat* lateral projection, *PA* posteroanterior projection

**Table 23.8** Estimated doses to the fetus during typical conventional CT trauma imaging (modified and adapted from [53])

| Examination | Estimated fetal dose (mGy) |
|---|---|
| CT head and neck | 0.001–0.01 |
| Chest CT | 0.01 |
| Abdominal CT | 1.3–35 |
| Pelvic CT | 10–50 |

result in spontaneous abortion which is often clinically silent, since pregnancy is often not known; birth defects are possible with a risk coefficient of 0.1% per mSv.

- phase of organogenesis (10 d–8 weeks gestation): high doses (>100 mSv) cause organ malformations as well as growth retardation and functional disorders; the risk coefficient for organ malformations is 0.05% per mSv which doubles at 200 mSv,
- fetal period (from the 3 months gestation to term): the central nervous system is the most susceptible organ during this phase and radiation exposure has been linked to severe neuromotor development disorders with risk coefficient of 0.04% per mSv from the eighth to the 15th week of gestation and 0.01% per mSv from 16th to the 25th week of gestation; reduction in the "Intelligent Quotient" (IQ) represents another known radiation effect, being more severe during early pregnancy: 30 IQ points for the eighth to the 15th week of gestation and 10 IQ points for the 16th to the 25th week.

The recent recommendations comparing normal x-rays or CT were analyzed by Raptis et al. [49].

The 2008 American College of Radiology practice guidelines for imaging pregnant or potentially pregnant patients, which are supported by the American College of Obstetricians and Gynecologists and the National Council on

Radiation Protection and Measurements stated, that a fetal radiation dose of <50 mGy is not associated with increased fetal anomalies or fetal loss throughout pregnancy [50–52].

### 23.5.2 Cancer Risk After Intrauterine Irradiation

A linear dose–effect relationship is presumed, however there is no known threshold. It is assumed that doses of less than 100 mSv may pose a significant risk for the development of leukemia and cancer. The risk coefficient is about 0.006% per mSv.

### 23.5.3 Genetic Effects After Irradiation

A linear dose–effect relationship is also assumed. There are no data available from human studies, we have however extrapolated from some animal studies in Table 23.5.

### 23.5.4 Imaging of the Pregnant Patient

Radiographs of the extremities can be safely performed during all stages of pregnancy, but adequate shielding is a MUST and can reduce the radiation dose to the unborn by up to 30%.

The generator settings should be on the lowest possible values where diagnostic information can still be gleaned. This necessitates discussion and close collaboration with both radiologists and radiographers.

Radiographic studies indicated for maternal evaluation including abdominal computed tomography should not be deferred or delayed due to concerns regarding fetal exposure to radiation [28].

In stable patients with suspected ligamentous injuries (e.g., ankle) MRI is preferable over repeated stress radiographs.

In abdominal trauma or polytrauma patients, ultrasound is the preferred first line imaging modality—e.g., "focus assessment sonographic trauma scan" (FAST) in order to detect free, intraperitoneal fluid. It is imperative to include the fetus as well as the placenta in every sonographic evaluation of the abdomen and pelvis [54].

CT is the preferred modality in unstable patients or in patients with clinical or sonographic signs of injuries to chest, mediastinum, aorta, spine, retroperitoneum, bowel, bladder, and pelvis.

Intravenous iodine contrast may be administered as indicated clinically, but this may induce hypothyroidism in the unborn as well as causing renal anomalies.

Therefore, after delivery follow-up investigations of thyroid and renal function are needed. CT should be performed with adapted dose values for the mother with considerations of her body habitus. It is important to note that with a 20% reduction in the ideal adjusted dose there will be more image noise. However, the images will be of good enough quality to diagnose traumatic lesions. Other means of reducing the radiation dose with CT scans include the adjustment of the scanogram and appropriate reconstructions protocols.

In newer CT systems, special attention to the image reconstructions is needed if automated exposure control systems are used.

In CT a total radiation dose of more than 100 mSv should not be exceeded by a single examination using standard trauma protocols. Several significant differences exist between the various CT scanner generations. Old multidetector CT scanners suffer from "overbeaming" where the x-ray beam extends beyond the edge of detector rows, exposing the patient to greater

radiation dose, while newer helical multidetector-row CT systems "overrange" as the reconstruction algorithm requires additional raw data on both sides of the planned scan, extra rotations outside the planned length are needed for image reconstruction. This can be reduced by adequate tailoring of scan length. Nevertheless, calculations of the International Committee on Radiation Protection (IRCP) estimate that a fetal dose of 10 mGy will increase the risk of leukemia or cancer considerably [55].

MRI is usually not an option in unstable pregnant patients, since the examinations are time consuming, not available 24 h/day and not at all MRI scanners offer monitoring facilities.

Field strengths of up to 1.5 T are preferable, as there are concerns about the heating effects of radio-frequency pulses as well as the effect of acoustic noise on the unborn. Gadolinium-based MRI contrast media have been shown to be teratogenic in animal studies if administered in doses of two to seven times greater than normal. Gadolinium crosses the placenta and is excreted by the fetal kidney into the amniotic fluid. In the light of new insights in gadolinium side effects including Nephrogenic Systemic Fibrosis (NSF) all statements regarding the use of gadolinium have to be re-evaluated, especially in pregnant women. NSF occurs in people with severely impaired renal function, but as fetal kidneys are immature the potential harm to the unborn is unquantifiable and extreme caution should be exercised [56].

Use of gadolinium-based contrast agents can be considered when maternal benefit outweighs potential fetal risks [28].

It is the authors belief, that if intravenous contrast is essential for clinical decision making, then CT should be considered, since the side effects of radiation and iodine contrast are known, whereas this is not the case for gadolinium and MRI.

We recommend that departments where pregnant trauma patients are treated should have a management algorithm. This should address the use of imaging both for initial assessment of the patient (including dose settings for plane radiography and CT) as well as the subsequent clinical treatment (including intraoperative use of imaging or further imaging for follow-up). Involvement of a radiologist from the outset of the management of the pregnant trauma patient is essential as imaging plays an integral role in all aspects of management and treatment of these patients.

## 23.6 General Recommendations for Surgical Interventions

Whenever possible, all elective procedures should be postponed until after delivery [57, 58]. However, provision of optimum emergency surgical care should not be compromised. Surgical management of fractures is dictated by the bony and soft tissue injury and it may not be feasible to postpone these procedures [26]. Most can be safely carried out in the pregnant patient. Consideration specific to anesthesia, intraoperative radiology and orthopedics should be taken into account.

The management of the airway can be a challenge in pregnant patients. The incidence of difficult intubations is 17-fold higher in advanced pregnancy. There is an increased risk of aspiration and the risk of hypoxia higher due to reduced functional reserve and increased oxygen consumption [59]. The combination of limited maternal reserve and a fetus sensitive to changes in maternal metabolism requires close monitoring and expedient action on the part of the anesthesiologist. The goals of ventilation include a high $PaO_2$ and a $PaCO_2$ normal for the gestation [60]. Frequent measurements of blood gases may be invaluable in these circumstances.

Uterine and fetal monitoring are useful as fetal distress maybe the first sign of maternal hypovolemia. Monitoring volume status in pregnancy may be difficult as some data show poor correlation between central venous and left ventricular filling pressures.

### 23.6.1 Intraoperative Radiology

During any operative procedure the fluoroscopy unit should be handled by radiographer. Exact placement of the primary beam, tight use of the shutter, and lead shielding are mandatory—especially the uterus should be as far as possible from the primary beam. Lead shielding reduces the scatter from the units itself and other outside sources, whereas scattered from the irradiated tissues cannot be reduced.

Of course irradiation time should be as short as possible and extensive use of the "Last Image Hold" technique is mandatory. The same guidelines apply for intraoperative radiography, typical doses to the fetus can be found in Table 23.5. The dose output of C-arm systems can differ considerably between manufacturers. This makes it difficult to estimate an absolute tolerable time period for irradiation of the pregnant uterus. Using the data published by Schueler et al. [61], and assuming that the gravid uterus is directly in the x-ray beam, the threshold dose of 100 mSv will be reached in about 3 min at a FOV of 28 cm, but only 1.5 min at a FOV of 20 cm.

- Design of an algorithm for the management of the pregnant traumatized patient with particular attention to the early involvement of a radiologist and medical physicist. Detailed knowledge of the cumulative dose received by the patient is essential for on-going management decisions.
- Ultrasound is the first modality of choice.
- If a CT scan is necessary, the region scanned should be kept as small as possible. Utilize all inherent possibilities to reduce dose of ionizing radiation including rigorous mAs lowering.
- If administration of intravenous iodine contrast is necessary, close monitoring of thyroid and renal function and referral to a pediatrician are essential for the child after birth.
- In non-acute imaging detailed counselling of the mother is necessary if the fetal dose is likely to go beyond 1 mGy.
- During intraoperative imaging, direct irradiation to the uterus should be avoided.

## 23.7 General Orthopedic Surgical Management

There is a paucity of literature on the outcomes of orthopedic injuries during pregnancy. In a study from New Orleans only 4% of pregnant trauma patients had orthopedic injuries [62] but these data are not representative.

Extremity fractures should be treated according to principles of the non-pregnant patient. The pregnant patient tends to be young and suboptimal surgical management of fractures may have profound long-term consequences. As long as direct irradiation of the uterus is avoided and adequate shielding employed, there are not contra-indications to intraoperative imaging.

In contrast women requiring pelvic and proximal femoral fracture fixation are associated with a higher radiation dose. Modifications of surgical technique may reduce the need of intraoperative imaging. Most minimally invasive techniques are highly dependent on intraoperative imaging and are therefore not advocated. An open technique of fracture reduction and fixation reduces the need for imaging.

Pregnancy is a prothrombotic state and prolonged immobilization and bed rest should be avoided. The increased risk of venous thromboembolism (VTE) begins in the first trimester and has a tendency to occur in the left lower limb [63].

In a recent Cochrane Database review, the relative risk (RR) for symptomatic thromboembolic events was as follows:

- post-cesarean LMWH/UFH versus no heparin, RR 1.30; 95% CI 0.39–4.27 (four trials, 840 women),

- post-cesarean LMWH versus UFH, RR 0.33; 95% CI 0.01–7.99 (three trials, 217 women),
- post-cesarean five-day versus 10-day LMWH, RR 0.36; 95% CI 0.01–8.78 (one trial, 646 women),
- postnatal UFH versus no heparin, RR 0.16; 95% CI 0.02–1.36 (one trial, 210 women).

No clear data are available regarding the pregnant trauma patient.

Some specific risk factors that may relate to the traumatized pregnant patient including immobility [64], blood loss, and transfusion [65] as well as having any surgical procedures. It appears that low-molecular weight heparins are safe to use in these patients [66, 67]. The decision to prescribe anticoagulation should be based on assessment of individual patients and with consideration of risk factors. Surgical treatment of an injury to get the patient mobile is clearly desirable and the benefits outweigh the risks of the procedure.

Positioning the patient in the left lateral decubitus position (left side down) moves the gravid uterus away from the vena cava and avoids the development of supine hypotension syndrome [19]. If it is not possible to position the patient in this way the uterus should be manually displaced. Any blood loss should be directly communicated with the anesthesiologist. Although the patient's hemodynamic parameters may remain within normal limits, this is at the expense of the blood flow to the uterus and fetus.

There are a few logical issues that must be considered to aid decision making in situations where operative intervention is required. These include fetal gestational age and viability, level of maternal and fetal compromise, the cumulative dose of ionizing radiation, and the necessities of fracture fixation. There simply are no easy answers and the treatment needs to be individually tailored to the patient.

## 23.8 General Outcomes

Trauma puts both mother and the developing child at risk. This is well recognized but quantification of the risks to the fetus and woman only relies on a few reports.

This is a reflection of the unusual nature of injuries in the pregnant patient and the difficulties in collecting data on their outcome.

Most of the data concentrates on the severely injured patient, but it should be borne in mind that even relatively minor trauma can lead to preterm labor and fetal loss. It has been estimated that between 4 and 61% of injured pregnant patients lose their fetuses [3].

Weiss et al. reported on the causes of fetal death related to maternal injury [68]. Data were collected from 16 states in the USA over a 3 year period. Motor vehicle accidents were by far the most common cause of fetal death (82%) with firearms (6%) and falls (3%) far behind. The physiological diagnoses associated with fetal loss were placental abruption (42%) and maternal death (11%). A trend between placental abruption accompanied by uterine rupture and advanced gestational age was noted.

Hemodynamic parameters are crude and do not provide a reliable indicator of the fetal status [3]. Some risk factors of acute termination of pregnancy have been identified. An Injury Severity Score (ISS) $\geq 9$ and a gestational age of $\leq$23 weeks are strong predictors of fetal loss [11]. Other authors have also demonstrated adverse fetal outcomes with increasing injury severity [69, 70] but it is interesting that even moderate maternal trauma can result in fetal death.

The rates of preterm labor are increased in the presence of head injuries with patients who have a GCS $\leq 12$ being three times more likely to go into labor, without an association of increased fetal death [35].

In general, it is difficult to truly predict outcome. Indicators exist but dramatic and devastating fetal outcomes are seen in relatively minor trauma. It is therefore prudent to exercise caution. All pregnant patients with a viable fetus need to be closely monitored and the early involvement of obstetricians is essential for the correct and judicious interpretation of fetal monitoring data.

## 23.9 Pelvic Fractures in Pregnant Polytrauma Patient

The pregnant polytrauma patient with a pelvic ring injury is rarely observed. Thus, only case reports were predominantly reported in the literature.

Already J.F. Malgaigne reported on birth canal obstruction as a result of an unstable pelvic ring fracture leading to problematic vaginal delivery [71].

Thus, the main goal in pelvic ring injuries during pregnancy is the anatomic restoration of the ring structure of the pelvis [72, 73].

- Chalk et al. in 1969 reported a case of a right-sided hemipelvic dislocation (type C1.2 injury according to Tile) in a 21 year old woman at 32 weeks gestation after a jump from great height [74]. She was unconscious and in severe shock. Beside her hemodynamic instability, an open fracture was present with a horseshoe-shaped tear in the perineal area with anterior vaginal wall and urethra (intact) avulsion. An immediate lower cesarean section was performed, as no heart sounds of the fetus could be heard but the fetus was dead and showed no obvious signs of injury. Thereafter, symphyseal cerclage stabilization was performed and debridement of the perineal wounds including suturing of the vaginal lacerations.
- During a second pregnancy, 9 months after the injury, the baby was delivered uneventful by elective cesarean section [74].
- Pals et al. in 1992 reported on a pregnant women in the 18th week of gestation with a transverse fracture of the right acetabulum, which was stabilized after 3 days. At the 40th week uneventful vaginal delivery of a healthy baby took place [75].
- A comparable case was reported by Dunlop et al., in 1997 with an uneventful spontaneous delivery of the baby 14 weeks later [76].

In a retrospective analysis on 24 years from a major trauma center only seven pregnant patients with a pelvic fracture were reported [30]. Of these patients five mothers and three fetuses survived. This group represents severely traumatized patient and their care needs to be undertaken in specialist units.

In general, pregnant women with pelvic ring injuries have to be distinguished from patients with acetabular fractures.

### 23.9.1 Pelvic Ring Injuries in Pregnant Patients

When dealing with pelvic ring fractures in pregnant patients, physiological changes of the pelvic joints have to be considered.

#### 23.9.1.1 Pelvic Joint Changes During Pregnancy

Luschka already in 1854 described ligament relaxation and pelvic joint distension [77].

Young stated that in 0.75% of pregnant women a so-called pelvic osteoarthropathy can develop the symphysis or SI-joints with resulting pain and tenderness in these regions aggravated by walking [78].

It was already stated that gliding of the symphysis in single leg stance/walking occurs without giving pathological values [78].

In 1940 Young analyzed in detail these radiological changes based on a literature research [79]. Based on a work by Roberts [80] an increase of the

sacroiliac width in nulliparae was observed from 3.6 mm to 4.5 mm, and of the symphyseal width of 2.6 mm to 4.5 mm, respectively. A great variability between women, no increase during labor, and a return to pre-pregnant values by the end of the third to the sixth month was described [79].

In a systematic review, it was stated that the laxity also of pelvic ligaments and joints reached its maximum at the second trimester [81].

A physiological laxity of ligaments and pelvic joint occurs during pregnancy with physiological widening of the pelvic joints. These aspects have to be considered when analyzing pelvic radiographs after trauma in pregnancy.

#### 23.9.1.2 Data on Pelvic Ring Fractures

As already mentioned, there is a severe danger in underestimating the severity of maternal blood loss due to a relative hypervolemia with a possible maternal blood volume of about 20%.

Kissinger et al. reported on seven pregnant patients with a pelvic injury without detailed report of treatment [35].

Pape et al. retrospectively reported on seven pregnant trauma patients from a group of 4196 polytraumatized patients [30]. All women had multiple injuries and a pelvic fracture after a blunt trauma mechanism, most often from motor vehicle accidents. The mean Injury Severity Score was 29.9 points indicating a severe polytrauma status. Two women and four fetuses (all with death on arrival) died as a result of their injuries. No association to the type of pelvic and acetabular trauma was observed.

Leggon et al. performed a literature review of pregnant women with a pelvic ring and acetabular fractures [82]. 89 cases were included in this analysis of factors resulting in maternal and fetal mortality. Unrestrained women hit by motor vehicles showed a trend towards higher maternal mortality rates, while motor vehicle accidents showed this trend to a higher fetal mortality compared to falls. Analyzing patients with pelvic ring injuries showed a maternal mortality rate of 9% and a fetal mortality rate of 35%. While the maternal mortality rate was comparable to the group of women with an acetabular fracture, the fetal mortality was significantly lower.

The main factor leading to fetal death was maternal hemorrhage, while direct trauma to the uterus, placenta, or fetus was of less significance [82].

Loetgers et al. reported on a 31 year old women in the 23rd week of pregnancy sustaining a closed type C injury of the pelvis with an unstable sacrum fracture and bilateral pubic rami fractures [83]. She was hemodynamically stable and the fetus showed no signs of injury during gynecological evaluation. Diagnostic included a dose-reduced CT scan and isolated posterior pelvic ring stabilization was performed by minimal-invasive ilio-iliacal plate stabilization in the prone position. The further course was uneventful and in the 38th week of pregnancy, elective cesarean section was performed. The baby was healthy without consequences of injury.

Almog et al., reported on a large series of 15 women, treated between 1987 and 2002 from 1345 cases of pelvic fractures [84]. Fifteen (1.1%) of these were pregnant women.

Of 14 women with pelvic fractures, 9 type A, 3 type B, and 2 type C fractures were observed. Two women had additional acetabular fractures. All type A pelvic ring fractures were treated nonoperatively. One type B injury was treated by internal fixation after preterm delivery of a healthy newborn.

In both type C injuries, stabilization of the pelvis was performed. One woman died during the resuscitation phase after external fixation of the pelvic ring, and the other woman had internal fixation after termination of pregnancy.

Nine fetuses were viable at delivery, seven after vaginal delivery, and two after caesarian section. In two women, elective pregnancy termination was performed. One fetus was dead on arrival. Another newborn died 3 days postpartum due to shock-related consequences.

During the last years, again only case reports were published [85–88].

Anatomic reconstruction of the pelvic ring is the primary goal of treatment. In the polytrauma patient survival of the mother is the primary aim (Fig. 23.1).

### 23.9.2 Acetabular Fractures in Pregnant Patients

Leggon et al. performed a literature review of pregnant women with a pelvic ring and acetabular fractures [82]. Twelve cases were included in this analysis of factors resulting in maternal and fetal mortality. Unrestrained women hit by motor vehicles showed a trend towards higher maternal mortality rates, while motor vehicle accidents showed this trend to a higher fetal mortality compared to falls.

Analyzing patients with pelvic ring injuries showed a maternal mortality rate of 8% and a fetal mortality rate of 25%.

Almog et al., reported on a large series of 15 women, treated between 1987 and 2002 from 1345 cases of pelvic fractures [84]. The acetabular fracture types included a nondisplaced posterior wall fracture, a minimally displaced

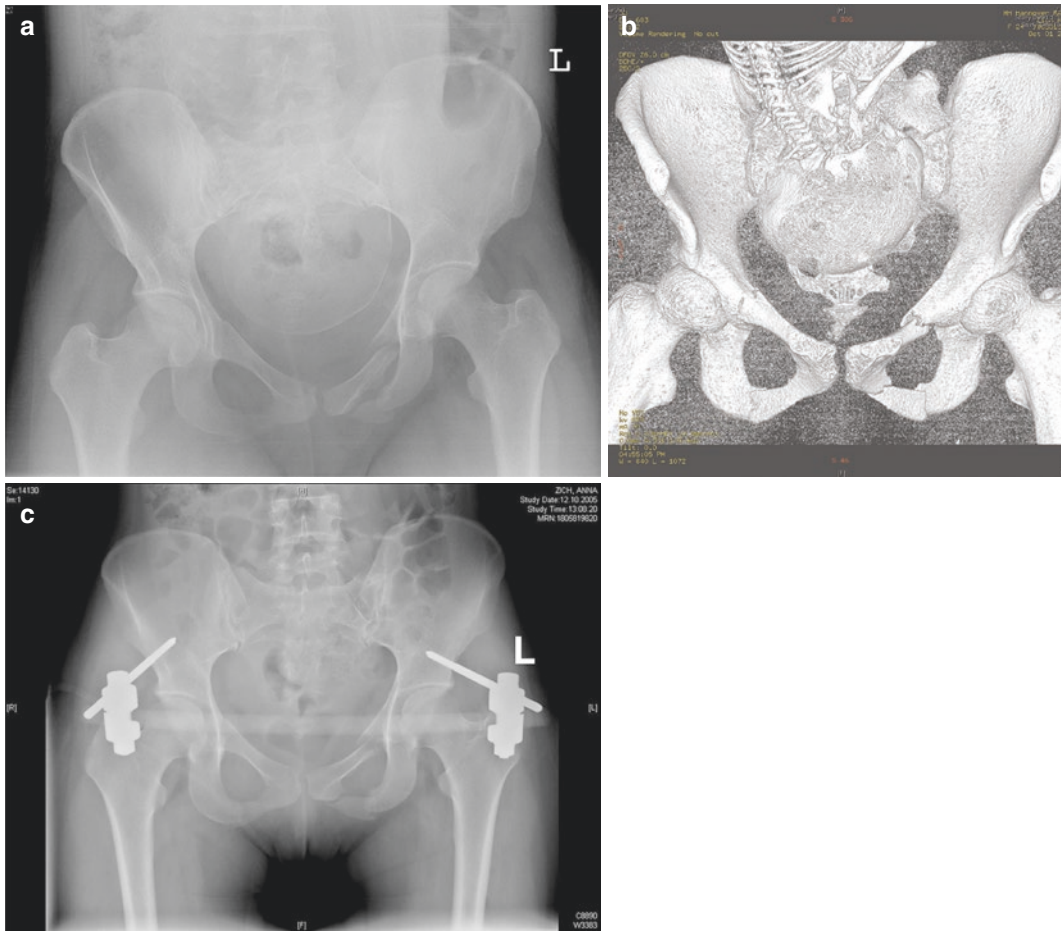


**Fig. 23.1** A 29-year-old woman in the 34th week of gestation after motor vehicle accident with a front-to-front crash. She sustained a moderate head injury (Glasgow Coma Scale 10), a moderate chest trauma with left-sided multiple rib fractures and a pelvic ring type B injury with a left sacrum fracture and bilateral pubic rami fractures (**a**, **b**). She was hemodynamically stable after two units of blood. After low dose CT examination, first the fetus was delivered by longitudinal cesarean section, followed by classical supraacetabular external fixation of the pelvis (**c**)

transverse fracture, and a displaced transverse fracture, respectively.

The nondisplaced fractures were treated non-operatively, while the displaced transverse fracture was stabilized. The further course was uneventful in all women with normal delivery.

During the last, except one larger series [89], only case reports were published [90–92].

Porter et al. in 2008 reported on 8 pregnant women with an acetabular fracture (1.5% of 518 acetabular fractures) [89]. All had ORIF of their acetabular fracture. The gestational age ranged from 5 to 26 weeks. Intraoperative pelvic fluoroscopy averaged 39 s. The majority of patients (7/8) had anatomic joint reconstruction.

Considering the radiation risk, ORIF is possible, without harming the mother and the fetus and therefore recommended as the treatment of choice in displaced acetabular fractures.

## 23.10 Special Features in treating Pregnant Women with Pelvic Ring Fractures

Several particularities have to be considered when treating women with pelvic and acetabular fractures:

- pelvic fractures in pregnancy result in an increased fetal mortality (35–60%) [30, 35, 82, 93].
- the mother should be assessed and resuscitated before the fetus [19].
- injury severity with its pathological consequences is the main mortality risk factor [16, 35, 69, 94].
- acetabular fractures can sufficiently be treated by open reduction and internal fixation (ORIF) without a relevant risk for the fetus.
- displaced pelvic ring injuries should be treated surgically to by a surgically skilled pelvic surgeon [84] for anatomical reconstruction of birth canal.
- consider delaying surgery in near term pregnancy [72].
- analysis of radiation exposure during intraoperative diagnostics and intraoperative is clearly recommended.
- minimal-invasive procedures should be avoided, as radiation exposure is often higher than with ORIF.
- the surgical approach should be adjusted as far away from the uterus as possible [84].
- all treatment modalities should be performed under fetal monitoring.
- opiates for analgesia are safe for use during pregnancy, while nonsteroidal anti-inflammatory drugs should be avoided in the second and third trimesters, adequate prophylactic anticoagulation is weighted against the risk for active bleeding.

## 23.11 Vaginal Delivery After Pelvic Fractures

Vaginal delivery is the physiological way of child-bearing. Even after sustaining a pelvic ring injury, it should be considered as the gold standard. Even after displaced pelvic ring fractures, vaginal delivery is possible without any disturbances [72, 73, 93, 95].

Several authors described their experience with child-birth after sustained pelvic ring injuries.

Voegelin et al. already in 1944 stated that the lateral compression fracture may distort the pelvic inlet, especially when the inferior pubic ramus is displaced [96], which may result in delivery impingement. The potential of bone healing has to be considered, as it was seen after some years, that callus formation and deformity even after severe fractures were reduced over time [96].

Elective cesarean section was recommended in severe lateral compression injuries resulting in narrowing of the birth canal, in acute displaced fractures and injuries with symphyseal disruption [96] and even anterior displacement of the coccyx does usually not result in relevant dystocia [96].

In 1957 Mulla discussed on the risk of immediate abortion or premature labor or even only not disturbing the pregnancy [72]. From the editorial view of this paper it was stated that approximately 10% of women after pelvic ring fractures develop obstruction of the birth canal requiring cesarian section [72].

It was already stated that vaginal delivery is typically possible without any impairment, even after pelvic ring injuries [96].

During the last 4 decades, several larger reports were presented.

Speer an Peltier reported on their own experience in former pregnant women with a pelvic ring injury [93]. The main results included:

- 10% fetal death
- 53.5% vaginal delivery
- 36.5% cesarean section.

Comparable cesarean section rates were reported by Zhou et al. [97], while Madsen et al. observed a rate of only 5.9% [95].

Recent studies reported a trend to higher cesarean section rates compared to non-injured women [98–100], ranging from 48% to 62%.

Reasons for these higher, up to 50–60% cesarean section rates, compared to standard rates of 15–21% in the USA or Great Britain [101], included [98–100]:

- no trial of labor,
- selection based on pelvic fracture history,
- unsuccessful trial of labor,
- dystocia secondary to the injury,
- cephalopelvic disproportion.

Several authors discussed whether stabilization of the pelvic ring and especially joint bridging implants of the pubic symphysis or the SI-joints lead to higher cesarean section rates.

Agreement exists that after former external fixation or iliac wing stabilization, vaginal delivery is without any risk [30, 95].

But even in the presence of joint bridging implants normal vaginal delivery can be successful [100, 102, 103].

In the presently largest series in 31 women with pregnancy after a healed unstable pelvic fracture, 16 women had vaginal delivery, even after implants in situ [100].

Recently, Riehl analyzed eight articles assessing 148 patients who underwent child-birth after pelvic fracture in a systematic review [104]. The following results were presented:

- 53% rate of vaginal delivery
- 47% rate of cesarean section
- cesarean section prior to the injury increased the cesarean section rate.

Overall, prior pelvic fixation had no demonstrable effect on pregnancy outcomes [104].

After pelvic trauma in pregnancy the rate of cesarean section is higher than expected. The reasons for this increase are not fully understood.

### 23.11.1 The Value of Implant Removal

Historically, implant removal was frequently performed after plate osteosynthesis of the disrupted pubic symphysis [105].

Raman et al. performed a literature review on 482 patients with symphyseal internal stabilization on implant removal and stated that no consensus could be derived for routine implant removal [103]. A 7.5% complication rate was observed with implant removal, with infection the most common complication.

Giannoudis et al. analyzed 74 patients after symphyseal plating. Implant removal was performed in only four patients (5.4%) in an observational period of 41 months [102]. It was stated that routine removal of the plate is not essential, while in women in child-bearing age no clear data were available.

A physiological secondary widening of the symphyseal space after osteosynthesis of a symphyseal disruption is frequently seen [106].

There is no indication for routine implant removal of symphysis bridging implants. Physiological implant mobilization is frequently observed. A high rate of infectious complications has to be considered [107].

## 23.12 Special Gynecological Injuries

Concomitant gynecological injuries are usually a result of direct injury (falling on an object, impaling, etc.). In combination with pelvic fractures, associated genital injuries are more common than vaginal injuries [108–110], whereas injuries to the non-gravid uterus are extremely rare [111].

Pohlemann et al. reported on treatment of 903 women with pelvic fractures. In non-pregnant women, 8 vaginal injuries (0.3%), 5 vulva lacerations (0.6%), and 4 significant perineal wounds (0.4%) were observed. Except for three women, all sustained roll-over mechanisms or high-energy trauma [112].

Genital trauma includes external injuries to the labia, vulva, vagina, urethra, or anus and internal injuries to the bony pelvis, bladder, bowels, or reproductive organs [113].

Traumatic vulvovaginal non-obstetrics injuries (VVI) are typically the results of "straddle" injuries, tearing and tissue laceration due to sudden abduction of the lower extremities or lacerations as a result of a pelvic fracture [114].

Such injuries can present as vulvovaginal lacerations, lacerocontuous injuries, vulvar or vaginal hematoma, and complex open perineal injuries.

According to Faringer et al. perineal genital trauma can usually be classified as zone I injuries [115]. Fu et al. developed a classification for grading of the perineal soft tissue injury (Table 23.9), integrating the injury characteristics and a resultant treatment protocol [116].

**Table 23.9** Classification of perineal soft tissue injury (modified according to [116])

| Type | Characteristics of injuries | Repair protocols |
|---|---|---|
| **A Urogenital zone injuries** | | |
| A1 | No urethral injury | No cystostomy, skin graft or flap transplantation |
| A2 | Urethral injury | Cystostomy + skin graft or flap transplantation |
| **B Anal zone injuries** | | |
| B1 | No anorectal injury | No colostomy, skin graft or flap transplantation |
| B2 | Anorectal injury | Colostomy + skin graft or flap transplantation |
| **C Both urogenital zone and anal zone injuries** | | |
| C1 | No urethral or anorectal injuries | Soft tissue reconstruction |
| C2 | Isolated urethral injuries | + cystostomy |
| C3 | Isolated anorectal injuries | + colostomy |
| C4 | Urogenital + injuries | + colostomy *and* cystostomy |

Pelvic fractures are a risk factor of genitourinary injuries. Using data from the National Trauma Data Bank, female reproductive organ injuries (vagina, vulva, ovary, uterus, ovarian) were present in approximately 3.6% in association with a pelvic fracture compared to approximately 0.3% without a pelvic fracture [117].

In pediatric and adolescent patients, blunt trauma is responsible to vaginal injuries in 74.3%, while vulva trauma was associated with a blunt trauma mechanisms in 84.4% [118].

### 23.12.1 Vulva Trauma

Blunt trauma to the vulva interrupts the rich vulvar vascular supply caused by frontal impacts, which crush the vulvar tissues against the osseous planes [119].

Goldman et al. reported on the frequency of blunt injuries of female external genitalia associated with pelvic trauma in 30% [120].

Blunt vulva trauma after polytrauma mechanisms is extremely rare. The typical blunt injury mechanism is a fall from small heights with direct trauma [119, 121–123].

Clinically, often an extensive hematoma is observed [124].

Concomitant injuries of the vagina, pelvis, or abdominal organs should be ruled-out by vaginal examination under general anesthesia [125].

Vulva trauma is classified according to the Organ Injury Scaling [126]:

- I Contusion or hematoma.
- II Laceration, superficial (skin only).
- III Laceration, deep (into fat or muscle).
- IV Avulsion; skin, fat, or muscle.
- V Injury into adjacent organs (anus, rectum, urethra, bladder).

Blunt trauma of the vulva or perineum may lead to micturition disturbances. Therefore, insertion of an urinary catheter is recommended [124].

The majority of vulva hematomas can be sufficiently treated by observation and only in resulting hemodynamic instability [123], drainage is considered an option [120]. The benefits of a prophylactic antibiosis are controversial.

Propst et al. stated that in a stable hematoma, after conservative treatment good results can be expected [127] but the length of hospital stay and increased of antibiotics and blood transfusion have to be considered [128].

Conservative treatment consists of rest, compression, and local cold application.

Increased hematoma formation may lead to surgical intervention [129] as vulvar hematomas of >4 cm can result in vulva necrosis [130].

The incision can be performed on the bulging or through the vaginal mucosa with comparable results [131].

Vulva lacerations should be treated by local wound debridement and secondary closure [124]. Concomitant vaginal injuries are treated by primary repair, if indicated.

### 23.12.2 Vaginal Injury

Vaginal lacerations are often associated with pelvic ring injuries, while isolated vaginal injuries after blunt trauma mechanisms are rarely observed.

The incidence of vaginal trauma was reported between 2% and 4% [110, 132–134].

In women with blunt genital injuries, blood at the vaginal introitus indicates potential vaginal injury. Thus, exclusion of vaginal injuries is mandatory and colposcopy and vulvovaginoscopy can help for diagnosis [135]. Additionally, urethral and bladder injury should be excluded [120, 135].

Often, these injuries are overlooked, as bleeding is reduced by contraction of vaginal smooth muscles and accompanying severe injuries are in the main primary focus.

Thus, vaginal inspection with specula is recommended, preferrable under general anesthesia as it is relative painful.

There is a potential risk of complications, e.g., pelvic infection, vaginal stenosis, and sexual dysfunction, with delayed diagnosis of vaginal trauma [110, 136].

Only few reports focused on pelvic injuries with associated vaginal trauma.

The vaginal injury can be classified according to the "Injury Scoring Scaling" of the American Association for the Surgery of Trauma [126]:

- I Contusion or hematoma.
- II Laceration, superficial (mucosa only).
- III Laceration, deep into fat or muscle.
- IV Laceration, complex, into cervix or peritoneum.
- V Injury into adjacent organs (anus, rectum, urethra, bladder).

Niemi and Norton depicted that the vaginal wall may be pulled, penetrated by the fracture ends of pelvic anterior ring as well as separated or floating pubic symphysis or pressed by the decreased pelvic volume [110]. An incidence of

3.5% vaginal injuries was reported. Conservative treatment and vaginal repair were performed.

Fowler et al. also emphasized that pubis and ischium could bruise or penetrate vaginal wall [137].

An unstable pelvic ring probably increased the risk of vaginal injury [138], independent on the type of pelvic ring instability (type B or C).

APC and VS injuries were highly associated with vaginal trauma [138].

#### 23.12.2.1 Treatment

For most adult vaginal lacerations, management includes debridement and primary surgical closure or vaginal packing with antibiotic coverage [139].

Lie et al. reported a classification-dependent treatment recommendation [138]:

- I–II: no special treatment, only gauze packing.
- II–III: surgical repair: 14× primary closure, 4× secondary vaginal repair.

### 23.12.3 Rectal Injuries

Rectal injuries can be associated with open perineal injuries. The classical treatment.

principle comprised of diversion, drainage, direct repair, and distal wash-out [64].

Anorectal injuries are expected in approximately 26% (overview in: [140]).

These injuries can be associated with pelvic vascular lesions and genitourinary lesions, with a resulting high mortality and morbidity [141]. A multidisciplinary management approach is therefore required.

Digital rectal examination is unreliable as up to 77% of these injuries are overlooked. While the specificity of digital rectal examination is 95%, the sensitivity of 24% is minimal [142–144].

Thus, in any suspicious case, rigid proctoscopy or flexible sigmoidoscopy is highly recommended [145].

Several fracture configurations can lead to suspicion of rectal injuries [146]:

- injury to the pubic symphysis (independent predictor, relative risk [RR] = 3.3),
- injury to an SI-joint (relative risk [RR] = 2.1).

The rectal injury can be classified according to the "Injury Scoring Scaling" of the American Association for the Surgery of Trauma [147]:

- I Hematoma Contusion or hematoma without devascularization.

Laceration Partial-thickness laceration

- II Laceration Laceration <50% of circumference.
- III Laceration Laceration >50% of circumference.
- IV Laceration Full-thickness laceration with extension into the perineum.
- V Vascular Devascularized segment.

Fecal diversion by proximal colostomy with or without presacral drainage and primary repair is considered the gold standard in treating traumatic extraperitoneal rectal injuries, while intraperitoneal injuries can be treated like injuries to the colon with

primary repair or resection and anastomosis with or without diversion [141, 148, 149].

In a systematic review of the published literature until the late 90ies, no difference in infection rates was found in patients treated with or without colostomy [150]. All patients with a clear diagnosed rectal injury were treated with colostomy and presented with a high infection and mortality rate. Patients with perineal/rectal wounds showed a benefit regarding infectious complications, but it was not distinguished, whether a rectal lesion was present or not.

Colostomy is the keystone of rectal trauma treatment [151].

A loop-type colostomy is favored [151, 152].

Anal sphincter repair should be initiated dependent on the hemodynamic status of the.

patient [152]. In stable patients, primary repair is favored [152, 153]. If sphincteroplasty is considered, delayed reconstruction is recommended. In the presence of massive anorectal lacerations and gross contamination, fecal diversion is favored [153].

Destructed anal sphincter injuries can be treated by delayed abdominal perineal resection [154], while anal tears should be debrided initially and left open. Rectal mucosa tears should be closed after debridement [154].

### 23.12.4 Uterus Trauma

Traumatic uterus trauma is extremely rare, and is observed in only 0.6% after blunt high-energy trauma [39, 155]. Only few case reports are available for uterus trauma [156].

During pregnancy traumatic uterus injury is potential life-threatening to both the mother and the fetus. Trauma is responsible to approximately 10% of all uterus ruptures [157].

Recently, Suchecki et al. presented a literature overview on case reports of uterus trauma [156]. The main conclusions were as follows:

- high-energy trauma is the predominant injury mechanism, especially after motor vehicle accidents.
- in >80% fetal demise has to be expected.
- the fetus was delivered at the time of surgical intervention.
- total hysterectomy and laceration repair have to be performed.

Traumatic injury to the uterus is an obstetric emergency and necessitates immediate action [158].

## 23.13 Summary

An algorithm focusing on the clinical situation of the mother and the fetus is recommended to get optimal results for both involved patients (Fig. 23.2).

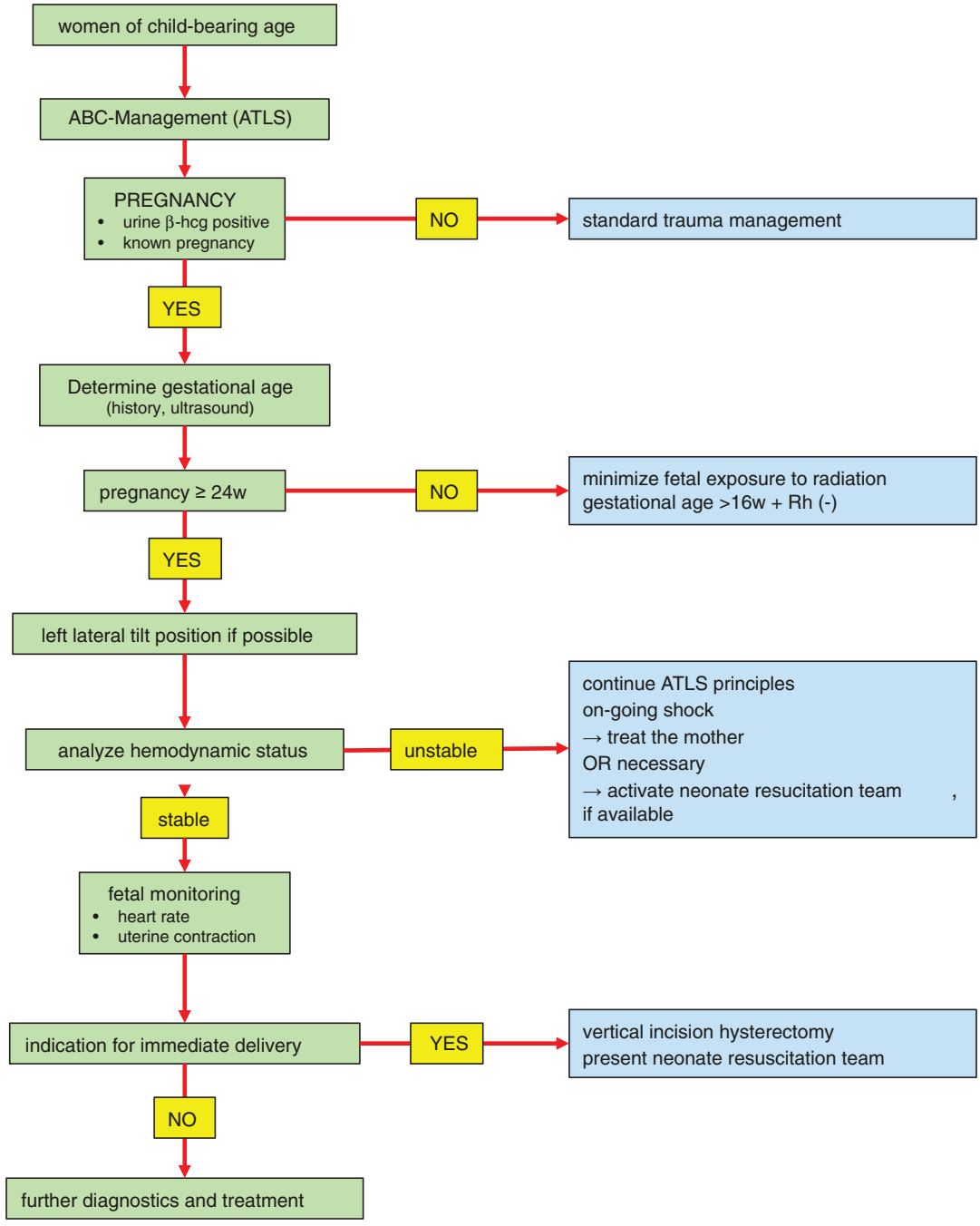


**Fig. 23.2** Proposed general treatment algorithm (adapted from [20])

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# Vascular Injuries

# 24

L. P. H. Leenen

## 24.1 Damage Control in Vascular Injury

The highest goal in damage control surgery is to stop bleeding. Major injuries to the vessels therefore pose the major challenge in the damage control approach. Vascular injuries of the torso are an immediate threat to the life of the victim, whereas vascular injuries to the extremity threat the preservation of the limb.

Early adequate diagnostics by CT and/or angio CT even in the hemorrhagic threatened patient seems to be feasible is treatment early on is possible in the same location, not losing much time by transportation between location within the hospital. This has major implications for the patient with vascular, profound bleeding patients.

Early pinpointing of the vascular injury and readily available treatment with catheter-guided embolization and balloon control of the lesion will further expedite control and treatment of these injuries and open a new era in damage control of vascular injuries.

Of course, adequate selection of these patients is of the essence.

Over the past years, major changes have taken place in the management of vascular injuries.

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The invention of hybrid rooms, where both operative and catheter-guided interventions can be performed, and the invention of Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) have revolutionized the treatment of the patient with vascular injuries.

The hemodynamically unstable patient is nowadays preferably received in a hybrid operating room with diagnostic CT capabilities. However still not the standard the current knowledge calls for such a facility to optimize quick and precise diagnostics by whole body CT and immediate possibilities for catheter-guided treatment of compelling bleeding.

However, diagnostic and treatment protocols are to be adjusted as they are considerably different from the standard ATLS protocols and trauma team approach [1]. Only if the circumstances are accommodated to the infrastructure, we can enter the new paradigm shift.

## 24.2 REBOA

For many years, uncontrollable hemorrhage in the abdomen and the pelvis was thought to be best treated with left anterolateral thoracotomy and cross-clamping the thoracic aorta subsequently increasing blood flow to the brain and heart. Nevertheless this heroic procedure, the results remained dismal. Already in the 1950s, balloon occlusion of the aorta was performed [2]. Only


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in the recent years when endovascular treatment of aortic aneurysms was popularized and a wide variety of vascular disease was treated endoluminally, new interest was pointed to the use of large balloon catheters to control non-compressible hemorrhage. Already in non-heartbeating donor procedures, catheters have been used to occlude the aorta above and below the renal arteries to perfuse the kidneys for preservation with a total blockage of the aorta, even without the need of fluoroscopic control.

After a series of preclinical experiments [3, 4], it was noted that this procedure had physiologic benefits for abdominal and pelvic hemorrhage and shock. Thereafter it was used increasingly in humans [5, 6].

The REBOA was further revolutionized by a group of physicians in several trauma centers throughout the United States and Japan. Recent case reports and multi-institutional trials have demonstrated safe and effective control of hemorrhage using REBOA in patients with life-threatening hemorrhage below the diaphragm [7, 8].

### 24.2.1 Indications

Indications and contraindications of REBOA are indicated in Box 1. In short, any of the indications for a emergency room thoracotomy are also an indication for this procedure, added with severe pelvic trauma with severe hemorrhage. A protocol is depicted in Fig. 24.1.

### 24.2.2 Technique

The technique can be performed safely in the resuscitation suite using X-ray, or in the operating room using fluoroscopy. Recently, a non-fluoroscopic technique was introduced [9].

The technique, among others, is nicely outlined in the article of Stannard et al. [10] It consists of five steps: arterial access, balloon selection and positioning, balloon inflation, balloon deflation, and sheet removal.

The procedure usually is performed as a Seldinger technique. The femoral artery is approached percutaneously however preferably by cut down, and a 12 French catheter is advanced over the wire through the artery into the aorta. Some authors prefer to use ultrasound to localize the artery in severely hypotensive patients; others rely on the rather invariable anatomic landmarks.

Typically, there are two zones af interest (Fig. 24.1). In Zone 1, the balloon is placed just above the diaphragm to control both the abdominal viscera and the pelvis; in Zone 3, the balloon is placed just above the bifurcation to control the pelvis and the lower extremities.

Consequently, injuries can be addressed, whereafter the balloon can be withdrawn, to avoid further metabolic problems and/or severe repercussion injury and a severe systemic inflammatory response.

### 24.2.3 Complications

As with any invasive procedure, complications can occur. In the first place, the catheter is a fairly large bore catheter, with the usual problems of discrepancy between vessel diameter and the catheter. Advancement in older people with tortuous iliac vessels can be a problem, and in the hectic circumstances the ER could cause perforation of the vessel. However, many of these problems have been noted in the endovascular procedures currently in vogue in vascular surgery.

As noted in the paragraph above, if the balloon remains long in a place, severe repercussion problems can occur, leading to severe inflammatory sequelae.

### 24.2.4 Courses

Currently, REBOA is coming to adulthood. There are several published training courses like the Basic Endovascular Skills for Trauma (BEST™) and Endovascular Skills for Trauma and Resuscitative Surgery (ESTARS™) designed

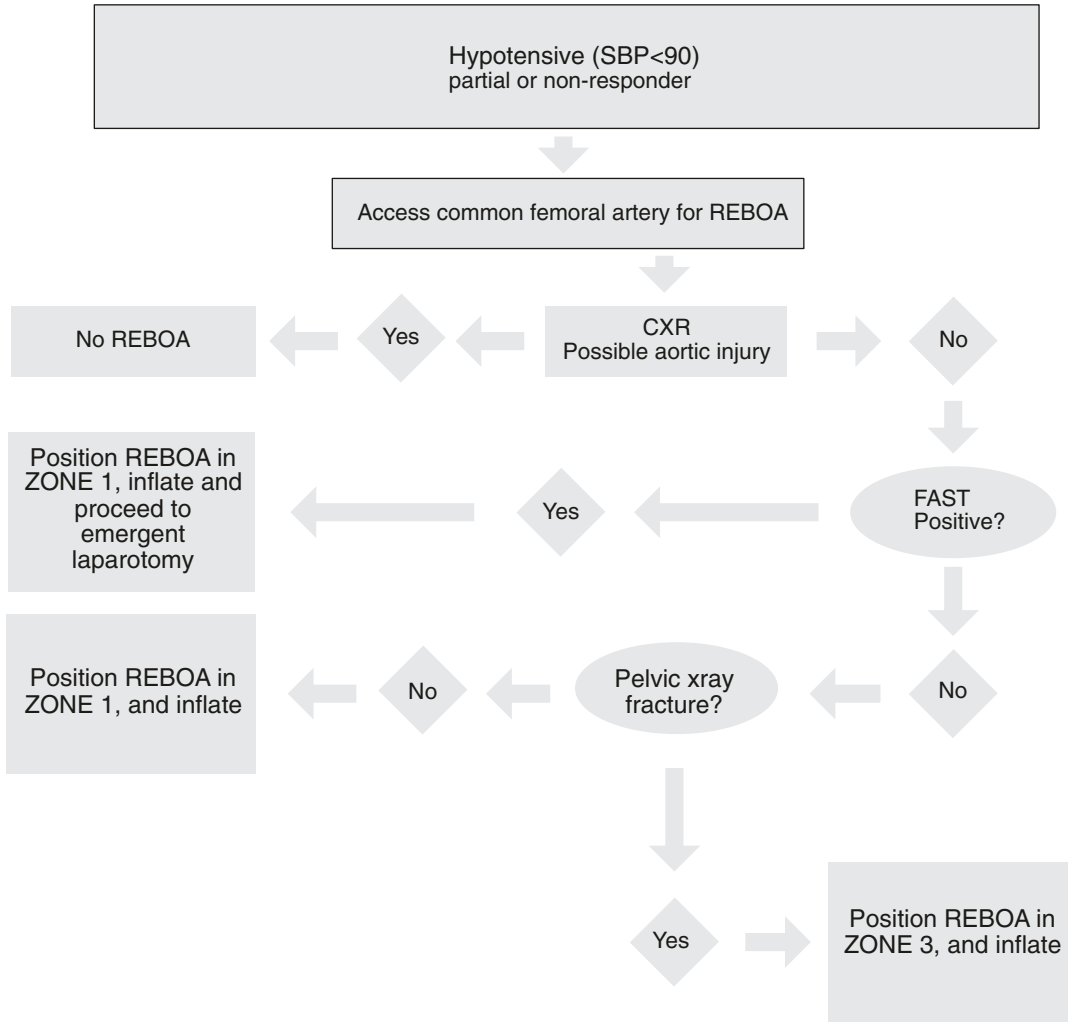


**Fig. 24.1** Reboa protocol. Modified after Shock Trauma Baltimore

to familiarize physicians with the basic endovascular techniques required to perform the REBOA.

## 24.3 Hybrid Rooms

The advent of the hybrid operating room coupled with the benefits of endovascular techniques in the setting of trauma will likely result in an increasing number of patients being diagnosed and treated with catheter-based interventions.

The combination of both catheter-guided and damage control operative care makes it possible to use both techniques in the same patient without the need for dangerous transport of a hemodynamically jeopardized patient. In the case of a damage control procedure, catheters can be used intraoperatively for additional diagnostics, for example, in a patient after packing of the liver and ongoing intraparenchymal arterial bleeding, followed by catheter-guided therapy with balloon occlusion or embolization.

Over the years, an increasing indication was noted for intra-arterial interventions already for over a decade as documented, for example, by Pryer and co-workers [11]. A combination of open operative intervention and intra-arterial adjuncts like stenting and embolization is more and more found to be indicated trying to combine less invasive and more targeted treatment of visceral bleeding [12] as well as pelvic bleeding.

Different authors have presented combined solutions where optimized combined care can be delivered [13].

The ultimate trauma diagnostics, resuscitation, and treatment room have been designed and realized in Switzerland [14], where CT, angio, and operating facilities have been realized (Fig. 24.3).

### 24.3.1 General Operative Techniques

In general in damage control, simple techniques have to be employed in order to gain control as quick as possible. Time-consuming complex repairs are most times not indicated and result in the loss of the patient, usually on the operating table.

Draping in case of suspicion of major vessel injury should be from sternal notch to the knees, as it might be possible to regain control of inflow and outflow in adjacent compartments.

In damage control situations, only a limited number of preoperative measures and diagnostic procedures are possible. In modern trauma care, airway, breathing, and circulatory management should be simultaneous.

### 24.3.2 Temporary Occlusion

In the prehospital or preoperative situation with extensive external blood loss, temporary occlusion with simple manual or digital pressure provides a simple effective measure to reduce further blood loss. Alternatively, a tourniquet in extremity injury can be applied. After being banned from clinical practice, because of the danger of venous congestion and the imminent danger of further damage by injudicious application, it is back as a result of the Iraqi conflict where it found renewed interest [15–17].

Another adjunct to temporary tamponade is the extraluminal balloon tamponade, which can be utilized in a wide variety of situations and anatomic localizations. A Foley catheter is placed through the trajectory of the injury and the balloon is inflated. Slight traction may bolster the effect. If the opening in the skin is too wide, it can be sewn together to minimize the opening.

Intraoperative bleeding can be stopped or diminished by manual compression or swabs on the inflow and outflow trajectory. In low pressure systems, for example, veins, which are easily damaged by clamping or attempts to dissect this provide a quick and effective approach to bleeding control (Fig. 24.2). For immediate control of abdominal aorta, an aortic occluder (Fig. 24.3)

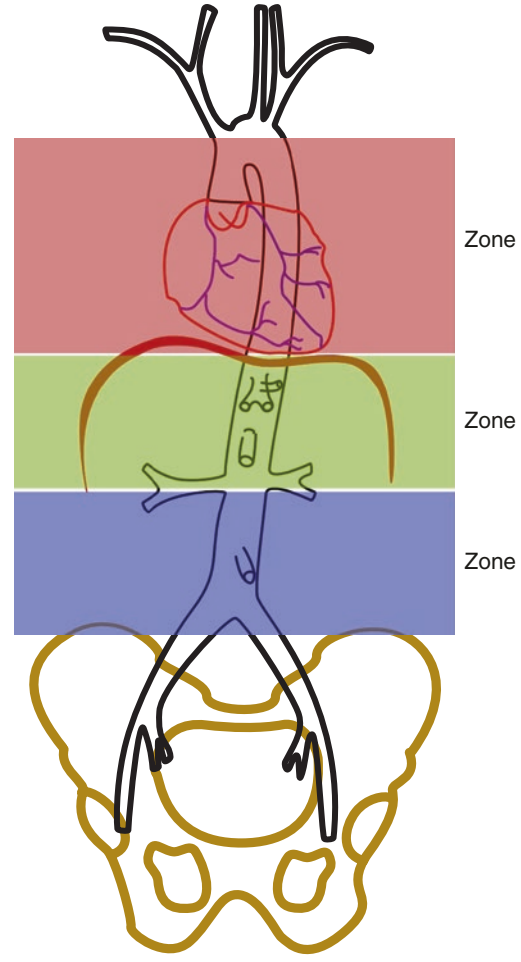


**Fig. 24.2** Aortic zones: Zone 1: from subclavian arteries to diaphragm, Zone 2: Visceral arteries, Zone 3: From renal arteries to Iliac bifurcation

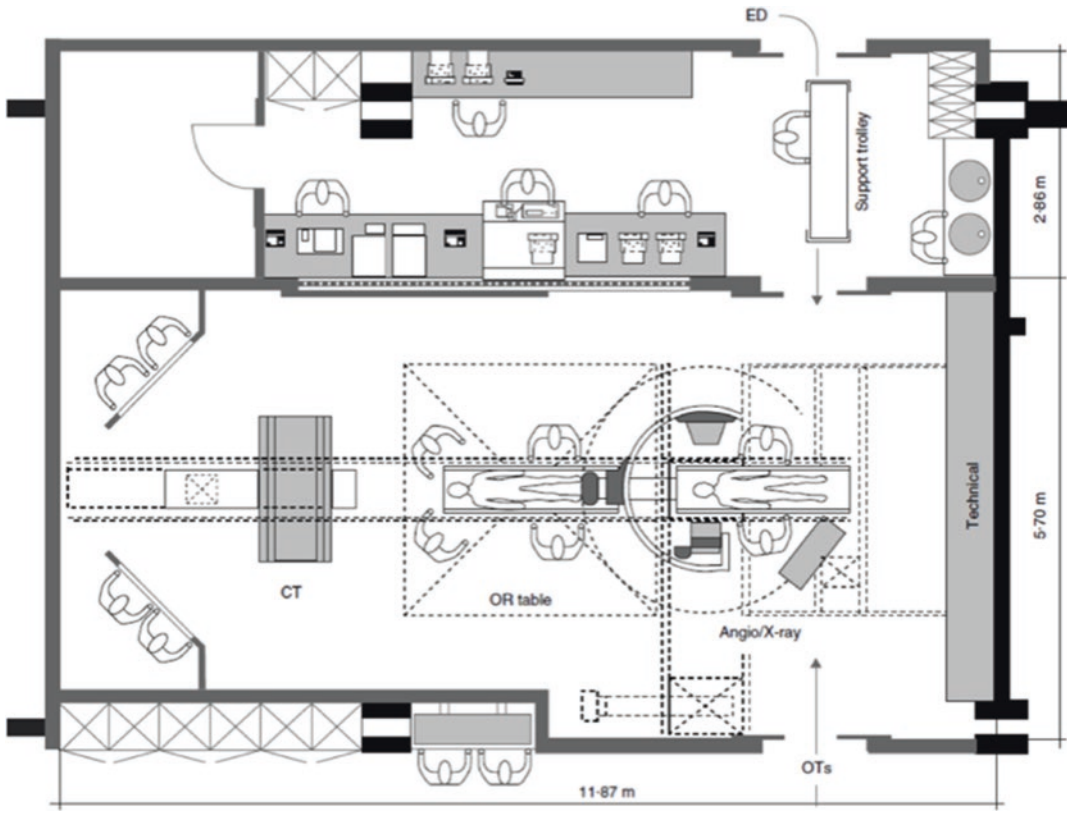


**Fig. 24.3** Combined CT, Angio and OR facilities in one room. From Gross et al., Br J Surg 2010

can be used (see section on abdominal vessel bleeding), which is placed in the diaphragmatic aperture. Intraluminal balloon occlusion can be used intraoperatively if the vascular structure can be readily identified. Also inflow and outflow control can be obtained with rubber tourniquets, without further damaging vulnerable vascular structures (Fig. 24.4).

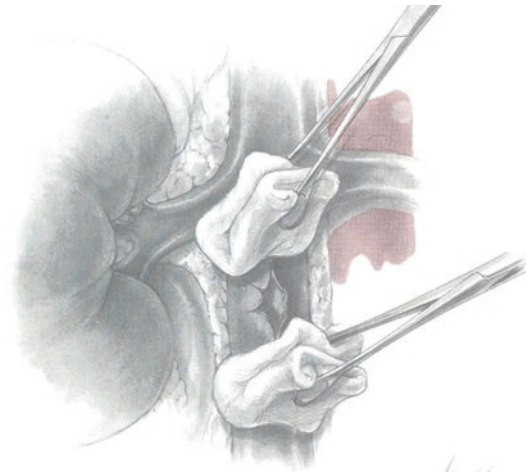

**Fig. 24.4** Swab sticks (Carrico, Thal, Weigelt)

## 24.3.3 Flow Restoration

### 24.3.3.1 Shunts

In recent years, intraluminal shunts have been used more and more as a temporary vascular conduit for almost any anatomic location. Basic research shows that (Fig. 24.5) even under low pressure circumstances the shunt remains patent for a considerable amount of time [18]. Recent experiences in Iraq showed a huge success for introduction of shunts even in the field. In a series of 54 shunts placed in the field, 43 in the proximal limb 37 (85%) remained patent until arrival in the definitive care area [19]. Even shunts placed in the venous system remained pat-

ent [20]. Commercially available shunts, used for carotid surgery (Fig. 24.6), can be utilized; however, they also can be constructed from simple iv line or endotracheal suctioning tubing. The shunt is secured from dislodging with a simple tie of any kind, but also sophisticated clamps can be used when available.

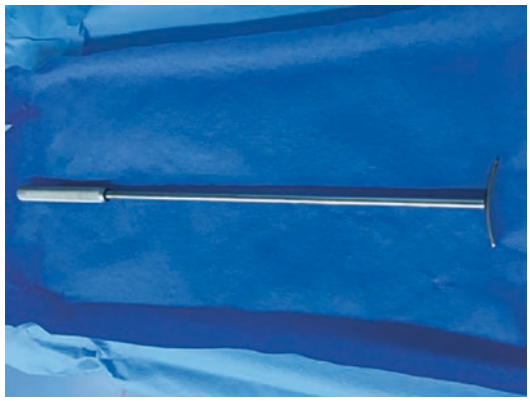

**Fig. 24.5** Aortic occluder (Stamper)

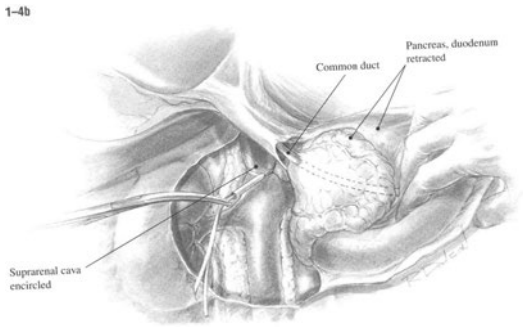


**Fig. 24.6** Tourniquets, vessel loop with tubing

Shunts can be left in place for a considerable amount of time without major drawbacks. The use of anticoagulants is not advised as most patients are coagulopathic anyhow and have other, potentially bleeding, injuries. The patency of the shunts depends on the physiological situation, local circumstances, and time of the distal ischemia. Shunts give the opportunity of quick revascularization of the organ or limb, minimizing the acidotic load to the patient and minimizing the reperfusion reaction. The skin can be closed over the shunt (Fig. 24.7) temporarily, where after other injuries can be addressed and/or the patient can be further resuscitated in the ICU. Repair of the vessel can be attempted when the patient is in a more favorable condition and an optimal plan for repair with the optimal operation team can be worked out. In case of a concomitant orthopedic injury, vascular repair can ensue the repair of the fracture [21] (Fig. 24.7).

#### 24.3.3.2 Lateral Repair

Simple lateral repair, in suitable cases, is preferable as a quick and effective measure. Lesions of larger truncal or extremity vessels can benefit from this technique. The lesion has to be clean and no devitalization of the vessel wall should be present. Also frayed ends or complete transaction are a contraindication to lateral repair. Major disadvantage is the high chance to create a stenosis, even with larger vessels like the aorta or vena

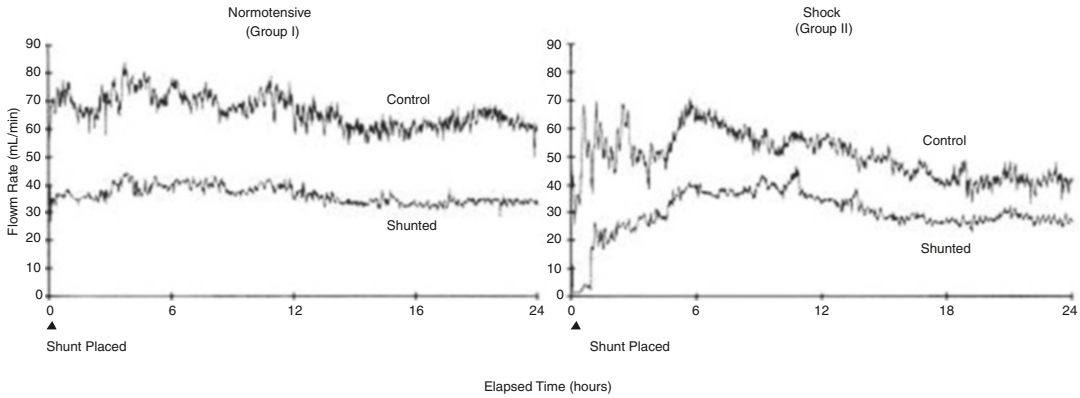


**Fig. 24.7** Animal lab shunts illustration article

cava. If possible, the repair should be transverse, even in the case of a length tear. Revision of the repair at a second instance is advised and where needed revision before thrombosis is apparent.

#### 24.3.3.3 Stents

With the increased availability of intraluminal stents, the use in selected cases has picked up. For numerous indications, stents can be used, with the major advantage of reducing the operative trauma. Of course, in the case of bleeding covered stents should be used. Main indication for stenting is the thoracic aorta, but also in other regions it has become the method of choice for vascular repair. Upper thoracic aperture vessels, axillary, but also iliac vessel injuries can be treated in this way in a damage control fashion. There is considerable debate whether these stent procedures should be regarded as bridge procedures, with removal of the stent and direct repair in a later phase. As most patients are young and the natural course of these stents is still unknown, there is a tendency to the latter.

#### 24.3.3.4 Complex Repairs and Grafts

In the context of damage control surgery complex repairs and the use of extended repair and the use of grafts is a bad choice. The lengthy operations needed are ill advised in a cold coagulopathic patient, whereas the quality of the repair in many cases is not optimal because of the time pressure the surgeon is confronted with.

### 24.3.4 Definitive Occlusion

#### 24.3.4.1 Ligation

The simplest method for regaining bleeding control is clamping and ligation of the bleeder. In a large range of bleeding problems, this remains a very attractive measure; however every named artery has its own rules if a simple tie is tolerated. Care has to be taken in the procedure of clamping. Wild undirected clamping in a pool of blood results in more damage and vulnerable structures like veins are the first to be severed. Moreover, the venous structures are most difficult to repair. Controlling inflow and outflow at some distance in an untouched area can be of great help to gain overview. For this, a vessel loop passed twice around a vessel and held in place with a clip, clamp, or tubing (Fig. 24.4) can be used.

#### 24.3.4.2 Coiling

A modern way of occlusion of the bleeding vessel is coiling through the intravascular route. Although a hemodynamic unstable patient in the angio suite is a bad combination, the disadvantages of additional operative trauma may lead to this approach. Moreover in a modern combined operation-angio suite, which should be state of the art in a level 1 trauma center, the best of these two worlds can be combined and a versatile approach to vascular trauma can be utilized. Of course, the nature of the bleeding must be arterial.

#### 24.3.4.3 Hemostatic Agents and Glues

In the case of severe bleeding and devastating wounds, sorting out the exact bleeding focus can be very demanding. As most of these patients are already coagulopathic, everything bleeds and discriminating between the structures is mostly not possible. Mainly for the use outside, the hospital hemostatic agents have been developed, which stops the bleeding immediately. These mineral hemostatic agents mainly draw water from the surroundings in an exothermic process developing temperatures up to 55 °C. In a comparative analysis in an animal model of lethal groin injury, the efficacy of zeolite was compared to classic dressings and other commercially available hemostatic agents. The results were astonishing where zeolite reduced blood loss 4–180 min after application to 10 mL/kg body weight and no deaths, however at the cost of high exothermic reaction with temperatures up to 55 °C [22] (Fig. 24.8). This could be attenuated by modification of the zeolite hemostatic dressing [23].

Another adjunct to damage control in vascular lesions is the use of fibrin sealant. Kheirabadi et al. [24] evaluated the use of fibrin sealant dressing in a high-pressure vascular lesion animal model and concluded that fibrin sealant can seal an arterial bleeding and prevent rebleeding for at least 7 days. It therefore can

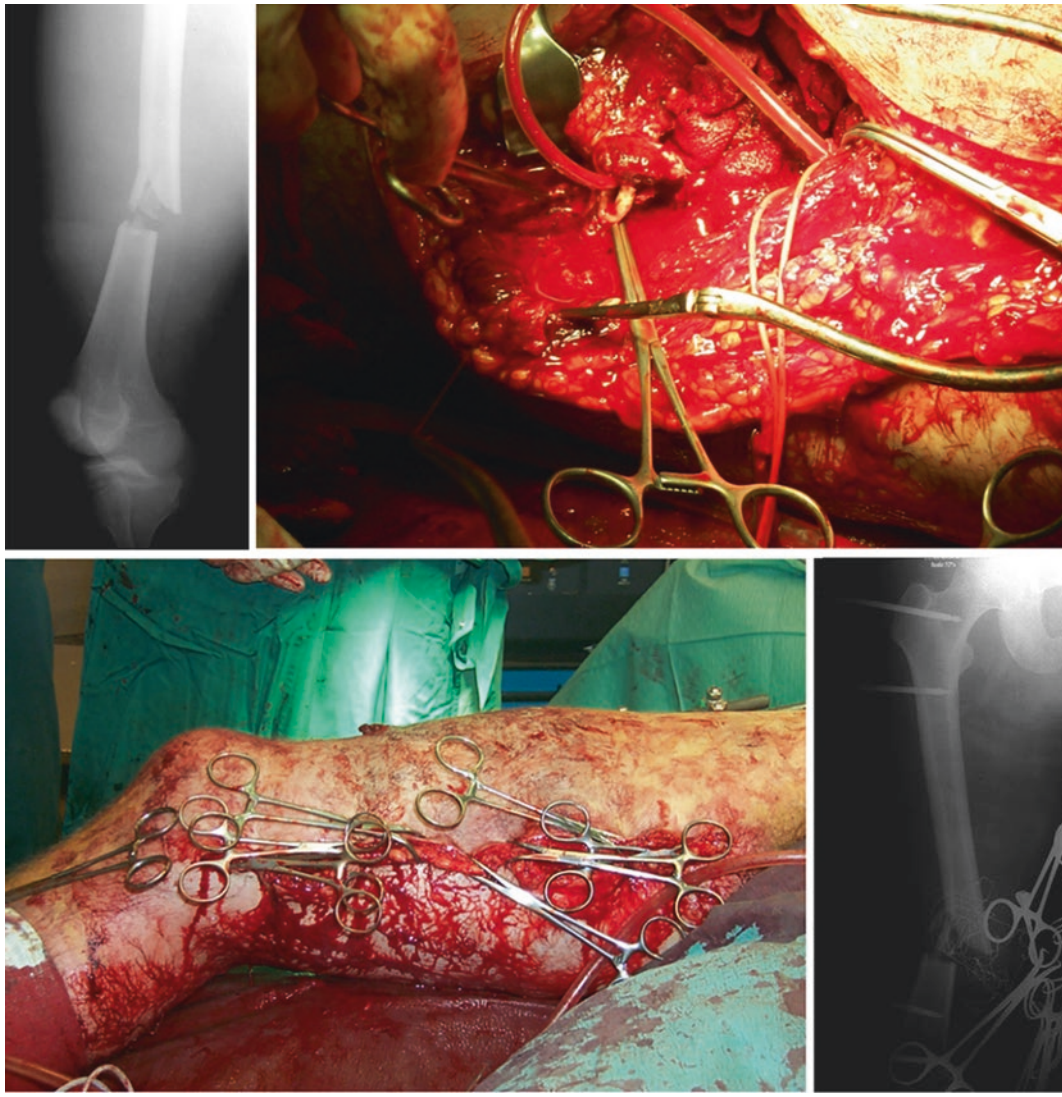

**Fig. 24.8** Shunt

be used as a bridging procedure for subsequent stenting or open repair procedures.

#### 24.3.4.4 Amputation

A very definitive way of dealing with a major bleeding problem can be amputation. In the case of a mangled extremity, with multiple injuries and severe hemorrhage it is wise to go for an amputation in order to save the patient. This team decision should be made early and expeditiously to gain time and prevent needless blood loss and additional shedding of waste products into the circulation. The preferred technique is a guillotine amputation, with compressive dressing afterwards, to prevent a lengthy procedure of modeling and flap creation. The guillotine amputation offers also the opportunity to have a second look and to judge whether the remaining tissues are viable and suitable for the creation of an adequate amputation stump.

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# 25 Compartment Syndrome: Pathophysiology, Diagnosis, and Treatment

Joseph Borrelli Jr. and David Donohue

## 25.1 Introduction

Traditional teaching is that an acute compartment syndrome (ACS) occurs when increased tissue pressure (commonly referred to as intra-compartment pressure) occurs within a fascial compartment, compromises local circulation, which inhibits neuromuscular function and threatens muscle and nerve viability [1–4]. Circulatory patency is what maintains normal tissue function including that of the nerves and muscles. Functional abnormality of the nerves and muscles within the affected compartment results from ischemia during the development of an ACS. Generally, blunt force trauma to an area of the body results in swelling, tissue damage, inflammation, and local ischemia, which lead to patchy oxygen metabolism deficiencies which can lead to an accelerated cycle resulting in increased intra-compartment pressures [5]. Hargens et al. found normal tissue capillary pressure to be between 20 and 33 mmHg, while others have found that normal interstitial fluid pressure to be around 10 mmHg in adults [6]. Intra-compartment pressures above these pressures are sufficient to compromise blood flow within the muscle compartment and cause ischemia and possibly the development of an ACS (Fig. 25.1).

Several investigators have proposed different mechanisms for the development of an ACS. Ashton H early on observed active closure of small arterioles occurring when transmural pressure is lowered either by decreased intravascular pressure or a rise in the surrounding tissue pressure, and passive collapse of soft walled capillaries when tissue pressures rise above intracapillary pressure. Ashton felt that these potential mechanisms could be involved in the development of ACS particularly when the involved tissues are surrounded by non-compliant fascia [7]. Gelberman et al. demonstrated in dogs that progressively higher applied external pressures lead to decreased blood flow to compartments casted and that the blood flow ceased before the difference between mean arterial and applied pressure became zero [8]. Pittman R demonstrated that tension in the walls of arterioles is actively produced by smooth muscle contraction. If tissue pressure is elevated enough, transmural pressure may exceed the arterioles ability to remain open and blood flow is compromised [9].

Additional investigators have offered the concept that increases in tissue pressure are responsible for the reduction in the local arteriovenous gradient and thereby local blood flow. When the metabolic demands of the tissue are insufficiently met by reduced blood flow from increased pressure, an ACS can result. This theory does not

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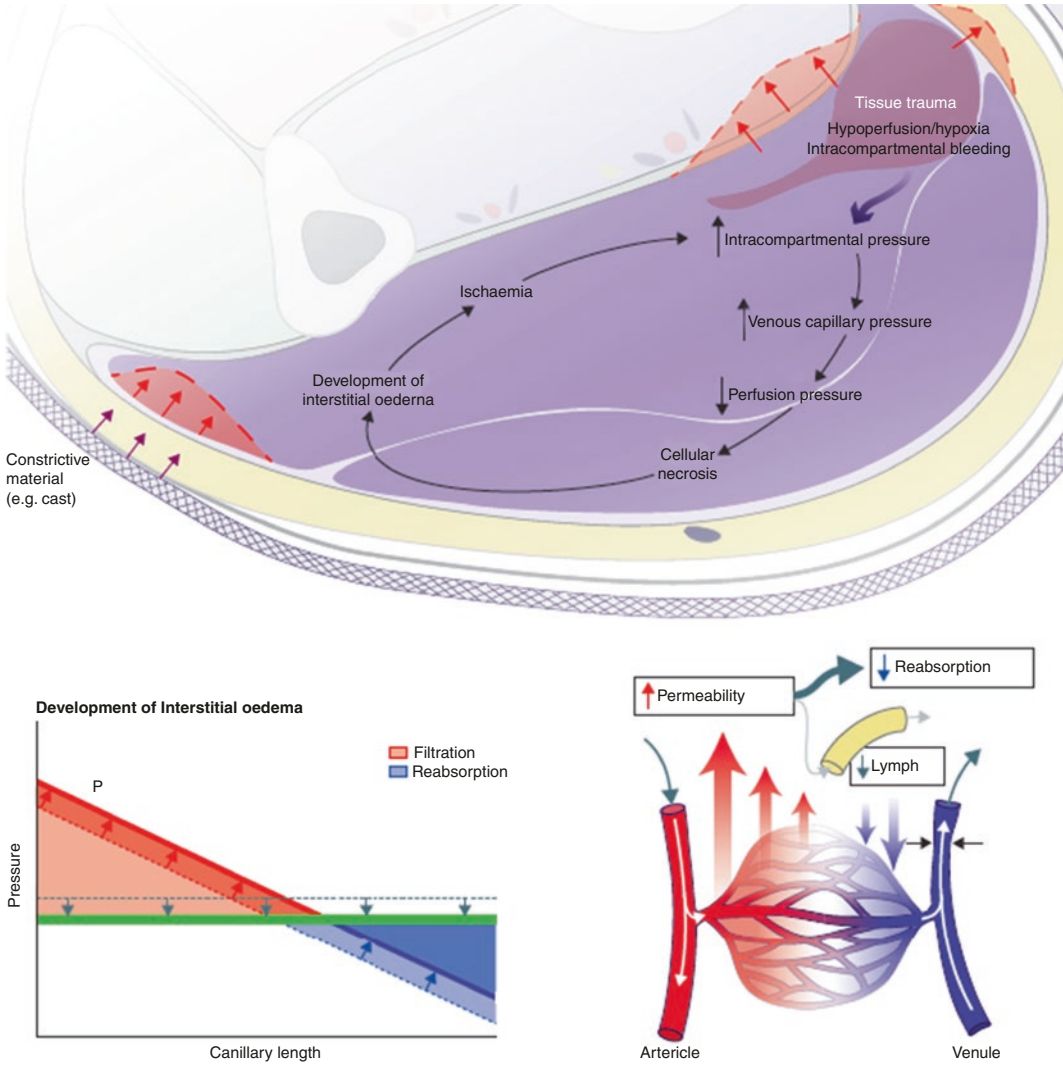


**Fig. 25.1** Pathophysiology of acute extremity compartment syndrome

$\Delta P$ = hydrostatic pressure, defined by the difference of the capillary pressure—the interstitial pressure. $\Delta\pi$ = colloid osmotic pressure

(Reproduced with permission from von Keudell AG, Weaver MJ, Appleton PT, et al. Diagnosis and treatment of acute extremity compartment syndrome. Lancet 2015 Sep 26;386(10000):1299–1310. doi: 10.1016/S0140-6736(15)00277-9.)

dictate a zero-flow scenario and more likely reflects the clinical scenario. Each of these factors that changes the metabolism of the traumatized tissues when combined with anatomic limitations in the blood supply, muscle fascial covering, and altered physiology result in ACS. Without a doubt, as pressure increases within a or multiple compartments or localized area is the best understood mechanism for this as the pathological event known as a ACS. Increased tissue pressure that follows causes compromise to the local circulation. Regardless of the methods by which these elevated pressures are measured, all have consistently showed that abnormally high tissue pressures are present in ACS [1, 3–6, 10–15]. These elevated tissue pressures negatively affect the ability of the local circulation to deliver oxygen to the tissues. Because of a multitude of physiological factors, no exact tissue pressure has been observed as the defini-

tive tipping point beyond which an ACS is absolutely likely to develop. In fact, certain studies have shown compromised blood flow and oxygen delivery at interstitial pressures of 20 mmHg. Most investigators believe that the physiological changes that occur within the muscles and nerves are directly pressure related. To look at the response of nerve and muscle to the intracompartmental pressure, Sheridan et al. inflated a latex balloon in a muscle compartment of a rabbit and found that the Po2 declined with increasing intra-compartmental pressure from a control value of 10.8 mmHg to a minimum of 2.8 mmHg at a pressure of 90 mmHg. The incidence of functional losses increased with increasing pressures and durations of pressure application. All animals subjected to 100 mmHg for eight or more hours lost both nerve and muscle function. These investigations demonstrate that increased intra-compartmental pressure alone, without other associated vascular injury, may produce muscle hypoxia and loss of neuromuscular function [16]. In these studies the integrity of the peroneal nerve and the leg muscles was tested by direct electrical stimulation. Higher pressures and longer periods of pressure application produced more functional losses. In the end, the authors felt that the pressure alone was a sufficient explanation for all changes seen in an ACS. Rorabeck et al. and Hargens et al. showed that nerve conduction velocities were slowed by the pressurized infusion of the anterior leg compartment of dogs [17]. In general, increased tissue pressure as low as 20 mmHg affected tissue blood flow, and tissue circulation decreased as the applied pressure was raised. Vollmar et al. were interested in the microvascular response to similar external pressure elevation seen in an ACS [18]. They used a skinfold model that was not an exact substitute for a compartment but illustrated a relevant physiological change in tissue flow. They studied the response of the different segments of the microcirculation in terms of vasomotor control (change of vessel diameter) and cessation of blood flow with progressive changes in external tissue pressure. The investigators felt that the study disproved the critical closing theory but supported the hypothesis of reduced arteriovenous pressure gradients as for an ACS. They found that there was an increased perfusion pressure gradient needed in order to restart blood flow in small vessels. It was seen as a confirmation of the existence of so-called yield stress in micro-vessels. The high susceptibility of capillaries to elevated external pressure indicated to these investigators that there was a need for early fasciotomy to restore impaired circulation. Lack of effective circulation is the factor that perpetuates further physiological changes and propagates the development of an ACS. Several investigators have shown that the amount of pressure the muscles can tolerate before deficits are produced is also altered by local blood flow changes with examples being limb elevation, arterial occlusion, hypotension, or hemorrhage [15]. Dilation in the arteriole system caused by injury, along with collapsing smaller vessels with increased permeability, leads to increased fluid extravasation and raised interstitial fluid pressure. As the interstitial pressure increases, perfusion to tissue decreases. Once tissue perfusion decreases to a certain level, tissue hypoxemia results. The combination of hypoxia, increase in oxidant stress of the muscle and nerve cells within the compartment, and the development of hypoglycemia in the compartment causes cells to swell due to a shutdown of the ATPase channels that maintain cellular osmotic balance [9]. Early ACS microvascular dysfunction results in a decrease in capillary perfusion and an increase in cellular injury. The loss of cell membrane potential results in an influx of chloride ions, leading to cellular swelling and ongoing cellular necrosis. The increase in tissue swelling worsens the hypoxic state and creates an ongoing feedback loop that furthers muscle and nerve necrosis. As the cascade of elevated pressure then compromises the microcirculation with decreased oxygen and nutrient delivery, tissue anoxia with eventual myonecrosis then proceeds. In some cases, systemic changes have been reported including those within the liver and kidney, which when severe, have been associated with multiorgan system failure and even death [19].

## 25.2 Diagnosis

The devastating effects of an undiagnosed or neglected compartment syndrome have been recognized for quite some time. In fact, the earliest published report of such was by Richard von Volkmann in 1881 [20]. In this case, von Volkmann described the presence of myonecrosis and contracture in the arm of a child due to prolonged muscle ischemia. Compartment syndromes have been known to occur in all age groups from infants to the very old, as well as in each gender, race, and ethnicity. Young active individuals, who are most likely to sustain high-energy trauma, are most commonly associated with the development of a compartment syndrome, however no one is immune to the development of this potentially devastating condition.

ACS have been associated with a variety of scenarios which lead to a compromise in the blood flow within the fascial compartment(s). ACS are most commonly associated with a traumatic injury (with or without a fracture), however, they have been known to develop as a result of significant swelling or bleeding into a fascial compartment(s), or from substantial external pressure (e.g., circumferential burns, casts, wraps) of a limb, particularly in the setting of limb swelling following injury or surgery. Additionally, ACS have been shown to result from the development of a space occupying mass within a fascial compartment. This type of situation has been seen when a compartment is accidentally infused with intravenous fluids, particularly cytotoxic solutions such as chemotherapy agents, the development of a soft tissue abscesses, spontaneous bleeding, particularly in patients taking anticoagulants. Once an ACS has developed, it is important to remember that "time is tissue," and that the sooner the compartment pressures are normalized the better the chance there is of limiting tissue damage, and therefore the better chance of preserving limb function.

## 25.3 History and Physical Examination

While assessing a patient for the presence of an ACS, it is essential to understand the circumstances by which the limb(s) may have been put into jeopardy. It is important to understand the timing of the insult as well as the relationship between the time of the "insult" and symptoms of an ACS developing. Fully understanding the nature of the insult, it will help the clinician gauge whether the development of an ACS is likely or not. Although ACS have been known to develop under unusual circumstances, there are many more common scenarios. In either case, everyone caring for patients must remain vigilant about the possibility that an ACS is developing or has developed. Also, understanding the mechanism and location of the insult or injury will also help determine the compartment(s) that are most at risk and the most likely symptomatology to be expected. In adults, the most common cause of a compartment syndrome is trauma, and in particular, trauma causing a long bone fracture, whether the fracture be open or closed. However, physicians and all who are caring for traumatized patients must remain vigilant as to the possibility of a compartment syndrome developing even in the absence of direct trauma.

A variety of signs and symptoms have been associated with an ACS. These signs and symptoms often present in a variety of combinations making definitive diagnosis difficult and quite challenging at times [1]. Generally, the first symptom that bring most patients to the attention of a health care worker is pain. Understanding that pain is subjective and its perception varies from person to person, pain associated with an ACS is generally "out of proportion" to the insult or injury. Additionally, there is an increase in pain with palpation in the vicinity of the insult or injury. This pain is generally also associated with a palpable firmness or tightness of the compartment(s) of concern. Two signs that create even more concern regarding the presence of an

ACS are "pain with passive stretch" of the muscles traversing the muscle compartment(s) of concern, and the development of paresthesia involving the distribution of the superficial sensory nerves passing through the compartment(s) of concern. Poikilothermia, or a body part that loses its ability to regulate its temperature, generally results in a coolness of the extremity in question when compared to other body parts, poikilothermia is a common finding in the setting of an advancing ACS. Pallor, paralysis, and pulselessness are late signs that an ACS has developed and often indicates that irreversible muscle and nerve damage may have already occurred. One should certainly not wait for the development of pallor, paralysis, or pulselessness to develop before definitively diagnosing an ACS and initiating treatment (fasciotomies).

Each of the above findings individually does not necessarily confirm the presence of a compartment syndrome, but the absence of these signs suggests that an ACS is not present. In fact, at least one study has shown that as the number of positive physical findings increases, the likelihood that a compartment syndrome is present also increases [21].

Most compartment syndromes are diagnosed and subsequently treated based upon the findings of serial clinical examinations, in awake and alert patients. In obtunded, uncooperative, multiple injured patients or those under the influence of alcohol or drugs, intra-compartmental pressure determinations may be necessary to diagnosis the presence of an ACS. Historically, a variety of pressure measuring devices have been used in conjunction with physical examinations for the diagnosis of an ACS. These devices utilize a combination of catheters, tubing, and nanometers linked to measure intra-compartmental pressures. A commercially available stick catheter (Stryker Surgical, Kalamazoo, MI) has been available for quite some time and is commonly used to augment clinical findings and to facilitate the diagnosis of an ACS particularly in obtunded, intubated, unconscious, or uncooperative patients. This device allows a quick and simple means to accurately measure intra-compartmental pressures and has proven to be quite reliable.

Indwelling pressure monitoring catheters have also been developed to measure intra-compartmental pressures in real-time. These devices allow minute to minute monitoring of intra-compartmental pressures and when compared with changes in a patient's systemic blood pressure can facilitate the diagnosis of an ACS at its onset [22–25].

Newer means of determining the presence of an ACS are being investigated. These "higher tech" devices are designed to be less invasive and improve our abilities to diagnosis an ACS earlier before irreversible muscle and nerve damage has occurred. These newer methods, which have not been validated for clinical use at this time, include near-infrared spectrometry (NIRM), measurement of intramuscular glucose and oxygen tension levels, and monitors to detect changes in muscle microvascular blood flow, oxygenation, pH, and perfusion pressure [26–29].

## 25.4 Interpretation of Intra-compartmental Pressures

Currently, intra-compartmental pressure measurements are most often used to confirm clinical suspicion (based upon physical findings) or to make the diagnosis of an ACS in an unconscious patient. The normal interstitial pressures, within an atraumatic muscle compartment are generally between 0 and 8 mmHg. The measured intra-compartmental pressure has been used in a variety of ways particularly if the clinician is uncertainty as to the presence of an ACS. In the past an absolute value has been used to confirm or refute the presence of an ACS. A measurement of 30 mmHg or greater, measured within 5 cm of the fractured or injured area, has previously been used to make the diagnosis of an ACS. Unfortunately, because of the wide variation in patient's blood pressures and other factors, the use of an absolute threshold value was found to result in a relatively high rate of false positives and lead to unnecessary fasciotomies.

The measured intra-compartment pressure (ICP) has also been directly compared to the patient's diastolic pressure at the time of the mea-

surement, and when the measured ICP rose to within 10–30 mmHg of the patient's diastolic blood pressure clinicians hypothesized that an ACS existed. The rationale was that as the ICP increased there was an inadequate perfusion of the local tissues and ischemia of the involved compartment developed which could lead to the development of an ACS.

More recently, in an effort to minimize the number of unnecessary fasciotomies while not missing any ACS, clinicians have begun to use the *delta* pressure to confirm or refute the presence of an ACS. The *delta* pressure = diastolic pressure—the measured intra-compartmental pressure, a *delta* pressure of less than or equal to 30 mmHg is often used to confirm the presence of an ACS and the need for fasciotomy [5, 6, 11, 12, 30, 31].

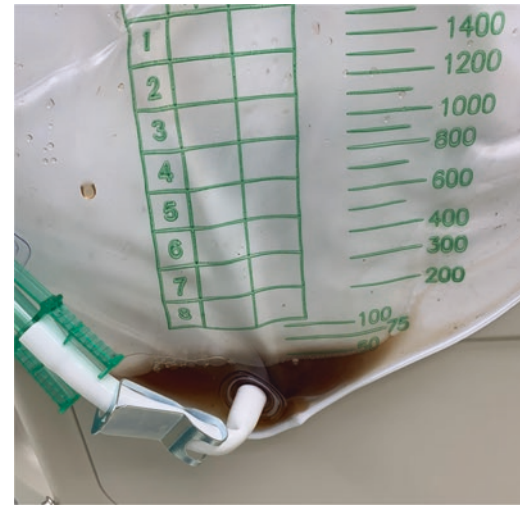


**Fig. 25.2** "Tea colored" urine from a patient suffering an ACS of his gluteus maximus and medius, thigh and the anterior and lateral compartments of his leg

## 25.5 Laboratory Measures

Patients who exhibit the signs and symptoms consistent with an ACS do not necessarily require additional laboratory investigation to confirm. In fact, ordering laboratory analyses and advanced imaging when the diagnosis of an ACS has been made is likely to delay definitive treatment and potentially leads to additional muscle and nerve injury. Laboratory studies are neither necessary to diagnose an ACS nor helpful in ruling out the presence of an ACS. However, in the presence of an ACS, particularly in those patients in which it is difficult to determine the moment of the insult or injury or the onset of symptoms, laboratory evaluation to assess the extent of the accompanying rhabdomyolysis may be indicated. In these situations, determining serum creatinine phosphokinase (CPK), renal function (BUN, creatinine), urine analysis (for the presence of myoglobin Fig. 25.2), may be helpful to assess the presence of ongoing muscle necrosis and its effect on renal function and they may be helpful to assess the adequacy of the fasciotomies, hydration, and alkalinization of the patient. A serum CPK level of ≥1000 U/ml and the presence of myoglobinuria strongly support the diagnosis of an ACS, and these findings require systemic treatment to prevent renal compromise and systemic acidosis. Serial CPK measurements when elevated are particularly helpful to monitor the response to treatment (fasciotomy) as rising serum CPK levels are indicative of ongoing muscle necrosis.

### 25.5.1 Treatment: Upper Extremity—Arm

Complete compartment releases via fasciotomy is the standard of care for treatment of an ACS to prevent muscle necrosis and neurologic compromise. Failure to decompress the involved compartments in a timely fashion will eventually lead to irreversible muscle necrosis and nerve injury and ultimately contracture of the affected muscles often rendering the extremity functionless. An ACS is a feared orthopedic complication and is a common cause for permanent functional damage, limb loss, and costly litigation in orthopedic surgery [32, 33].

### 25.5.2 Fasciotomies: Authors Preferred Technique

In the arm (brachium) there are three compartments: the volar (anterior) compartment which contains the biceps (short and long heads), the brachialis m., and coracobrachialis m. The anterior compartment of the brachium is typically decompressed through a long extensile incision either in the midline or the anterolateral lateral aspect of the arm ending proximal to the flexor crease. This incision must be long enough to allow complete fasciotomies of each of these three muscles.

Fasciotomies of the arm for the treatment of an ACS involving the three heads of the triceps m generally include a long posterior midline incision and then fasciotomies to decompress each muscle belly. Care must be taken to avoid injury of the radial nerve, profundi brachial artery and vein when developing the interval between the lateral and long heads of the triceps to reach the medial head. Anteriorly, the incision is also made in the midline stopping short of the flexor crease.

### 25.5.3 Treatment: Upper Extremity—Forearm

The forearm is the second most common site for the development of an ACS. When taken into consideration that the forearm and hand are critical for prehension and grasp, the functional loss due to an ACS potentially devastating. ACS of the upper extremities shares common etiologies for ACS seen in areas of the body. That is either the external reduction of compartment volume by pressure from circumferential cast, splint or dressings, or burns, or an increase in compartment contents as with bleeding, abscess formation, fracture displacement/bleeding/edema, soft tissue edema, microvascular basement membrane damage from ischemia/reperfusion, burn injury, and envenomation. Several additional etiologies are pertinent to the upper extremities, these include iatrogenic extravasations of intravenous fluids and complications from upper extremity arterial catheterizations and from wayward self-administration of illicit drugs, and electrocutions [34–36].

The forearm has three well defined compartments: lateral compartment includes the "mobile wad" (i.e., brachioradialis m. (BR), extensor carpi radialis brevis m. (ECRB), and the extensor carpi radialis longus m. (ECRL); the dorsal extensor compartment includes the extensor digiti minimi m. (EDM), extensor carpi ulnaris m. (ECU), abductor pollicis longus m. (APL), extensor pollicis brevis m. (EPB), extensor pollicis longus m. (EPL), and the extensor indicis m. (EI); and the volar compartment includes the pronator teres m., flexor carpi radialis longus m., palmaris longus m., the flexor carpi ulnaris m., and the flexor digitorum superficialis m. During the treatment of a forearm ACS, care must be taken to assure thorough decompress each muscle belly including those of superficial and deep compartments. This includes the investing fascia of individual fascial compartments of the deep flexor muscles (PQ, FDP, FPL). Proximally, the lacertus fibrosus must also be released as a possible site of compression as well as the carpal tunnel distally.

The dorsal extensor compartment is approached through a dorsal midline straight incision—the mobile wad can usually be released via either the volar or dorsal approaches. While the standard extended Henry approach is generally sufficient, a Brunner style zigzag approach with extension into the carpal tunnel and antecubital fossa can also be used. By creating flaps which maximize a radial-based forearm flap and ulnar to radial dissection across the flexor crease of the wrist will optimize median nerve coverage, as well as preserve the option for later radial artery-based flap coverage for complex soft tissue defects of the hand. When performing fasciotomies of the forearm, special emphasis must be placed on decompressing the muscles of the deep flexor compartment due to their nonredundant blood supply which makes them especially prone to ischemic damage [37].

### 25.5.4 Fasciotomies: Authors Preferred Technique

There are three compartments in the forearm, the volar (superficial and deep), dorsal, and mobile wad of Henry (lateral) compartment, must each be completely decompressed when an ACS of the forearm is diagnosed. The typical volar incision begins 1 cm proximal and 2 cm lateral to the medial epicondyle and passes obliquely across the antecubital fossa and over the volar aspect of the mobile wad. The incision is carried down along the ulnar aspect of the forearm curving radially as it approaches the junction of the middle and distal thirds of the forearm. The incision is then continued just medial to the palmaris longus tendon to avoid the palmar cutaneous branch of the median nerve. The incision should cross the wrist crease at an angle and extend into the mid-palm to allow for a release of the carpal tunnel. The lacertus fibrosus proximally and the fascia overlying the flexor carpi ulnaris m. are released, the flexor carpi ulnaris m. is then retracted ulnarly and the flexor digitorum superficialis m. is retracted radially to permit opening of the fascia of the deep volar compartment. Care must be taken to avoid injury of the ulnar nerve and artery. For release of the dorsal compartment, a dorsal longitudinal incision is made (essentially a Henry approach to the dorsal forearm) beginning 2 cm distal to the lateral epicondyle and coursing toward the midline of the wrist. Once through the subcutaneous fat and fascia the interval of extensor digitorum communis m. and extensor carpi radialis brevis m. is developed. After decompression, the muscles of the forearm should be palpated to assure complete decompression. Assessment of muscle viability includes the assessment of the color of the muscle fibers, their response to mechanical stimulation and their bleeding when cut. If the muscle bellies are completely decompressed and the muscle is contractile and bleeds when cut, no further action is necessary [35].

## 25.6 ACS of the Hand

There are felt to be eleven separate compartments within the hand, with some slight variations. ACS of the hand commonly arise from crush injuries (exploded hand syndrome), high-energy fractures and dislocations, as well as intravenous extravasations and infection. There are four dorsal interossei compartments, three volar interossei compartments, a thenar compartment, a hypothenar compartment, and adductor compartment and the mid-palm compartment.

### 25.6.1 Fasciotomies: Authors Preferred Technique

The eleven compartments of the hand can generally be released, and each compartment decompressed with two longitudinal incisions, one over the second and one over the fourth metacarpals, these incisions are used to decompress volar/dorsal interossei and adductor compartment, a longitudinal incision along the radial side of the first metatarsal for decompression of the thenar compartment, a longitudinal incision over the ulnar side of the fifth metacarpal, decompression of the hypothenar compartment.

## 25.7 Treatment: Lower Extremity

### 25.7.1 ACS of the Gluteal Compartment

ACS of the gluteal compartments are uncommon and typically occur in individuals with altered mental status due to drugs or alcohol who have remained in a recumbent position for an extended period of time. Prolonged recumbency on a firm surface and cause muscle compression which can lead to excessive muscle edema and ischemia, which can facilitate the development of an ACS of the gluteal compartments. ACS of the gluteal muscles has also been reported after high-energy

pelvic trauma (with or without fractures or dislocations), or from vascular injury often resulting from penetrating trauma or spontaneous bleeding or vascular rupture. As with all ACS, complete fasciotomy of the gluteal musculature (gluteus maximus, medius, and minimus), as well as the tensor fascia latae, prior to the development of irreversible muscle and nerve damage, is ideal. In all cases where muscle necrosis and nerve damage are ongoing "time to fasciotomy is established to be a key factor in predicting patient outcome." Because ACS of the gluteal muscles are uncommon, they often go undiagnosed and can result in marked rhabdomyolysis, renal failure, multiple-organ failure, and even possibly death. The anatomic constraints of the muscle compartments do not accommodate excessive swelling and edema well and increased compartment pressures with the resultant decreased blood flow can result in significant muscle loss, nerve function compromise, amputation, and poor functional outcomes [38–42].

### 25.7.2 Fasciotomies: Authors Preferred Technique

The presence of an ACxS involving the gluteal muscle is relatively uncommon but must be considered in those patients with crush injuries of the pelvis and trunk, with or without pelvic fractures or dislocations and the occasional obtunded patient who has been "found down" for an unknown period. ACS of the buttock/gluteal muscles generally presents with firmness, swelling, pain to palpation, and pain with hip flexion, in the hip and gluteal area. The incision made in the setting of an ACS of the buttock must be sufficient in length to allow complete decompression of the gluteal maximus, medius, and minimus as well as the tensor fasciae latae. Ideally the incision is placed lateral enough to allow dressing changes without the need for significant movement of these often severely traumatized patients.

## 25.8 ACS of the Thigh

ACS involving the thigh are typically the result of high-energy blunt trauma with or without an accompanying femur fracture, ischemia-reperfusion injuries, or bleeding from a vascular injury (often the result of penetrating trauma), and spontaneous bleeding with or without the presence of a coagulopathy, into the muscular compartments. Once an ACS of the thigh has been diagnosed, immediate and complete compartment releases are required. There are three recognized muscular compartments within the thigh: the anterior compartment, which contains the quadriceps, the sartorius as well as the femoral nerve, the posterior compartment, which contains the hamstrings and the sciatic nerve, and the adductor compartment which contains the hip adductors as well as the obturator nerve (Fig. 25.3). Each of these muscle compartments is enveloped by a strong, well defined fascia [43–47].

### 25.8.1 Fasciotomies: Authors Preferred Technique

Generally, two long incisions are sufficient to decompress each of the muscle compartments within the thigh. One of the incisions is generally placed along the anterolateral aspect of length of the thigh. Below the subcutaneous fat, the tensor fascia latae proximally and the iliotibial band distally is found and incised. Through this incision, the 4 muscle bellies of the quadriceps can be decompressed. The vastus lateralis can be elevated off the lateral intermuscular septum and incising this thick fibrosis sheet allows decompression of the posterior compartment of the thigh. Care must be taken to avoid disrupting the perforating vessels that pass from posterior to anterior around the lateral aspect of the femoral shaft, in an effort to avoid additional blood loss and further bleeding into the thigh compartments. To decompress the medial "adductor" compart-

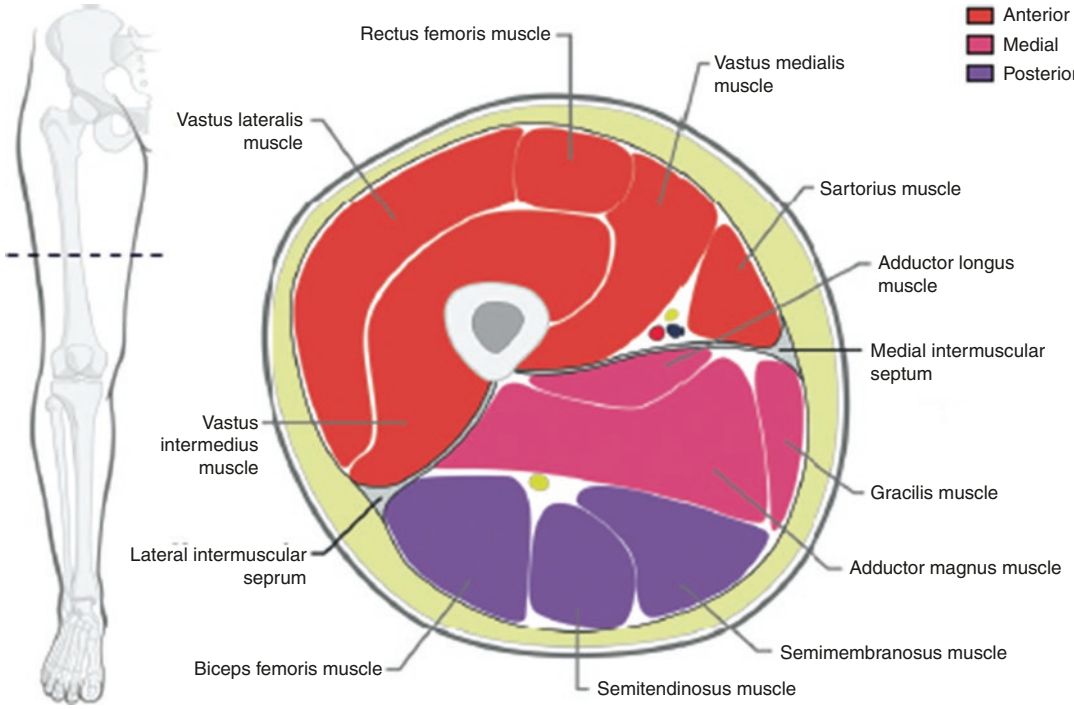


**Fig. 25.3** Cross sectional anatomy of the thigh (Reproduced with permission from von Keudell AG, Weaver MJ, Appleton PT, et al. Diagnosis and treatment of acute extremity compartment syndrome. Lancet 2015 Sep 26;386(10000):1299–1310. doi: 10.1016/S0140-6736(15)00277-9.)

ment of the thigh a second incision is made medially, care should be taken to avoid the saphenous vein superficially and entering the adductor canal and injuring its contents deep within the medial compartment.

## 25.9 ACS of the Leg

The mechanism of injury for the development of an ACS of the leg varies considerably, and its development has been found to occur after low-energy, as well as high-energy trauma, equally. McQueen et al. reported that routine traffic accidents (involving both vehicle vs vehicle and vehicle vs pedestrian) were the most common causes of acute compartment syndrome, followed by sport-related injuries. Other common causes of an ACS of the leg include crushing injuries, falls, direct blows, burns, and penetrating injuries [48–50]. Important to note ACS have been associated with fracture and nonfracture injuries. In fact, Blick et al. found a higher incidence of ACS in open tibia fracture as compared to closed tibia fractures, presumably as a reflection of the amount of energy experienced to have caused the fracture [51]. As in other areas of the body circumferential dressings and casts which restrict compartment expansion and decrease venous flow have also been associated with the development of an ACS of the leg [52, 53].

Previously investigations have indicated a difference in the age and sex distributions of those patients who develop ACS of the leg. These data indicate that men in their thirties ("typical" trauma patient is between the ages of 18 and 45 years) have the highest likelihood of developing an ACS, which may be explained by the relatively larger muscle mass in men within strong enveloping fascia. McQueen et al. reported that the average annual incidence of compartment syndrome for women was 0.7 per 100,000 (mean age of 44 years), while for men the annual incidence was 7.3 per 100,000 (mean age of 32 years) [49]. Fractures are the

major contributing factor for presentation in approximately 75% of patients with an ACS of the leg [49, 50, 54, 55]. The most common fracture is tibial diaphyseal fractures, but ACS have been reported in patients with a wide variety of tibial fractures including low-energy fractures of the tibial plateau, as well as the tibial plafond fractures. Leg ACS have been reported in 2–9% of all tibial fractures [50, 51, 55]. Hope et al. reported the first series of patients to develop ACS in the absence of a fracture, excluding those with a crush syndrome. They showed that these patients were typically older, had a greater number of comorbidities, and have an increased chance of delay to fasciotomy, leading to increased muscle necrosis at the time of fasciotomy. These investigators cited the low awareness for the risk of ACS in the presence of isolated soft tissue injury. In this investigation the posterior compartment was found to be most commonly involved in ACS without a fracture [56].

There are four well defined and well recognized compartments within the leg. The anterior compartment which is situated just lateral to the tibial crest and anterior to the fibula contains the extensor hallucis longus m., extensor digitorum communis m., tibialis anterior m., and the peroneus tertius m. The deep peroneal nerve and the anterior tibial artery also lie within the anterior compartment. In the typical high energy tibia fracture patient the anterior compartment of the leg is the most commonly associated with an ACS. The lateral compartment contains the peroneus brevis and longus muscles and is localized along the lateral aspect of the leg and confined anteriorly by the anterior intermuscular septum (AIS) and posteriorly by the posterior intermuscular septum (PIS). The lateral compartment also contains the superficial peroneal nerve, and the proximal portion of the compartment also contains a portion of the deep peroneal nerve before it passes into the anterior compartment. The peroneal artery, a branch of the popliteal artery also resides within the lateral compartment. The lateral compartment is also commonly asscoiated with an ACS in trauma patients. The posterior compartment is organized into superficial and deep posterior compartments. The superficial compartment contains the gastrocnemius m., soleus m., and the plantaris m it also contains the sural nerve. The deep posterior compartment contains the tibialis posterior m., flexor hallucis longus m., the flexor digitorum longus m., and the popliteus m. The deep posterior compartment also contains the tibial nerve and the posterior tibial artery and vein (Fig. 25.4).

### 25.9.1 Fasciotomies: Authors Preferred Technique

Although several different approaches for complete decompression of each of the leg compartments have been described over the years, to assure a thorough decompression of each of the muscles the authors prefer a two-incision technique. To decompress the anterior and lateral compartments of the leg, a 15–20 cm incision is made longitudinally along the lateral aspect of the leg parallel to the intermuscular septum. Proximally care must be taken to avoid injury to the peroneal nerve as it passes from posterior to anterior around the fibular neck and distally the superficial peroneal nerve as it exits the anterior compartment and passes distal parallel with the distal fibula. Elevation of the subcutaneous tissue, generally anteriorly, off the underlying fascia allows better identification of the anterior and lateral compartments. Through this incision the anterior and lateral compartments can be completely decompressed. To assure that this is the case the fasciotomies can be carefully extended proximally and distally by further undermining the subcutaneous tissue beyond the extent of the incision. Once decompressed the viability of each muscle belly should be assessed for color, contractility, and bleeding and these findings documented accordingly.

The superficial and deep posterior compartments of the leg are generally decompressed with a single incision placed along the medial aspect of the leg. This incision is generally positioned 1–1½ finger breaths posterior to the medial edge of the tibia. Care should be taken to avoid injury of the saphenous vein and nerve which pass along this aspect of the leg. Decompression of the deep compartment can be performed by elevating the soleus attachment to the tibia for at least half of its attachment. Release of the posterior superficial compart-

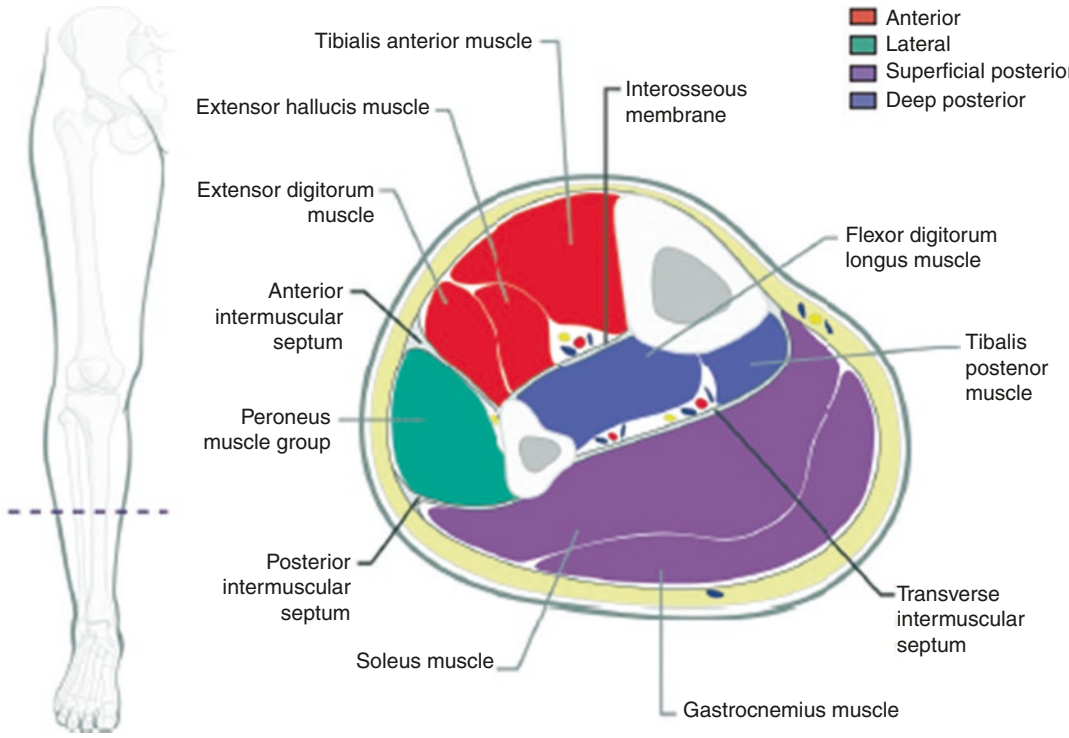


**Fig. 25.4** Cross sectional anatomy of the leg
(Reproduced with permission from von Keudell AG, Weaver MJ, Appleton PT, et al. Diagnosis and treatment of acute extremity compartment syndrome. Lancet 2015 Sep 26;386(10000):1299–1310. doi: 10.1016/S0140-6736(15)00277-9.)

ment is accomplished by incising the fascia as far proximally as possible and distally at least to the level of the muscle tendonous junction. Again, once the compartments are completely decompressed the viability of the muscle bellies should be assessed and the findings documented. When ACS's are recognized and treated before advanced necrosis of the muscles has occurred, it is not uncommon for the muscles to "pink up" several minutes after the decompression. To fully understand the extent of the muscle necrosis it is recommended that serially assessments of the muscle viability be performed during the course of the acute treatment and for several days afterwards.

The fasciotomy incisions can be initially managed in a variety of ways. The authors prefer the "vessel loop technique," where vessel loops are weaved back and forth across the width of the fasciotomies, much like shoelaces, securing the vessel loops to the edges of the incisions helps re-approximate the edges and prevents further retraction of the skin edges. As the swelling in the limb recedes the skin edges will be further re-approximated. Sterile moist dressings are then placed, and plans are made for a second look generally 48–72 h later (Figs. 25.5 and 25.6).

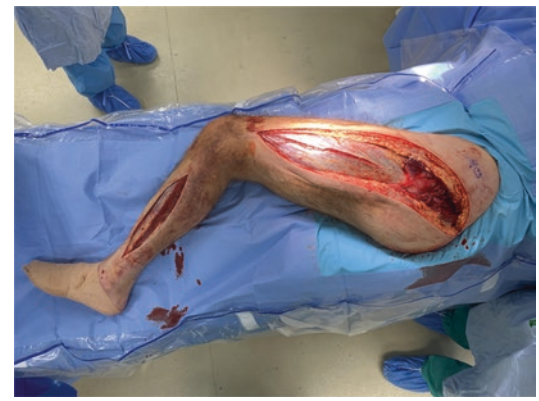

**Fig. 25.5** Fasciotomies of the left gluteal compartment, the entire thigh compartments, as well as the compartments of the leg

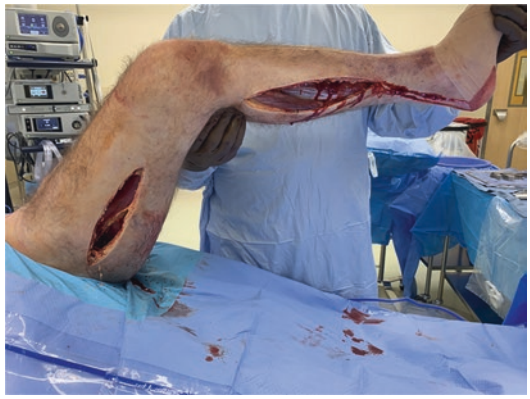

**Fig. 25.6** Fasciotomies of the left adductor and posterior thigh compartments and the superficial and deep posterior compartments of the leg, accomplished through medial incisions

## 25.10 ACS of the Foot

Inadequately managed foot compartment syndrome is poorly tolerated and often lead to myoneural ischemic necrosis of the foot leading to permanent functional loss associated with contractures, weakness, sensory neuropathy, and ultimately a claw-like deformity [57]. These complications often necessitate multiple procedures for rehabilitation, ranging from physical therapy with corrective bracing to limb amputation [58–60].

Compartment syndrome involving the feet is often the result of direct or indirect trauma. In a systemic review of published articles reporting ACS in trauma situations, Ojike et al. found that 28% of ACS of the foot developed following crush injuries, 26% following falls from a height, 26% from motor vehicle accidents, and 7.5% from motorcycle accidents. Certain injuries of the foot and ankle have been associated with ACS of the foot. Ojike et al. also reported that 23% of the ACS of the foot reported were associated with calcaneus fractures, 21% were associated with a Lisfranc fracture, 18% were associated with metatarsal/phalangeal fractures, 18% were associated with fracture of the leg without foot fractures, and 5% were associated with isolated soft tissue injuries without fracture [60].

Although the exact number of muscle compartments within the foot is somewhat controversial, in general the foot is thought to contain nine main muscle compartments. These compartments include the medial compartment containing the abductor hallucis m. and the flexor hallucis brevis m., a lateral compartment containing the abductor digiti minimi m. and the flexor digiti mini brevis m. The four interosseous muscles are often considered to be contained within their own compartments. There are three central foot compartments: superficial compartment contains the flexor digitorum brevis m., central compartment contains the quadratus plantae m., and the deep central compartment contains the adductor hallucis m. and the posterior tibial neurovascular bundle.

### 25.10.1 Fasciotomies: Authors Preferred Technique

Fasciotomies of the foot to treat foot ACS generally include two dorsal incisions for access to forefoot/interossei compartments, and one medial incision for decompression of the calcaneal, medial, superficial, and lateral compartments. The two dorsal incisions are placed just medial and in line with the second metatarsal and another lateral to the fourth metatarsal shaft. The fascia of the interosseous muscles is opened dorsally through these two incisions. Additionally, the interosseous muscle can be stripped off the second metatarsal medially and the fascia of the adductor compartment can be opened within the first interspace.

The medial incision is made along the arch of the foot parallel to the abductor hallucis m. Dissection is then carried dorsal and plantar to the abductor hallucis m. to allow incision of the superficial and deep components of the central compartment and decompression of the adductor m.

### 25.10.2 Prognosis

Long-term sequelae of foot compartment syndrome (FCS) may include contractures, deformity, weakness, paralysis, and sensory neuropathy. Mild compartment syndrome of the

foot may leave very minor sequelae only. Claw toe deformity following calcaneus fractures appears to be due to late contracture of the quadratus plantae m. within the calcaneal compartment, since it can communicate with the deep posterior compartment of the leg. These contractures can lead to severe compromise of the foot function as well as deformity of the foot and ankle. Additionally, if the posterior tibialis m. necroses or dies, it can lead to further foot compromise as the result of a severe equina-cavovarus deformity.

### 25.10.3 Well Leg Compartment Syndrome (WLCS)

Following the first reported compartment syndrome resulting from surgical positioning by Gordon et al., this potentially devasting complication of surgery has associated with: general surgery, colorectal surgery, urological surgery, obstetrics and gynecologic surgery, and of course orthopedic trauma surgery [61]. Although ischemia of the muscle and nerves within the affected compartments is the ultimate culprit in an ACS following direct trauma, crush injury, and other causes as outlined previously, a compartment syndrome that develops in an uninjured limb (most commonly the leg) as a result of body positioning during surgery develops by a somewhat different mechanism. Over the past several decades, factors that influence the development of what is now referred to as "well-leg compartment syndrome" or WLCS have been illustrated. Although WLCS has been reported in at least two patients who were operated upon in the lateral decubitus position, in most reported cases of WLCS the patients were positioned in the lithotomy or hemi-lithotomy positions during surgery. In the hemi-lithotomy position commonly used in orthopedic trauma surgery (although other positions are also available), particularly during antegrade femoral nailings, the "well leg" is flexed at the hip and knee and abducted and externally rotated and held in this position with a padded platform placed beneath the calf. This position allows fluoroscopic assessment of the operative hip and proximal femur in both the AP and lateral projections [62]. This position has been shown to subject the muscular compartments in the well leg to a decrease in perfusion pressure and an increase in the intercompartmental pressures. If allowed to remain in this position for a prolonged period of time (generally 4 h or greater) compartment syndrome within the well leg has been reported to develop. The perfusion pressure within the leg has been shown to decrease by 0.78 mmHg for each centimeter that the leg is elevated above the right atrium of the heart. Thus, perfusion in each compartment is reduced by approximately 24 mmHg by elevation of the lower extremity by 30.5 cm (12 in.) [63]. Additionally, surgery performed under relative hypotension, whether intentionally or related to the patient's injuries will further reduce the leg's perfusion pressure [64].

WLCS is best prevented by avoidance of this position and vigilance. It is imperative that the orthopedic trauma surgeon be aware of the possibility that a WLCS can develop and take the appropriate steps to prevent them from occurring. If possible, the hemi-lithotomy position should be avoided, particularly if the planned procedure(s) are likely to take more than 4 h to complete. Oftentimes, scissoring the legs by extending the well leg at the hip and knee will prevent the development of a WLCS. If the hemi-lithotomy position is necessary, hip flexion should be maintained at less than $90^0$ and the platform supporting the calf should be well padded and a well leg holder that supports the heel and knee only should be considered. Ideally the time in the hemi-lithotomy position should be minimized by taking the leg down once there is no longer a need for fluoroscopy (i.e. during closure). Also, if possible during the procedure when the leg is in the hemi-lithotomy position, frequent compartment checks including palpation and if deemed necessary intercompartment pressure measurements should be taken and the leg brought down from the well leg holder at the first sign of swelling, firmness, and increased intercompartment pressure and continued to be monitored for the development of a WLCS.

If it is determined that a WLCS has developed, a thorough four compartment fasciotomy of the leg and affected compartments should be performed immediately.

## 25.11 Wound Management After Fasciotomies

Timing of closure following the development of ACS is commonly a topic of debate among surgeons and techniques vary between institutions. Although it is well known that early closure is favorable, the principles of debridement must be followed. Therefore, the timing to definitive closure is always dependent on the degree of soft tissue injury at presentation and throughout serial debridement. The main types of closure techniques are primary closure, delayed primary closure, closure by secondary intention, split thickness skin grafting, or rotational flaps. Although rare, primary closure may have a role in settings in which clinical suspicion of a compartment syndrome crossed the threshold for intervention, but upon inspection in the operating room it is apparent by the lack of muscle herniation that the compartment was not in fact under pressure. The second scenario that may be encountered in the atraumatic setting is that of an exercise induced compartment syndrome in which the conditional increase in intracompartmental pressure results in decreased oxygen delivery to the tissue requiring release of the compartment. However, at the time of the surgery this swelling is absent thus primary closure of the skin is reasonable. In general, primary closure of the skin in the setting of ACS is not recommended.

For the vast majority of trauma induced ACS the decision of coverage comes down to delayed primary closure vs split thickness skin grafting following adequate muscle debridement. Healing by secondary intention is not commonly performed due to increased risk of infection as well as prolonged hospital stay and rehabilitation. The advantage of a delayed primary closure includes improved cosmesis and of course no donor site morbidity. The main disadvantage is the increased hospital length of stay due to returns to the OR that are frequently required to achieve such closure. On the other hand, a split thickness skin graft done more acutely minimizes the risk of infection and decreases the length of hospital stay at the expense of donor and recipient site morbidity. Harris et al. demonstrated that fasciotomy wounds not amenable to delayed primary closure at 48 hours were unlikely to go on for definitive closure. Thus patients are routinely consented for a split thickness skin graft on the second trip to the operating room and the procedure carried out as long as the remaining muscle is viable and no additional debridement is necessary.

Various methods of closure relying on a myriad of mechanical devices are available to gradually stretch the skin thus minimizing the size of the recipient and donor sites. However, the results of these closure methods when compared to management with a negative pressure dressing (NPD) have not shown a significant improvement in the time to closure. NPD has been shown to decrease bacterial load, decrease local edema, and increase wound vascularity, and is therefore an excellent primary or adjunct closure method.

### 25.11.1 Authors Preferred Technique

In general ACS following a proper index debridement can be definitively closed 48–72 hours later with the use of a negative pressure dressing in the interim. This serves to increase vascularity to the skin edges and better approximate the wound itself. The medial fasciotomy wound can often be closed with a tension free repair using an Allgower Donati suture technique while the anterior and lateral compartments are easily treated with a split thickness skin graft. This is harvested from the ipsilateral thigh assuming no soft tissue injury to this region with a thickness equal to a 15-blade scalpel and a 1:1 mesh. The graft is secured to the wound beg using interrupted 2-0 chromic suture with tacking sutures placed through the muscle as needed to improve the contact of the graft with the recipient site. The recipient site is dressed with a NPD, which is left on for

5 days. Thereafter a non-adherent dressing can be applied until the graft has completely incorporated. The donor site is dressed with a tegaderm. Fluid from the donor site is allowed to collect beneath the dressing thus preventing this from adhering and making this quite painless. The fluid is evacuated as needed and the dressing reinforced. The process is repeated for 3 days at which point the donor site is epithelialized and can be covered with a non-adherent dressing as well.

## 25.12 Systemic Morbidity of ACS

In addition to the local tissue necrosis caused by elevated intra-compartmental pressures, there is systemic morbidity associated with ACS related to the return of the necrotic end products to the circulatory system. Rhabdomyolysis, as mentioned above, is a potentially fatal result of ACS and can be made acutely worse following release of the compartments as blood flow returns to the ischemic extremity. As oxygen tension is decreased in the tissue the level of ATP is depleted, and the energy dependent ion pumps necessary to maintain the normal electrochemical gradient of the sarcolemmal membrane. This leads to an increase in the concentration of intracellular calcium, which in turn activates proteolytic enzymes resulting in cell membrane destruction.

Reperfusion is harmful in the setting as neutrophils are returned to the ischemic extremity resulting in intense inflammation and generation of oxygen free radicals which further cell necrosis. A large number of intracellular contents including myoglobin, creatine kinase, calcium, and potassium are returned to circulation resulting in electrolyte imbalances, cardiac conduction abnormalities, and renal dysfunction. The resulting acute kidney injury (AKI) can compromise systemic pH leading to disseminated intravascular coagulopathy (DIC) and multisystem organ failure. Thus, patients with evidence of rhabdomyolysis must be closely monitored and managed with a medical team, often in the intensive care unit, to ensure proper renal function and pH is maintained. Surgical intervention with amputation of the extremity is often a life-saving procedure for patients demonstrating worsening renal function and pH following fasciotomy.

### 25.12.1 Missed Compartment Syndrome

The consequences of a missed compartment syndrome are severe. In the event of terminal tissue necrosis, amputation is often required. If there is enough residual perfusion to maintain the viability of the limb and the systemic sequelae are not of sufficient severity to warrant amputation, the contracted state of the affected muscle groups and hypoesthesia or hyperesthesia commonly results in an extremity with very little function and chronic pain. Despite understanding the morbidity of a missed compartment syndrome surgeons are often faced with a difficult decision regarding the utility of a fasciotomy in a patient who has presented past the acute phase of ACS.

A relatively recent systematic review by Glass et al. suggested that patients presenting with a missed compartment syndrome may be best treated with observation as the surgical intervention may require extensive debridement of nonviable muscle and result in infection. Both scenarios are often treated with amputation and indeed the amputation rate was found to be significantly higher in patients who were treated surgically for a missed compartment syndrome. Of course, there is no way to determine the functional loss in patients who were treated nonoperatively, but the data are compelling and non-operative treatment should be considered [65]. Success with this treatment strategy depends heavily on physician communication with the patient and their family.

### 25.12.2 Author's Preferred Technique

Surgical intervention is decided by the chronicity of the symptoms and their current evolution. If patients present with a clear history of a trau-

matic event followed by a period of intense pain, progressive numbness, eventual resolution of the pain, and persistent paresthesia, it is reasonable to treat with observation. This includes frequent monitoring of the patient's renal function and pH. Decline in either mandates operative intervention. Similarly, progressive loss of sensation in the foot is a good indication for intervention as preservation of sensation in the foot can dramatically improve the function of the extremity and often the benefit of fasciotomy outweighs the risk.

At the time of surgery, a two-incision fasciotomy performed to ensure nonviable muscle can be properly debrided. As in acute compartment syndrome, the viability of the muscle is determined by its color, consistency, ability to contract and observed bleeding at the muscle surface. Unlike acute compartment syndrome in which all nonviable muscle should be debrided to avoid systemic morbidity, patients presenting with a missed compartment syndrome may not have as severely elevated laboratory markers. In this setting a more limited muscle debridement can be performed, and the skin closed to increase the chances of successful limb salvage. These patients must be monitored very closely, and evidence of systemic morbidity is best treated with amputation.

### 25.12.3 Morbidity of Properly Timed Fasciotomy

Given the severe functional consequences of a missed compartment syndrome it is in the patient's best interest that the surgeon error on the side of intervention in cases of ACS. However, there are several potential complications related to a properly timed fasciotomy that surgeons should be sure to communicate to patients.

As described previously, large incisions are necessary to ensure complete fascial release as the skin itself can act as a tether in traumatic ACS. On closure one or both surgical wounds may require skin grafting which can lead to a poor cosmetic outcome. In addition, the transient changes in interstitial pressure that occur normally as the result of muscle contracture and relaxation within a compartment are removed with a full release of the compartment. Significant edema due to venous stasis as well as lymphedema can result. Typically, the soft tissues of the traumatized extremity exacerbate this problem. The resulting swelling of the extremity can be quite unsettling to patients. Observation, reassurance, and compression stockings are frequently sufficient to solve this issue.

Lastly the risk of injury to neurovascular structures, in particular the superficial peroneal nerve and saphenous nerve can lead to distal sensory disturbances or painful neuroma that may require later excision.

## 25.13 Outcomes

Several studies have been performed to investigative the effect of compartment syndrome on union rates and incidence of infection regarding the lower extremity. The results of these studies are mixed but provide useful information when counseling patients on expected recovery in the setting of ACS. Regarding tibial plateau fractures, Ruffulo et al. reported no increased risk of deep infection or nonunion in patients with ACS. In the same study, the rate of deep infection was higher in patients who were treated with definitive fixation prior to closure of the fasciotomy wounds [66]. Morris et al. reported a statistically significant increase in the risk of deep infection of 36% following treatment of bicondylar tibial plateau fractures with ACS without an effect on union [67]. Blair et al. combined tibial plateau fractures and tibial shaft fractures into a single cohort and found a significantly higher risk of infection and nonunion with ACS. However, the results of this study were confounded by the presence of a higher percentage of smokers in the group presenting with ACS [68]. Longer term results regarding the tibial shaft showed no difference in union rates or risk of infection in the presence of ACS [69]. Interestingly, in this study there were no differences in functional outcomes although patient satisfaction was lower in the group who presented with ACS.

Compartment syndrome of the upper extremity is associated with a 33% risk of poor outcome defined as limb amputation, persistent neurologic deficit, and contracture [70]. Worse outcomes are expected with crush injury mechanisms [35]. The degree of residual dysfunction is variable and may manifest as persistent sensory deficits or permanent loss of motor function depending on the location and extent of the injury.

In an important study, Giannoudis et al. examined the effect of ACS treated with fasciotomy on patient reported quality of life. In this study, a group of patients with tibial fractures presenting with ACS and treated with emergent fasciotomy were compared to a matched cohort with closed tibia fractures. Baseline demographics were similar between the two groups and the EuroQual patient reported outcome measure was used. The authors found that there was no significant difference in the patient reported quality of health between the two groups [71].

## 25.14 Summary

ACS is a condition resulting from decreased oxygen delivery to the tissues due to increased intra-compartmental pressures. Prompt clinical diagnosis and surgical treatment are necessary to avoid functionally devasting complications including permanent sensory abnormalities, myofibrosis, contracture, and possibly amputation. The most sensitive instrument in making the diagnosis is the physical examination of an experienced orthopedic trauma surgeon. Several assessment and treatments have been proposed over time to prevent missing the diagnosis of an ACS. Figure 25.7 represents via algorithm for the assessment and treatment of patients with a

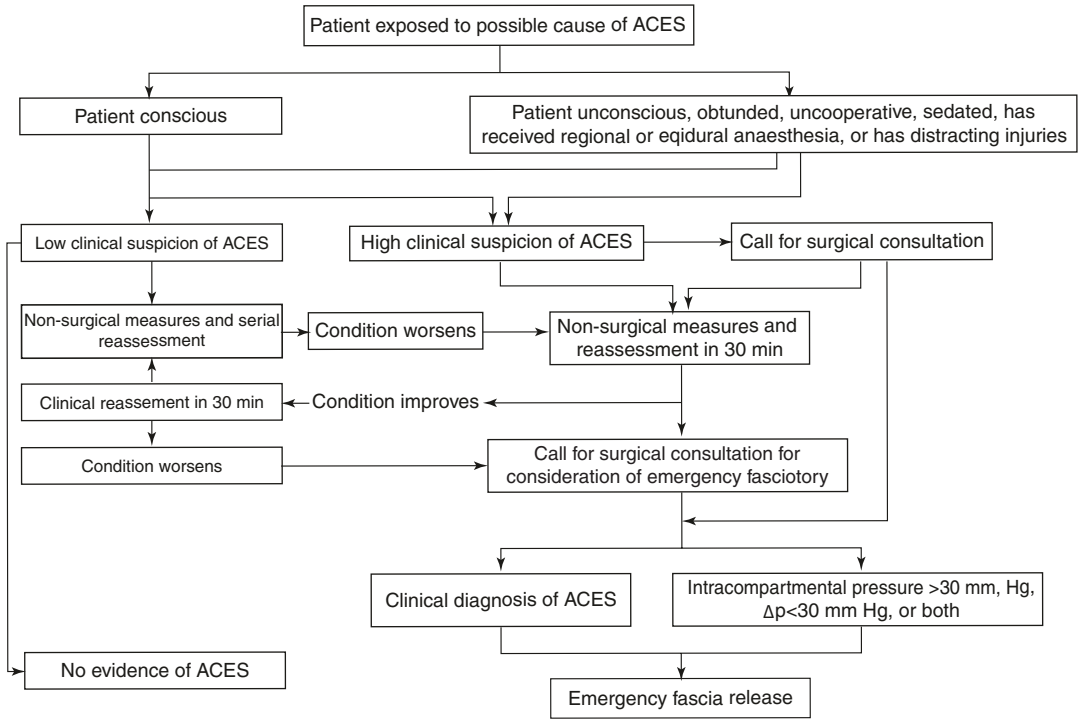


**Fig. 25.7** Proposed clinical treatment guidelines

ACES = acute compartment extremity syndrome. $\Delta p$ = diastolic blood pressure – intra-compartmental pressure

(Reproduced with permission from von Keudell AG, Weaver MJ, Appleton PT, et al. Diagnosis and treatment of acute extremity compartment syndrome. Lancet 2015 Sep 26;386(10000):1299–1310. doi: 10.1016/S0140-6736(15)00277-9.)

suspected ACS (Fig. 25.7). Although there are functional consequences to a fasciotomy, the benefits far outweigh the risks aside from select cases in which a late presentation may be treated with observation. Following compartment release, a thorough debridement of nonviable muscle is necessary to prevent systemic complications such as rhabdomyolysis. After the viability of the remaining tissue has stabilized, soft tissue coverage with delayed primary closure and split thickness skin grafting are the treatments of choice.

A thorough discussion with the patient if possible or his/her loved ones is necessary to communicate the risks and benefits of surgical intervention (fasciotomies) in the setting of an ACS. Patients should be counseled that there may be a higher risk of infection particularly in the presence of other factors such as smoking, diabetes, obesity, extent of soft tissue injury and that the effect of the fasciotomies on fracture healing is not fully understood. Prior to the first procedure, the patient should be informed that several operative interventions will likely be necessary to fully complete the treatment for the ACS. Lastly, the patient should be counseled on the consequences of a delay in treatment and be reassured that despite the possible unfavorable outcomes the need for intervention is quite clear.

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# Damage Control in Abdomen and Thorax

# 26

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**Learning Objectives**

- Describe the phases of damage control surgery.
- Understand the indications for damage control surgery in the chest and abdomen.
- Understand the technical maneuvers to accomplish damage control in the chest and abdomen.
- Recognize the various methods to manage a temporarily open chest or abdominal wound.
- Understand markers and methods of volume resuscitation in the damage control setting (Damage Control Resuscitation).

## 26.1 Statement of Problem and Historical Context

Trauma, whether caused by an accident or from violence, represents 12% of the overall disease burden around the world. Over 80% of operating room deaths in the context of trauma are attributed to hemorrhage. Of deaths that occur within the first 24 h, 50% are due to bleeding. Overall, 30–40% of all trauma mortality is due to uncontrolled bleeding [1].

Pringle, in the context of liver trauma, noted in 1908 that packing could achieve hemostasis for hepatic wounds [2]. Continued study in coagulopathy identified the "lethal triad" of coagulopathy, hypothermia, and acidosis, which occurs commonly after trauma-induced hemorrhage. Thus, by the 1970s, packing of liver wounds became more common. In 1981, Feliciano et al. noted that in patients with continued hepatic bleeding, packing with laparotomy pads and delayed removal led to survival in 9 out of 10 patients [3]. These results were replicated in a series by Svoboda et al. [4]

In 1983, Harlan Stone et al. described a series of 31 trauma patients who were noted to have "major bleeding diathesis" during surgery. The first 14 had standard surgery, reconstruction, drain placement, and abdominal closure. Of this group, only one survived. A second group of 17 patients had "laparotomy terminated as rapidly as possible" after major vessel repair and ligation of resected bowel ends or temporary purse-string closure of traumatic enterotomies. Further hemorrhage was controlled by packing. After resuscitation, re-laparotomy was performed at between 15 and 69 h. Eleven of these 17 patients survived [5]. The importance of control of major bleeding

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and gastrointestinal contamination during the first operation, followed by temporary closure of the abdomen became apparent in the Stone et al. series.

The term "damage control surgery" was attributed to Rotondo et al., who in 1993 described a retrospective series of 46 patients with penetrating abdominal trauma requiring more than 10 units of packed red blood cells [6]. Twenty-two underwent definitive laparotomy, but the remining 24 patients had a "damage control" approach. Utilizing a military term that involved temporary repairs to a ship during active crisis, Rotondo et al. described three phases of care. "Phase 1" represented temporary control of hollow viscus injuries via ligation, staples, or running suture, definitive vascular repair of major vessels, packing of remaining bleeding, and temporary abdominal closure. "Phase 2" represented resuscitation in an intensive care unit, treatment of hypothermia, acidosis, and coagulopathy. "Phase 3" was definitive reconstruction and abdominal closure, which was accomplished after correction of derangements in temperature, coagulation, and hypovolemia.

Since then, other authors have described several phases of damage control, including: [7, 8].

- Phase 0: Initiation of goal-directed resuscitation without delaying surgery.
- Phase 1: Identification of injury pattern and physiologic derangement in the patient.
- Phase 2: Control of hemorrhage and contamination.
- Phase 3: Reassessment during surgery.
- Phase 4: Physiologic restoration in the intensive care unit with correction of acidosis, hypothermia, and coagulopathy.
- Phase 5: Definitive repair and abdominal wall closure.

Damage control surgery occurs over several phases, where injuries are identified and abbreviated surgery with control of hemorrhage and contamination performed (Table 26.1). Definitive repair of traumatic injuries occurs after correction of coagulopathy, acidosis, and hypothermia [7].

**Table 26.1** Phases of damage control surgery

| | |
|---|---|
| Phase 0 | Initiation of goal-directed resuscitation without delaying surgery |
| Phase 1 | Identification of injury pattern and physiologic derangement in the patient |
| Phase 2 | Control of hemorrhage and contamination |
| Phase 3 | Reassessment during surgery |
| Phase 4 | Physiologic restoration in the intensive care unit with correction of acidosis, hypothermia, and coagulopathy |
| Phase 5 | Definitive repair and abdominal wall closure |

While damage control surgery is an important tool for trauma surgeons, significant morbidities including organ failure, extended intensive-care unit stays, enterocutaneous fistula, and ventral hernias can develop. Correctly selecting patients and applying the principles of damage control surgery remain a challenge.

## 26.2 Damage Control Resuscitation in the Pre-operative Phase: Initiation of Goal-Directed Resuscitation Without Delaying Surgery

The first phase of damage control occurs in the pre-hospital setting and in the trauma bay. As codified in the ATLS program, efforts are made to stabilize airway, breathing, and circulation [9].

Airway issues are managed with endotracheal intubation, or, if needed, cricothyroidotomy. Breathing for patients in extremis is supported with supplemental oxygen or mechanical ventilation.

Hemothoraces or pneumothoraces are addressed with chest tubes. If insufficient time or equipment prevents full placement of chest tubes, needle decompression, and/or finger thoracostomies can be performed as temporizing measures.

Circulation is addressed by obtaining vascular access and volume resuscitation. Shoemaker et al. in the 1980s proposed the concept of oxygen debt and emphasized the need for large volume resuscitation to replenish intravascular loss and support enhanced cardiac output [10]. A subsequent randomized trial by Hayes et al. in 1994

showed that such supra-normal oxygen delivery actually doubled mortality [11]. Perhaps the most significant development was Brickell et al. findings in 1994 showing that permissive hypotension in the pre-hospital and pre-operative setting improved mortality in penetrating trauma patients [12]. In their seminal trial of 598 patients with penetrating torso trauma, patients with a pre-hospital blood pressure of less than 90 mm Hg were randomized between immediate and delayed fluid resuscitation. They noted a survival rate of 70% in the delayed resuscitation group, as opposed to 62% in the immediate resuscitation group ($p = 0.04$). Thus, it is thought that in patients with penetrating trauma needing surgery, delaying crystalloid resuscitation until surgical control of bleeding would prevent any partially formed clots from being disrupted and producing more hemorrhage. Since then, many centers have extended this practice to blunt trauma patients though the original trial studied only penetrating trauma.

While many centers practice a restrictive approach to crystalloid in pre-surgery bleeding trauma patients, there has been a focus on transfusing blood in the trauma bay. The latest iterations of the Advance Trauma Life Support manual suggest limiting crystalloid to one liter and giving early transfusion of red blood cells, FFP, and platelets [9]. Centers with access to sufficient blood resources often proceed directly to transfusing blood products. While this shift theoretically focuses on correcting the hypothermia, coagulopathy, and acidosis that accompanies hemorrhage, further studies are needed to delineate the optimal resuscitation strategy. It remains clear, however, these measures are a bridge to surgical control of bleeding and contamination.

## 26.3 Abdominal Damage Control Surgery and Organ-Specific Damage Control Maneuvers

Trauma management continues to place an emphasis on timely operative management of life-threatening bleeding and organ injury. In the operating room, the injury pattern is ascertained while the physiology pattern of the patient is monitored and corrected. When definitive management of the patient's traumatic injuries would be too physiologically taxing for the patient, a transition is made towards temporary measures to control contamination and bleeding while minimizing operative time. Various articles in the literature have suggested several indications for damage control surgery, such as need for massive transfusion (more than 10 units PRBC), metabolic acidosis with pH < 7.3, hypothermia (<35 °C), coagulopathy manifesting itself as non-surgical bleeding, or lactate higher than 5 mmol/L [13]. Ultimately, however, the decision towards damage control surgery is dependent on clinical judgment based on the injury pattern and intraoperative physiologic status of the patient.

### 26.3.1 Hollow Viscus

In bowel injuries, damage control can be accomplished by temporary suture closure of perforated areas or, more commonly, bowel resection. The bowel may remain in discontinuity for about 3 days before significant edema develops. Small bowel left in discontinuity can often be re-anastomosed at re-operation. If needed, ostomy can be created.

Re-anastomosis of the colon in the damage control setting has been more controversial, with many feeling that the leak rate from colonic anastomosis may be too high in the damage control setting. Indeed, many non-randomized trials suggest a higher leak rate with damage control surgery in comparison to single-stage laparotomy though only one trial reached statistical significance [14]. Nevertheless, delayed primary colonic anastomosis is often successful in damage control patients, with the greatest anastomotic leak rate present in patients who have received large-volume resuscitation and those with left colon injuries [15].

An area of continued study remains consideration for performing a small or large bowel anastomosis at the index surgery, even if the abdomen remains open. While the focus of damage control surgery is minimizing operative time, many sur-

geons note that an anastomosis can take only a few minutes to complete. A 2016 retrospective multi-center trial of patients with damage control with bowel resection compared those with primary anastomosis with those left in discontinuity [16]. The authors noted a higher trend towards mortality in the discontinuity group (8.3% vs 16.9%) though it did not reach statistical significance ($p = 0.096$). In a multivariate model, they noted a higher rate of bowel ischemia in the discontinuity group (32.5% vs 13.1%, $p = 0.035$). While they note the limitations of a retrospective trial, consideration for primary anastomosis in appropriate patients should be given.

### 26.3.2 Liver

Manual pressure and packing are initial maneuvers to accomplish control of hepatic bleeding. Packing above and below the liver is necessary to accomplish pressure tamponade on the liver. Keeping the falciform ligament intact and avoidance of mobilizing the right lobe of the liver in unstable patients can help further maintain tamponade on the liver. In addition, the use of a thin plastic barrier (such as a sterile radiology cassette cover) between the liver and lap pads can prevent bleeding at time of laparotomy pad removal.

Patients with limited injuries may receive definitive repairs including utilization of hemostatic agents, suture hepatorrhaphy (sometimes with the assistance of a flap of omentum), or even major or minor liver resection. An adjunct to control liver hemorrhage include clamping or placement of Rommel tourniquet on the hepato-duodenal ligament (Pringle maneuver). Continued bleeding despite control of the hepato-duodenal ligament may be indicative of hepatic vein or inferior vena cava injury. While the maximum length of duration for hepato-duodenal occlusion is unclear, approximately 1 h of clamping is often tolerated. Another option, improvized balloon tamponade of a missile tract, can be used when there is a through-and-through penetrating wound into the liver [17].

Patients in extremis and continued coagulopathy should be considered for damage control maneuvers. Hemorrhage control can be accomplished by manual approximation of the liver segments affected and utilization of packing around the liver with laparotomy pads to maintain the segments in approximation. If necessary, balloon tamponade through a missile tract can be continued and removal planned at time of re-laparotomy [18]. Clamping or Rumel tourniquet of the hepato-duodenal ligament should be done for as short as a time as possible. If necessary, it can be maintained until time of vascular liver angiogram, with the Rumel tourniquet released when the vascular interventionalist is ready to traverse the hepatic artery.

An area of continued study is use of hemostatic gauze for packing. Kaolin is a silicate clay that is known to activate the coagulation cascade, specifically the intrinsic pathway at Factor XII. Kaolin impregnated gauze is available under the trade names Combat Gauze, Trauma Pads, and QuikClot. While the agents have been validated in a swine model, it's benefit in human patients remains controversial. Choron et al. noted in a retrospective review of such agents that patients packed with kaolin pads plus standard lap pads tended to present with greater illness (lower initial blood pressure and greater blood loss at index laparotomy) then patients who had standard lap pads only. Despite this, there was no difference in blood products after index laparotomy. Thus, while kaolin packs did not seem to confer additional benefit, there was no additional morbidity detected [19].

Angiography is an important adjunct in damage control of liver trauma. Matsumoto et al. studied National Trauma Data Bank patients with AAST Grade IV or Grade V injuries. Comparing those who underwent post-surgery angiography with those that did not, 1:3 propensity-score matching was performed. Matsumoto noted that post-surgery angiography resulted in a survival advantage (mortality rate 24.5% vs. 35.9%; odds ratio 0.58; 95% confidence interval, 0.40–0.84) though these patients had a higher hospital length of stay and higher deep and organ space infection [20]. Nevertheless, use of angiography in combination with surgery may lead to decreased mortality in severe liver trauma.

After initial damage control surgery and correction of metabolic derangements, patients can return to the operating room for definitive surgery. Options include hepatotomy with selective vascular ligation, suture hepatorrhaphy with wide placement of sutures, use of omental patch in complex lacerations, non-anatomic wedge resection (also known as resectional debridement), and anatomic resection (rarely needed or recommended).

### 26.3.3 Spleen

While certain splenic injuries in stable patients can be managed non-operatively (and perhaps with or without the adjunct of splenic artery embolization), unstable patients require laparotomy. For many patients who are stable in the operating room, definitive surgery and abdominal closure can be performed. In these patients, splenorraphy or splenectomy can be performed. Unstable patients requiring damage control should undergo splenectomy, which can be accomplished very quickly, followed by temporary closure of the abdomen. Definitive abdominal closure is performed at a later time when coagulopathy and concomitant injuries are managed.

### 26.3.4 Pancreas

Patients with pancreatic trauma who are unstable enough for definitive surgery should be managed with packing and wide drainage. Peri-pancreatic vascular injuries, such as Henle's gastrocolic trunk, can be managed with ligation [21].

When intravascular volume has been restored and coagulopathy has resolved, patients can return to the operating room for definitive management. Consideration should be given to the location and status of any main pancreatic duct injury. Pancreatic duct injury to the left of the superior mesenteric artery (in the body or tail of the pancreas) can be managed with distal pancreatectomy, which has less complications than drainage alone [22, 23]. Mortality with drainage alone can be as high as 50–100% in some series [24]. Consideration at re-operation can be given for distal pancreatectomy with splenic salvage if possible, which may reduce later infectious complications. Roux-en-y pancreatico-jejunostomy to the pancreatic stump has been performed though its effectiveness remains unclear and should be avoided even in the second phase of damage control operations [25, 26].

Destructive injuries involving the pancreatic head are much more complicated than the distal pancreas, owing to the confluence of the pancreas, duodenum, and common bile duct, as well as associated vascular structures. In the initial operation, packing and drainage should be the only procedures performed. In some circumstances, most of the dissection necessary for a Whipple procedure has already been done by the traumatic injury itself; however, an astute surgeon should contain the temptation to perform a complex reconstruction in the first operation. With the help of a pancreato-biliary surgeon during the second operation the most appropriate decisions are made. The options include endoscopic stenting by ERCP or pancreatico-duodenectomy. While reports of successful secondary pancreatico-duodenectomy have been published in the literature [27], such a reconstruction should be performed with an experienced multidisciplinary team in a completely stable and compensated patient.

### 26.3.5 Kidney/Ureter/Bladder

For patients requiring operative intervention, the decision to explore a renal injury is complex. Traditionally, penetrating injuries to the renal parenchyma (Retroperitoneal zone 2) are explored for bleeding or for injuries to the renal pelvis. Patients with blunt trauma in the operating room for other reasons can potentially be managed with observation if the retroperitoneal hematoma is stable. Patients with exsanguination from injury to the renal parenchyma, whether blunt or penetrating, may require partial or complete renal resection [28].

Renal injuries at time of damage control laparotomy can present a special challenge. If the

renal injury is not thought to be the main contributor to the patient's unstable physiology, the injury can be packed and managed at re-exploration [29]. Massive bleeding in the damage control setting may require nephrectomy and packing of the raw surface of Gerotta's fascia. Hilar control can be performed by directly accessing the renal hilum after mobilizing and lifting the kidney from its bed inside Gerotta's fascia with subsequent use of a vascular clamp placed across the hilum. Renal injuries may produce urinary extravasation which may require complex repairs. However, external drainage of urine via a local drain to afford temporary control is usually sufficient to bridge the patient to more complex reconstruction when they are more stable [30, 31]. After initial damage control efforts, adjunctive studies while patients are more stable can include computed tomography to reconstruct the anatomy of the injury. If necessary, angioembolization of areas of bleeding can also be accomplished after initial damage control efforts [32]. At time of re-operation, when coagulopathy is corrected, consideration can be made for more complete evaluation of the injury, and resection or repair if needed. Any necessary exploration should be pursued to fully grade and characterize the injury, in order to properly repair any injuries. Consideration should be given for ureteral stents or continued Foley catheter drainage to minimize resistance to the regular flow of urine.

While ureteral injuries can have definitive repair at the index operation, in unstable patients, damage control maneuvers are appropriate for the ureteral system. This is because ureteral injuries can be time consuming to repair and require complex mobilization; despite this, massive bleeding from the ureter itself is uncommon [33]. A preferred damage control maneuver is placement of a catheter proximally into the injured ureter. Passing the catheter over a guide wire can assist in advancing the catheter into the renal pelvis. A silk tie around the ureter can secure the catheter properly, and the catheter can be externally routed through the abdominal wall and into a drainage bag. An alternative method is ligating the ureter and pursue image-guided nephrostomy tube drainage in the post-operative setting. In case of complete transection of the ureter, a plastic tube functioning as a stent (similar to those used in peripheral arteries) is also contemplated and is a quick solution to maintain urinary flow until the definitive repair can be done days later. Finally, if the patient is too unstable for any of these maneuvers, placing an external drain in the proximity of the injured ureter provides some local control of a urinary leak. When the patient is more stable, re-operation with complete evaluation of injury and definitive repair can be pursued. Mobilization of the ureter or bladder and creation of various conduits to replace the injured segment of the ureter may be needed. Consideration should be given for repair over a ureteral double J stent to prevent stenosis and provide proper urinary drainage while the injury is healing.

Regarding bladder injuries in the damage control setting, after control of hemorrhage, the first consideration should be given to trans-urethral Foley catheter or supra-pubic cystostomy catheter placement. If there is a large bladder injury, however, urinary control is unlikely to be accomplished with these maneuvers alone. If needed, catheters can be passed into the ureteral orifices and then externalized to effect better urinary control. Eventually a running suture with absorbable material to close a large defect accompanied by Foley catheter drainage can be accomplished quickly and effectively. More definitive repair can be accomplished when the patient is more stable and further adjunctive imaging is available [34].

Urethral injuries in unstable patients require supra-pubic cystostomy catheter placement to afford urinary diversion. Definitive repair of urethral injuries may be pursued weeks or months after injury. An alternative is early endoscopic realignment when the patient is more stable.

### 26.3.6 Intra-Abdominal Vascular

While early approaches to damage control in the abdomen utilized definitive vascular repair and temporary measures for other organs, damage control efforts now include temporary vascular maneuvers.

In unstable patients with intra-abdominal bleeding, initial efforts are directed at wide exposure and packing all four quadrants of the abdomen. If there is free and massive bleeding supra-celiac aortic control may be necessary. To accomplish this, the left lobe of the liver is mobilized and retracted to the patient's right. The esophagus is retracted to the left, potentially with the assistance of a Penrose drain around the lower esophagus. The aorta can be manually compressed with manual pressure, a sponge stick, or a purpose made aortic occluder. Ideally, a vascular clamp is then placed on the aorta using the spine as the posterior limit of depth for the tip of the clamp. Circumferentially freeing the aorta should be initially avoided to prevent injury to posterior arterial branches [35].

An alternative measure to obtain control of aortic inflow includes aortic cross-clamping above the diaphragm via a left anterior-lateral thoracotomy in the fifth or sixth rib space. A more contemporary option is the use of the REBOA catheter, which can be placed via common femoral artery by the Seldinger technique or direct cutdown. The balloon is placed by landmarks or fluoroscopy or X-ray, and aortic occlusion at various levels can be accomplished [36].

Once initial bleeding control is accomplished, identification of specific injuries and delineation of repair maneuvers can be pursued. Most commonly, injuries to major arterial structures can be repaired primarily, or via prosthetic graft (PTFE or Dacron). Most venous injuries in the abdomen can be ligated, exception to the supra-renal IVC, which requires shunting initially and definitive repair if the patient survives the initial insult. As vascular repair can be time consuming, especially if venous harvest is necessary, temporary intravascular shunts can be pursued in patients not candidates for immediate repair. Shunts can take the form of Javid or Argyle shunts, or for large vascular structures even modified chest tubes can be used.

Specific areas of concern include the aorta, which can be repaired with 3-0 or 4-0 prolene suture and venous patch, PTFE, or Dacron. Shunting of the aorta can be accomplished with a large chest tube secured with silk suture or umbilical tape [37].

The inferior vena cava can similarly be shunted or primarily repaired; if necessary, the inferior vena cava can be ligated. Infra-renal ligation may result in lower extremity venous congestion, and bilateral lower extremity fasciotomy may eventually become necessary. Supra-renal ligation of the inferior vena cava can be especially morbid due to decreased venous return and renal failure [38].

The celiac artery or superior mesenteric artery are ideally repaired either primarily or via interposition vein graft or prosthetic graft [39–41]. The vessels can tolerate shunting if needed with definitive repair at a later date. Ligation of either the celiac or the superior mesenteric artery can be considered if needed, though collateral flow from an uninjured arterial counterpart is needed. Nevertheless, celiac ligation can produce gallbladder ischemia necessitating cholecystectomy. Asensio et al. reported that superior mesenteric artery ligation was tolerated, but bowel ischemia can develop. Mortality from ligation ranged from 24% to 77%, with a worse prognosis generally for proximal SMA ligation [42].

Portal vein and superior mesenteric vessel injuries are rare, and the vessels can be difficult to access. These veins are ideally repaired, which can be performed primarily or with vein patch. However, patients in extremis may need portal or SMV ligation for hemorrhage control. Ligation of the portal vein can cause systemic hypotension from diminished venous return [43]. Stone et al. noted an 87% mortality in eight patients from 1958 to 1973; in 10 patients between 1974 and 1980 there was a 20% mortality rate [44]. Superior mesenteric vein injuries are similarly morbid. Donahue and Strauch in 1988 reported on 33 SMV ligations and 75 SMV venorrhaphy; there was a 15% and 36% mortality rate, respectively [45]. Coimbra et al. noted that concomitant injuries play a major role in the hospital course of these patients. In a 2004 series of patients with portal or SMV injuries, most patients had more than one associated injury. 61% had additional vascular injuries, and mortality rate rose with the presence of increased associated organ injuries [46].

Iliac artery and iliac vein injuries can produce significant blood loss and mortality. In Asensio et al. series of 148 patients, estimated blood loss was greater than 6 liters and mortality was 49% [47]. The common and external iliac arteries should be repaired, or in patients in extremis, shunted and repaired at a later time. The internal iliac artery tolerates ligation. Similarly, the common, internal, and external iliac artery can be ligated. In some series, however, patients needing iliac vein ligation had higher mortality than those who received repair [48]. A summary of organ-specific interventions used in abdominal damage control is shown in Table 26.2.

### 26.3.7 Management of the Open Abdomen

Early patients for whom damage control surgery was performed received skin or even fascial suture closure to assist with achieving laparotomy pad tamponade and hemorrhage control. Some early efforts also used towel clips for temporary skin closure. The subsequent high rates of abdominal compartment syndrome led to other methods to temporarily close the abdomen [49]. Now, a hallmark of damage control surgery in the abdomen is temporary abdominal closure to allow for re-exploration at a time when the patient is more stable.

**Table 26.2** Damage control in the abdomen: principles of management

| | Initial damage control maneuver | Adjunctive maneuvers |
|---|---|---|
| Hollow viscus injuries | Temporary closure of enterotomies or bowel resection | Consider re-anastamosis or stoma; may defer to later surgery date |
| Liver | Manual pressure and packing | Hemostatic agents<br>Suture hepatorrhaphy<br>Minor liver resection debridment<br>Pringle maneuver<br>Balloon tamponade through a missile tract<br>Post-surgery angiography, especially for AAST Grade IV or Grade V injuries |
| Spleen | Packing | Splenectomy preferred over splenic repair in damage control |
| Pancreas | Packing and wide drainage | Pancreatic resection depending on location of injury<br>Avoid complex reconstruction (such as Whipple) at time of initial operation |
| Kidney | Packing | Nephrorrhaphy<br>Nephrectomy<br>Consider drain placement if suspect urinary leak<br>Post-operative angio-embolization<br>More complex reconstruction at subsequent surgery |
| Ureter | Packing and identification of injury | Intubating and externally draining an injured ureter<br>Ligating the ureter and plan for image-guided nephrostomy tube drainage post-operatively<br>Shunting of ureter<br>Wide drainage |
| Bladder | Trans-urethral Foley catheter or supra-pubic cystostomy catheter placement; primary repair of bladder | If needed, catheters can be passed into the ureteral orifices and then externalized to effect better urinary control |
| Urethra | Passage of Foley catheter via urethra or supra-pubic cystostomy | Early endoscopic re-alignment of urethra<br>Definitive repair of urethral injuries may be pursued weeks or months after injury |
| Intra-abdominal vascular | Initial damage control maneuver: packing and identification of injury; proximal and distal control<br>Consider intra-thoracic or intra-abdominal aortic control via manual pressure, occlude, or vascular clamp, or REBOA device | Aorta: Primary repair, prosthetic or vein graft repair, shunting<br>IVC: Repaired or shunted; intra-renal IVC can be ligated<br>Celiac artery and SMA: Repaired or shunted; consider ligation in extremis<br>Portal vein and SMV: Repaired or shunted; consider ligation<br>Iliac artery and vein: Repaired or shunted; consider ligation of vein injuries |

Early improvized methods to manage the abdominal wall include sterilized intravenous fluid bags, PTFE sheets, and Bogota bags [50]. While these methods are rapid, they do not allow for the removal of built-up abdominal fluid and do not prevent abdominal wall retraction. Since then, trauma teams have paired these methods with various ways to place the abdominal wall on tension. This includes dynamic retention sutures or Velcro-assisted closure ("artificial burr" or "Wittmann patch").

Currently, negative pressure wound therapy has proven to be a popular method of managing the open abdomen. Barker et al. in 2000, advocated for a negative pressure setup that included a perforated polyethylene sheet as a barrier against the bowel, which was then covered with a moist towel and suction tubing, and which was finally covered with an iodophor-impregnated adhesive polyethylene sheet. In his series of 122 patients with open abdomens, there was a 4.5% rate of enterocutaneous fistula and 4.5% rate of intra-abdominal abscess [51]. While the Barker negative pressure therapy setup is easily created from available materials, many centers now have purpose-built wound vacuum systems.

The best way to manage an open abdomen remains debated, and the data remain heterogenous. A 2008 meta-analysis showed successful fascial closure was 90% with Velcro-assisted closure, 85% with dynamic retention sutures, and 60% with negative pressure therapy [52]. A separate metanalysis in 2012 showed that fascial closure was achieved with 78% of Velcro-closure, 71% with dynamic retention sutures, and 61% with the a commercially available negative pressure system (wound vac) [53]. Another 2012 meta-analysis with differing methodology suggested the use of sequential fascial closure [54]. A more contemporary 2016 study compared negative pressure therapy vs standard temporary closure. Rates of fascial closure and enterocutaneous fistula were similar (63.5% vs 69.5%, $p = 0.57$ and 2.1% vs 5.8%, $p = 0.57$, respectively). There was decreased mortality in the negative pressure system group (28.5% vs 41.4% $p = 0.03$) as well as decreased ICU length of stay [55]. To offer guidance on a strategy of abdominal closure, a position paper by the World Society of Emergency Surgery suggests the open abdomen be initially managed with a negative pressure dressing. Should fascial closure be not achieved within 5–7 days, the utilization of a fascial traction device such as Wittmann Patch or modified wound-vac is suggested [56].

An emerging concept to reduce bowel edema in patients with open abdomen is direct peritoneal resuscitation (DPR). Intra-peritoneal dialysate solutions are instilled into the abdomen while the wound vac removes excess fluid. In 2010, Smith et al. studied the use of DPR in a series of 60 patients (20 using DPR and 40 using standard techniques) [57]. The DPR group achieved abdominal closure in less time (4.35 ± 1.6 days versus control 7.05 ± 3.31; $p = 0.003$). DPR also demonstrated a higher rate of primary fascial closure and decreased number of hernias at the 6-month mark. While open abdomen management was not standardized in the control group, subgroup analysis showed that DPR had decreased time to closure in comparison to Velcro-assisted closure (DPR 4.4 ± 1.7 days versus Velcro 6.4 ± 1.3, $p = 0.003$). While this relatively small study shows the potential for DPR, further prospective studies are required.

Use of neuromuscular blockade to prevent abdominal wall retraction is an area that requires continued study. De Laet et al., in a prospective study, showed that cisatracurium could reduce intra-abdominal pressure. Abouassaly et al. analyzed 192 patients with open abdomens; patients receiving neuromuscular blockade were more likely (93% vs. 83%, $p = 0.024$) to have primary fascial closure within 7 days. There was no increase in ventilator-associated pneumonia [58]. However, in a prospective study by Teixeira et al., the authors did not identify neuromuscular blockade as a contributor to successful fascial closure [59].

Timing for return to the operating room with an open abdomen patient is a continued concern. Pommerening et al. multi-center series of 499 patients with open abdomens showed a median time of return-to-operating room of 36 h. However, it was noted that rates of fascial closure decreased when time to re-operation was greater

than 24 h. Each hour increase beyond 24 h was associated with 1.1% decrease in the odds of fascial closure. There was, furthermore, a trend towards greater rate of complications in patients returning to the operating room after 48 h [60]. Consideration should be made for return to the operating room as soon as physiologic optimization has been achieved.

While damage control surgery can improve survival in the correct patient, significant complications can arise from the open abdomen. In a multi-center study of 517 patients with open abdomens, 111 were found to have intra-abdominal sepsis or enterocutaneous/entero-atmospheric fistulae. Predictors of these complications included large bowel resection, large volume resuscitation, and increasing number of re-operations [61]. Minimizing the number of re-operations and judicious resuscitation may be an important factor in patient outcomes. Limiting damage control surgery to patients who truly require it is also advisable. Higa et al. made a concerted effort to decrease the rate of open abdomens. During the study period, the number of patients undergoing damage control laparotomy decreased from 36.3% to 8.8% ($p = 0.001$). During that time, the mortality rate for patients requiring laparotomy also decreased from 21.9% to 12.9% in ($p = 0.05$) [62]. While damage control surgery remains a critical tool, its application to the correct situation and correct patient remains vital.

While there are variable strategies to achieve abdominal closure after damage control surgery, one option is to use negative pressure dressings at initial surgeries. Continued inability to close the fascia may necessitate a fascial traction device. In patients for whom fascial closure is unfeasible, planned hernia and delayed abdominal wall reconstruction may be necessary. An algorithm delineating the steps for abdominal closure is depicted in Fig. 26.1.

## 26.4 Thoracic Damage Control

Damage control maneuvers in the chest are not as common as in the abdomen, and there is less data to guide management. Lang et al. retrospectively compared temporary chest closure versus definitive management in trauma patients who underwent emergent thoracotomy, received 10 or more units of blood (or had cardiac arrest before chest closure), and survived to intensive care unit arrival. Over the 61 patients included, there was no difference in survival between temporary chest closure versus definitive management (survival rate 47% vs 57%, $p = 0.56$) [63]. It is clear, however, that coagulopathy, acidosis, and hypothermia, all independently contribute to mortality [64–66]. The presence of these factors will dictate the need for damage control maneuvers. In this, the philosophical principles of damage control surgery remain salient in the chest: control of hemorrhage and contamination.

### 26.4.1 Cardiac

The heart can be accessed via left anterior-lateral thoracotomy or sternotomy. In the trauma bay, urgent access via the former is usually easier and faster. There should be low threshold for converting it to a clamshell thoracotomy by extending the incision to the right hemithorax, which can allow improved access to the mediastinal structures. Initially, cardiac wounds are managed with manual pressure. An adjunct after this initial maneuver can include the use of an 18-french Foley catheter, which can then be inflated and gently pulled on tension to effect hemostasis. A clamp can be used on the Foley catheter's external opening to prevent exsanguination; alternatively, blood can be transfused via the intra-cardiac Foley catheter. In the case of the pliable atria, vascular clamps can be used for temporary control. With large or multiple wounds, a skin stapler can be used for initial bleeding control [67]. Whether or not an adjunct is used for temporary control, 2-0 or 3-0 prolene sutures can then be placed for formal repair; pledgeted sutures can assist with preventing the sutures from tearing through the thinner-walled right heart. Concomitant valvular injuries may require evaluation with echocardiogram and valve repair or replacement at a later date [68].

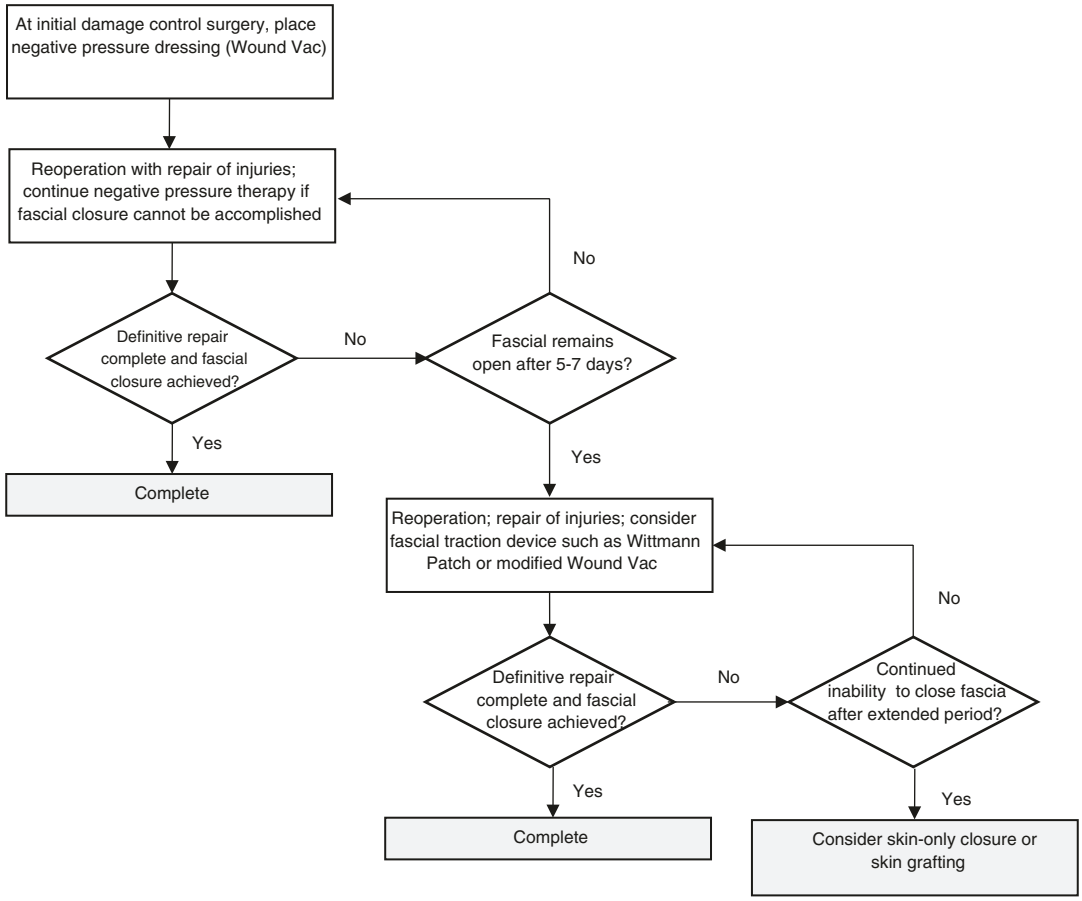


**Fig. 26.1** An algorithm for abdominal closure

### 26.4.2 Intra-Thoracic Vascular

Injury to the non-aortic great vessels is relatively rarely seen in the trauma center, as many of these patients do not survive to the hospital.

Injuries to the innominate, subclavian, or intrathoracic carotid artery can be a challenge. Patients with external bleeding can be temporarily controlled with a balloon Foley catheter [69]. Stable patients can be managed with endovascular approaches. Unstable patients with continued bleeding should proceed immediately to the operating room, where tenets of repair include proximal and distal control, which may require sternotomy or infra-clavicular incision with even disarticulation or resection of the clavicle. Depending on the extent of the injury, primary repair, prosthetic or venous conduit repair, or temporary shunting may be needed. Definitive repair can be affected when the patient is more stable. If a prosthetic vascular graft was used in a contaminated field, it can be replaced with autologous vein at time of delayed reconstruction.

Patients with low-grade (minimal) aortic injuries can be potentially managed with impulse (heart rate) control and surveillance. Endovascular repair is an option at many centers for more substantial injuries. Unstable patients, however, should be managed in the operating room. Repair with a prosthetic graft is a likely possibility but shunting of the aorta is a described damage control approach complemented by delayed repair by a multidisciplinary team as a viable approach in the severely injured patient [70, 71].

### 26.4.3 Pulmonary

Pulmonary injuries can be managed in a variety of ways, and lung-sparing techniques are a reasonable initial approach. Suture pneumonorrhaphy with or without tissue sealant can be used to repair small wounds and effect hemostasis. Through-and-through penetrating injuries creating a long tract in the lung parenchyma may require tractotomy to visualize the whole tract an to identify bleeding vessels which are individually ligated as well as ligation of areas of air-leakage [72]. As an alternative to selective ligation, argon beam coagulation can also be used to effect hemostasis along the exposed lung parenchyma [73]. Peripherally located injuries can be quickly managed with non-anatomic stapled wedge resection. Further injuries may necessitate lobectomy or pneumonectomy.

Patients requiring pneumonectomy often have central hilar bleeding. In this setting, a pulmonary hilum twist can control bleeding and prevent air embolism [74]. This is performed by first transecting the inferior pulmonary ligament. A clockwise twist of the hilum is then performed. Intra-pulmonary packing with lap pads can then maintain the lung and hilum in the twisted position. Alternatively, vascular clamps or a Rumel tourniquet can be used to control the hilum. Ultimately, a stapled pneumonectomy with a transverse anastomosis (TA) stapler will control hemorrhage and complete the resection [75].

Care should be taken to perform the minimal necessary resection of the lung parenchyma. Karmy-Jones et al. noted that mortality increases with extent of lung resection, with tractotomy patients having mortality of 13%, wedge resection 30%, and lobectomy 43% [76]. Mortality for pneumonectomy can be as high as 50–62% [77], in part due to acute right heart failure from dramatic increases in afterload.

### 26.4.4 Chest Wall

Intercostal vessels can produce massive hemothorax. Unstable patients are typically managed in the operating room with thoracotomy. Depending on the location of the vessel, ties around the rib can be placed proximally and distally to the vessel to control hemorrhage. Direct ligation of the vessel is typically difficult due to its location under the rib space. Intercostal vessel injury close to the spine carries further technical difficulty due to the proximity of adjacent ribs. Direct electrocautery is one option, but one group reported on using a rolled surgical pad that was sutured against the chest wall for tamponade affect [78]. In patients with a lesser bleeding diathesis, or in those for whom some temporary control can be obtained, endovascular approaches remain an option. Embolization of the intercostal vessels can be performed, but as the intercostal vessels have dual arterial in-flow (via the aorta posteriorly and the infra-mammary artery anteriorly), proximal and distal embolization is often needed [79].

### 26.4.5 Aerodigestive

Intrathoracic airway injuries are rare and can be difficult to access. For example, in patients undergoing a left anterolateral thoracotomy, only the left distal mainstem bronchus is accessible. Tracheal injuries should be initially managed by advancement of an endotracheal tube beyond the injury. Use of double-lumen tubes or bronchial blockers to preferentially ventilate the unaffected lung is a further option. This is particularly useful in patients with significant bleeding into the airway of the affected lung, "flooding" the opposite lung and further compromising ventilation and oxygenation. In unstable patients with bronchial injuries, lobectomy or pneumonectomy may be required.

Thoracic esophageal injuries are much less common than intra-abdominal hollow viscus injuries. The esophagus can be temporarily closed, or a segment divided with a stapling device. Decompression proximal to the site of injury is necessary via nasal-gastric tube. Wide external drainage of the injury bed is also vital. Principles of management include control of leak and prevention of mediastinitis [80, 81]. Definitive reconstruction, whether via primary repair, gastric conduit, or colonic interposition

can be performed when the patient is more stable [82]. The use of omentum or a pleural flap to cover a repair at the time of reconstruction is also a reasonable maneuver.

### 26.4.6 Temporary Chest Closure

There are various methods to manage an open thoracic wound though there is little consensus on the optimal method. Chest closure methods must account for intra-thoracic pressure and respiratory mechanics. Lang et al. noted that temporary chest closure yielded decreased peak ventilatory pressures in comparison to definitive closure (20 cm $H_2O$ vs 32.5 cm $H_2O$, $p = 0.003$) [63]. The sternum and thorax can tolerate packing, and while there is theoretical risk of thoracic compartment syndrome with excess packing, some series show that packing is well tolerated [83, 84].

Temporary closure of the sternum can be effected with synthetic materials, such as polytetrafluoroethylene, which is sutured to the sternal and skin edge [85]. In other patients, skin closure without sternal approximation have been used [86]. Other maneuvers described in the literature include using chest tubes to elevate the sternum over the heart and thus stent open the sternum [87], as well as using a traction device to maintain the sternum in an open position [88]. Similarly, a wound vac device can be used in the sternum.

A wound vac device can also be used for the thorax, whether with improvized methods (with sterile plastic sheets and gauze and suction tubing) or re-purposing an abdominal wound vac for use in the thoracic cavity. Perhaps more simply, chest tube drainage and temporary skin closure can be used. At times, the chest can be left completely open and the wound covered by iodine-impregnated self-adhering sheets. A summary of organ-specific interventions used in thoracic damage control is shown in Table 26.3.

**Table 26.3** Damage control in the chest

| | Initial damage control maneuver | Adjunctive maneuvers |
|---|---|---|
| Cardiac | Access by sternotomy or thoracotomy; manual pressure over cardiac injury or occlusion with Foley catheter; temporary skin stapler application; for atria vascular clamp can be applied | 2-0 or 3-0 proline suture (possibly with pledgets); post-operative echocardiogram and evaluation for valvular or septal injury |
| Innominate, subclavian, carotid arteries | Packing | Proximal and distal control with repair; shunting; endovascular measures |
| Thoracic aorta | Shunting | Multidisciplinary repair with prosthetic graft; endovascular measures |
| Pulmonary | Identification of injury; clamping of peripheral injuries; hilar twist | Suture pneumorraphy; tractotomy with selective ligation of bleeding vessels; non-anatomic lung wedge resection; lobectomy; pneumonectomy |
| Chest wall | Ties placed around ribs to ligate vessel; direct electrocautery | Endovascular embolization |
| Airway | Advancement of endotracheal tube beyond injury, use of double-lumen tube, insertion of bronchial blocker | Lobectomy or pneumonectomy |
| Esophagus | Repair or resection with proximal nasal-gastric tube decompression and wide external drainage | Repair with gastric conduit or colonic interposition at future date |

## 26.5 Damage Control Resuscitation in the Operating Room and Post-operatively

Armand and Hess noted in 2003 that when a unit of whole blood is separated into the component packed red blood cells, plasma, and platelets, the resulting products do not have the same activity as the whole unit. Even if the units are returned in a 1:1:1 ratio, there is still a dilutional effect [89]. Malone et al. in a 2005 poll of world-wide trauma centers, noted much variation in transfusion practice. They noted anecdotally, however, that prevention of coagulopathy can be accomplished with 1:1:1 RBC, plasma, and platelet transfusion. The simplicity of such a ratio would also assist in transfusion logistics [90]. While many transfusion protocols at the time emphasized sustained administration of red blood cells early and administration of plasma at a later time, Ketchum et al. in 2006 postulated that earlier administration of plasma could reduce coagulopathy [91].

Borgman et al. in 2007 offered further clinical insight into transfusion ratios. In a retrospective review of 246 military combat patients, red blood cell to plasma transfusion ratios of 1:8, 1:2.5, and 1:1.4 were compared. They noted, respectively, a 65%, 34%, and 19% mortality rate in these groups ($p < 0.001$). They recommended a 1:1 red blood cell to plasma transfusion ratio [92]. Holcomb et al. in 2008 noted similar results in 466 civilian trauma patients, ultimately recommending a 1:1:1 ratio for red blood cells, plasma, and platelets [93].

At this time, many centers strive for 1:1:1 transfusion ratio. The optimal ratio, however, is still being studied. The PROPPR trial in 2015 enrolled 680 trauma patients likely to need massive transfusion, and randomized them to 1:1:1 vs 1:1:2. There was no overall difference in mortality, though subgroup analysis showed death from exsanguination was decreased in the 1:1:1 group (9.2% vs 14.6%, $p = 0.03$) [94].

It would seem that whole blood transfusion would be the most optimal option. Military field hospitals often utilize whole blood donated from available military personnel. The data, however, have been mixed. A 2009 retrospective study of 354 military trauma patients transfused more than one unit of blood showed that there was improved 24-h and 30-day survival in the group with warm fresh whole blood, as opposed to those component therapy [95]. A separate retrospective military study from 2011, however, studied component therapy vs fresh whole blood in massively transfused patients. There was no difference in 24 or 30-day survival in this study [96].

Civilian studies on the matter remain inconclusive. A 2011 study of 353 consecutive trauma patients requiring massive transfusion showed that the whole-blood group attained improved coagulation laboratory parameters, but there was no difference in blood transfusions or mortality. A pilot study from 2013 compared "modified whole blood" (cold-stored whole blood and a component of platelets) versus component therapy. There was no difference in transfusion requirements, but subgroup analysis of patients without traumatic brain injuries showed that the modified whole blood group had a decrease in transfusion volumes [97]. The optimal blood transfusion strategy remains debated.

To add to the complexity of transfusion strategies, viscoelastic assays have emerged as an additional laboratory indicator to guide transfusions. The first clinical application was reportedly during the Vietnam War, but viscoelastic assays were more dominantly used in the liver transplant and cardiac surgery literature [98, 99]. In 1997, Fairfax regional medical center published its data of a popular viscoelastic assay, thromboelastogram (TEG) in trauma. It found that TEG was predictive of early transfusion [100]. At Ben Taub Hospital, TEG was historically used to guide transfusion in blunt and penetrating trauma patients. The center later transitioned to a 1:1:1 strategy. Retrospectively comparing the two different time periods, the authors did not find any overall difference in mortality. In a subgroup analysis of penetrating trauma patients requiring more than 10 units of blood, however, mortality was higher with the 1:1:1 MTP method in comparison to the TEG method (54.1% vs 33.3%, $p = 0.04$) [101]. A

2016 randomized prospective study by Gonzalez et al. studied TEG vs conventional coagulation assay (CCA) to guide massive transfusion. They noted that the CCA group received more platelets and plasma, but the TEG group had improved mortality (19.6% vs 36.4%, $p = 0.049$). Limitations of the trial include its relatively small size and weekly-alternating method of randomization [102]. The optimal method of guiding transfusions remain debated.

Also, critical to overcoming the lethal triad of coagulopathy, acidosis, and hypothermia is warming of the patient. Forced air warming, convective-fluid warming-pads, and warming of infused volume and blood are common strategies to combat hypothermia. A relatively novel method in trauma patients, however, is the utilization of intravascular warming catheters. Originally devised for targeted temperature management after cardiac arrest, the catheters can also be used to warm circulating blood that flows past the intravascular catheter. A case report from Japan in 2014 described the successful utilization of a warming catheter in a coagulopathic trauma patient that had required thoracotomy for intrathoracic bleeding. Core temperature improved from 32.4 °C to 36.0 °C after 125 min of intravascular warming [103]. A US case series from 2018 described usage of an intravascular warming catheter in three torso gunshot victims who had pre-hospital cardiac arrest. Despite a mean of 104 units of blood required for the three patients, a mean warming rate of 1.04 °C per hour was achieved. Two of the three patients survived to discharge with intact neurologic function [104]. The use intravascular warming devices in damage control patients requires further study.

## 26.6 Conclusions

Damage control resuscitation remains a strategy to maximize injury control while considering the physiologic reserve of the patient. It is a tool that is used in severely injured trauma patients for which definitive surgery may be too physiologically taxing. The surgical aspect of damage control emphasizes control of hemorrhage and control of gastrointestinal contamination. Various technical maneuvers can be used to accomplish these goals, whether the injury is in the chest or abdominal cavity. Perhaps the most common actions are bowel resection without anastomosis and packing to control hemorrhage. Definitive reconstruction can be accomplished after the patient has been more completely resuscitated and physiologic reserve has been restored.

The resuscitation aspect of damage control emphasizes balanced volume restoration with a 1:1:1 ratio for red blood cell, plasma, and platelet transfusions. This must occur without delaying any necessary surgical control of hemorrhage. However, the optimal method of resuscitation remains debated, and thromboelastography-based transfusion algorithms or whole-blood transfusion strategies deserve further study.

Various techniques are available to manage the temporarily open chest or abdominal cavity. Negative pressure wound therapy is a popular option, though the optimal wound management method remains debated. Significant complications, however, can result from damage control maneuvers. The open chest or abdominal wound carries risks of wound complications such as fistulae and hernia. Differentiating between patients who can receive definitive repair at initial surgery and those requiring damage control is a key aspect of trauma care. From the pre-hospital setting to the trauma bay, and to the operating room and after, balancing timing, resuscitation, and extensiveness of surgery can improve mortality and other patient outcomes.

**Key Concepts**

- Damage control resuscitation and its various phases.
- Technical aspects to control hemorrhage and gastrointestinal contamination in the chest and abdomen.
- Temporary wound management.
- Balanced resuscitation and physiologic restoration.
- Definitive management of injuries at time of physiologic optimization.

**Take-Home Messages**

- Damage control surgery remains an important tool for managing unstable trauma patients.
- Initial priorities are surgical control of hemorrhage and gastrointestinal contamination.
- During and after initial surgery, focus is also placed on balanced resuscitation with restoration of normothermia, correction of acidosis, and resolution of coagulopathy.
- Definitive surgical repair of injuries is reserved after correction of these physiologic parameters.
- Various methods are available to temporarily manage open wounds. While the optimal method is uncertain, negative pressure therapy is a popular option.
- Damage control methods can still result in significant complications, such as fistulae and hernia. Timely reconstruction and definitive repair may result in improved outcomes.

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# Fracture Management

# 27

Roman Pfeifer and Hans-Christoph Pape

**Learning Objectives**

- The management of severely injured patient with fractures has changed over the last decades.
- Diagnosis and assessment of the true degree of soft tissue damage in closed fractures is crucial.
- Open injury scores (Gustillo, MESS, Ganga Hospital Score) may guide the decision-making.
- Indications and interventions of DCO in unstable polytrauma patients and in those with stable isolated musculoskeletal injuries are described.
- Four different phases of the posttraumatic course are separated.
- Patients with multiple blunt trauma have to be assessed for "four pathophysiologic cascades."
- Surgical priorities and special situations are described in the presence of concomitant injuries.

## 27.1 Introduction

The management of severely injured patient with fractures has changed over the last decades. In the 1980s and early 1990s, early definitive stabilization of all fractures within 24 h after injury was the mainstay of treatment in trauma surgery [1, 2]. This treatment approach has developed in a time where polytraumatized patients were treated in a staged fashion in order to avoid the development of the so-called "Fat Embolism Syndrome." Thus, long bone fractures were mainly temporally stabilized by traction and recumbency. This concept was associated with numerous complications such as pulmonary infections, atrophy of the musculature, and thromboembolic complications due to prolonged immobilization [3]. The early total care (ETC) was also stimulated by advances of osteosynthesis techniques and implants over these decades. Early fracture fixation was associated with in early mobilization, reduced nutritional depletion, and wound infection [2, 4]. Thus, early total care has become a standard approach in polytrauma in the 80s and early 90s. However, several authors also criticized that early fixation might be detrimental for several patient groups [4, 5]. Especially, patients with severe head injuries and blunt thoracic trauma have been found to be at risk to develop systemic complications [3, 6]. Moreover, it has been discussed that additional

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bleeding during the surgery may induce a "second hit" beyond the systemic impact of the initial injury [6, 7].

In the late 1990s, it became clinically evident that definitive stabilization of all fractures in all severely injured patients was inadequate, and the management of major fractures changed to a more selective method called damage control orthopedics (DCO) [8, 9]. It has been widely accepted that one should differentiate between those patients who can tolerate prolonged surgical procedures and those for whom this is not advisable [10]. By using external fixation techniques, unstable or critically ill patients can be temporally stabilized and wait until stabilization of patient condition so that definitive fixation of fractures can achieved. Prolonged surgical procedures undertaken early after the injury may increase the risk of the development of the systemic complications such as Systemic Inflammatory Response Syndrome (SIRS), Acute Respiratory Distress Syndrome (ARDS), and Multiple Organ Failure (MOF).

Since then, multiple polytrauma management strategies have been adapted to improve the outcome in these patients, such as defined transfusion protocols (point of care strategy), permissive hypotension (damage control resuscitation), and surgical strategies to limit the amount of bleeding in the first operative. Recent publications, therefore, have argued if an early definitive fixation or damage control approach is advantageous. In the following chapter, we are going to describe relevant factors and parameter for decision-making in polytraumatized patients with fractures.

## 27.2 Assessment of the Fracture

### 27.2.1 Soft Tissue Injury in Closed Fractures

Proper diagnosis and assessment of the true degree of soft tissue damage in closed fractures is crucial. Contusions may raise more therapeutic questions than simple inside out puncture wounds. Weakening of the skin barrier may be followed by necrosis and infection. Assessment of the severity of a closed fracture helps guide the timing and type of osteosynthesis (Table 27.1). Early detection and evaluation of neural, vascular, and muscular injuries also affects the overall outcome.

**Table 27.1** Classification of soft tissue injuries in closed fractures [11]

| |
|---|
| **Closed fracture G0**: No injury or very minor soft tissue injury. The G0 classification covers simple fractures, i.e. fractures caused by indirect injury mechanisms. |
| **Closed fracture G1**: Inside out contusions caused by fracture fragments. |
| **Closed fracture G2**: Deep, contaminated abrasions or local dermal and muscular contusions. Impending compartment syndrome is usually associated with a G2 lesion. These injuries usually are caused by direct forces that shear off soft tissue and are often associated with moderate to severe fracture types. |
| **Closed fracture G3**: Extensive skin contusions, muscular disruption, decollement and obvious compartment syndrome combined with any closed fracture are graded as G3. In this subgroup, severe fracture types and comminuted fractures are usually seen. |

Specific attention has to be dedicated to the occurrence of compartment syndromes. These should be anticipated when the capillary perfusion pressure is less than intracompartmental pressure. Pain out of proportion in responsive patients is the hallmark indicator. In sedated patients, measurement of intracompartmental pressure is mandatory. If in doubt, early fasciotomy has to be performed as a surgical emergency.

### 27.2.2 Open Fractures

The standard classification system for open fractures was described by Gustilo [11]. It is a descriptive classification describing a spectrum of soft tissue injury. The classification is associated with the risk of infection, non-union, and help guide fracture management. Type I are lower energy injuries with a skin defect of 1 cm or less in length. Type II injuries have a large skin defect ranging from 1 to 10 cm. Type III injuries are involved with higher energy and more injury to the soft tissues. In Type IIIa inju-

ries, primary soft tissue coverage can be obtained without a flap in contrast to Type IIIb injuries associated with severe soft tissue trauma requiring rotational flap or free tissue transfers to obtain soft tissue coverage. Type IIIc open fractures are associated with vascular injuries (see the chapter Open Fractures).

Initial care of open fractures consists of thorough irrigation, debridement, and assessment of the soft tissues damage, followed by fracture fixation. Exposed bone requires soft tissue coverage which should be performed as soon as possible. The extent of vascular and nerve damage and the general patient condition are important. In soft tissue trauma, the extent of the injury and devitalized tissue may not be completely evident at the same time of the initial debridement. In severe soft tissue trauma, planned reevaluation is often required, not only in highly contaminated wounds.

Amputation versus reconstruction of upper and lower extremity fractures associated with severe open injuries remains a question. Time-consuming reconstructive surgery in severely injured patients may increase morbidity and mortality. In cases of pending amputation, the MESS score (Mangled Extremity Severity Score) can be of some help which provides an objective evaluation [12]. The Ganga Hospital Score (GHS) is another clinical open injury score that was describe by Rajasekaran et al. [13] from a high-volume center in India (Table 27.2). The score was developed after three clinical trials and has been shown to be effective at predicting whether a limb can be salvaged or will need amputation. The GHS considers the injury to the bone, skin, and musculotendinous units individually, as well as comorbid conditions. Recent publications indicate the predictive value of this score in patients who present with an open fracture of the tibia [14].

Open fractures with limited soft tissue injury can usually be stabilized definitively at the time of initial debridement. After the initial debridement, the fracture is stabilized with the most suitable implant and method of fixation. Open fractures caused by high energy trauma are usually associated with severe soft tissue damage and commonly combined with extensive bone loss or destruction. This injury requires a graded concept of care. Usually, a temporal fixation strategy is used, if soft tissue coverage of the hardware cannot be achieved. Placement of the external fixator should consider the definitive stabilization until closure of the wound. The personality of each fracture requires individual treatment. In multiply injured patients, the overall injury severity has to be considered as well as the extent of shock and any initial blood loss.

**Table 27.2** Ganga Hospital Score allows the classification of covering tissues, muscle and nerve injuries, and skeletal structures [13, 14]

| | |
|---|---|
| **Covering tissues: skin and fascia** | |
| • Wound with no skin loss and not over fracture site | 1 |
| • Wound with no skin loss and over fracture site | 2 |
| • Wound with skin loss and not over fracture site | 3 |
| • Wound with skin loss and over fracture site | 4 |
| • Wound with circumferential skin loss | 5 |
| **Functional tissues: musculotendinous and nerve units** | |
| • Partial injury to musculotendinous unit | 1 |
| • Complete but repairable injury to musculotendinous unit | 2 |
| • Irreparable injury to musculotendinous unit/nerval injury | 3 |
| • Loss of one compartment of musculotendinous unit | 4 |
| • Loss of two or more compartments or subtotal amputation | 5 |
| **Skeletal structures** | |
| • Transverse or oblique fractures | 1 |
| • Large butterfly fragment >50% circumference | 2 |
| • Comminution or segmental fractures without bone loss | 3 |
| • Bone loss <4 cm | 4 |
| • Bone loss >4 cm | 5 |
| **Co-morbid conditions** | |
| • Injury to debridement time interval > 12 h | |
| • Sewage or organic contamination or farmyard injuries | |
| • Age > 65 years | |
| • Drug-dependent diabetes or cardiorespiratory diseases leading to increased anesthetic risk | |
| • Polytrauma with Injury Severity Score > 25 or Fat Embolism | |
| • Hypotension with systematic blood pressure less than 90 mmHg at the time of presentation | |
| • Another injury to the same limp or compartment syndrome | |

During initial debridement, all soft tissues should be assessed. If necrotic tissue is left in place, further contamination, bacterial growth, and infection are likely to occur. Sufficient surgical exposure of the injury is essential for adequate assessment.

Special situations include the following:

1. Local Soft Tissue Injury vs. Degloving.

   A degloving injury has to be ruled out or diagnosed properly. The assessment includes the degree of soft tissue laceration and periosteal stripping. Thereby, assessment of osseous vascularity is helpful to decide whether fragments should be maintained or removed.
2. Treatment of Morel-Lavallée lesions (subcutaneous degloving).

   Morel-Lavallée lesions are defined as large subcutaneous tissue degloving injuries induced by shearing forces. This mechanism causes a large underlying hematoma. In contrast to other soft tissue injuries, Morel-Lavallée lesions should *not* be debrided aggressively. Small incisions allow complete evacuation of the hematoma. The cutaneous skin flap is decompressed and has a better chance to survive.
3. Consultation of the Plastic Surgeon.

   Exposed bone and tendons in an area with limited soft tissue coverage often requires early treatment with soft tissue flaps. If severe muscle injury or nerve damage is present, muscle or tendon transfer procedures can be performed in a timely fashion to avoid severe disabilities secondary to loss of motion.

In multiply injured patients, there is a higher risk of increasing soft tissue necrosis due to impaired soft tissue perfusion (in post-traumatic edema and increased capillary permeability caused by massive volume resuscitation). Therefore, multiple planned operative revisions have to be scheduled. These "second look" surgeries allow for recurrent assessment of the soft tissues and any additional muscle or skin necrosis. This strategy enables the surgeon to do a timely repeat debridement if required. These operative revisions of soft tissue injuries should be scheduled every 48 h as long as there is an impairment of local perfusion. The traumatic wound should be left open and covered with a synthetic saline-soaked dressing or by vacuum therapy. Local vacuum therapy may save the patient some of the planned "second look" surgeries. It has been shown to be successful in treatment of a variety of wounds including extensive degloving injuries [15]. Subatmospheric pressure on the wound site enhances wound healing, reduces the amount of fluid, and increases local blood flow [16, 17]. These effects have been shown to minimize the risk for wound infection [18].

When definitive internal fixation is possible from the soft tissue point of view, the insertion of stable devices is preferred. In case of shaft fractures of the femur or tibia, the use of intramedullary nails is recommended whenever possible. For intra-articular open fractures, most surgeons prefer a two-step strategy. Some authors recommend limited internal fixation and gross reduction of severely displaced fragments for soft tissue decompression. The minimally invasive fixation comprises the reconstruction of the joint itself and temporary stabilization with K-wires followed by stabilization with lag screws and adjusting/set screws. Definitive fixation is carried out secondarily following consolidation of the soft tissues.

## 27.3 Fracture Treatment

Since 2018, a group of experts has met to focus on the role of surgical interventions for any orthopedic fixation strategy. The aim of this group was to discuss indications and interventions of DCO in unstable polytrauma patients and in those with stable isolated musculoskeletal injuries with systemic disease issues [19]. Table 27.3 describes indications and interventions in isolated musculoskeletal injuries. Certain extremity injuries are subjected to a staged management even in a physiologically stable patients: due to (1) severe soft tissue damage, (2) gross bacterial contamination, (3) long segment bone loss, and (4) complex articular fractures. To use

**Table 27.3** Indications and interventions with agreement for isolated musculoskeletal injuries

| | Indications | Interventions |
|---|---|---|
| Spine | Unstable thoracic and lumbar spine fractures | Percutaneous dorsal instrumentation |
| Pelvis | Complex pelvic ring injuries with concomitant nerve or vascular injuries | External pelvic fixation |
| | Open pelvic injuries | External pelvic fixation |
| | Stabilization of the pelvis for pelvic packing | C-clamp |
| | Posterior pelvic ring injuries | Percutaneous screw fixation |
| | Hemodynamic instability with unstable pelvic fracture | Pelvic packing |
| Extremities | Open fractures with soft tissue contamination | External fixation of long bones |
| | Open fractures with large soft tissue defects | External fixation of long bones |
| | Large bone defects | External fixation of long bones |
| | Complex intra-articular fractures | External fixation of long bones |
| | Fractures with concomitant vascular injuries | External fixation of long bones |
| Soft tissues | Morel-Lavallée lesion | VAC therapy |
| | Soft tissue contamination | VAC therapy |
| | Large soft tissue defects | VAC therapy |
| | Compartment syndrome | Compartment fasciotomy |
| | Mangled extremity with uncontrollable hemorrhage | Amputation |

the term "Damage Control" in physiologically stable patients what do not suffer severe trauma would lead to confusion. Therefore, the use of the term "MusculoSkeletal Temporary Surgery" or "MuST Surgery" has been suggested. Table 27.4 summarizes indications and interventions in multiply injured patients.

Whenever possible, polytrauma patients with multiple injuries should undergo definitive fixation of their major fractures. If patients with mul-

**Table 27.4** List of indications and interventions with agreement for damage control surgery of musculoskeletal injuries in polytrauma

| | Indications | Interventions |
|---|---|---|
| Spine | Occipito-cervical dissociation | Halo fixation |
| | Unstable thoracic and lumbar spine fractures | Percutaneous dorsal instrumentation |
| Pelvis | Unstable pelvic ring fractures | External pelvic fixation |
| | Complex pelvic ring injuries with concomitant nerve or vascular injuries | External pelvic fixation |
| | Open pelvic injuries | External pelvic fixation |
| | Posterior pelvic ring injuries | Percutaneous screw fixation |
| | Type C pelvic fracture disruption of sacroiliac joint and sacrum fracture | C-clamp |
| | Hemodynamic instability with unstable pelvic fracture | Pelvic packing |
| | Exsanguinating hemorrhage related to pelvic injuries | REBOA |
| Extremities | Open fractures with soft tissue contamination | External fixation of long bones |
| | Open fractures with large soft tissue defects | External fixation of long bones |
| | Large bone defects | External fixation of long bones |
| | Complex intra-articular fractures | External fixation of long bones |
| | Fractures with concomitant vascular injuries | External fixation of long bones |
| | Complex peri-prosthetic fractures | External fixation of long bones |
| Soft tissues | Morel-Lavallée lesion | VAC therapy |
| | Soft tissue contamination | VAC therapy |
| | Large soft tissue defects | VAC therapy |
| | Compartment syndrome | Compartment fasciotomy |
| | Mangled extremity with neurologic injuries | Amputation |
| | Vascular injuries with ischemia more than 6–8 h | Amputation |
| | Mangled extremity with uncontrollable hemorrhage | Amputation |

tiple injuries cannot be cleared for safe initial definitive care, DCO [20] has been incorporated in order to stabilize the osseous injury, reduce the risk of bleeding, pain, and associated inability to mobilize the patient. The strategy has been successfully applied in injuries of long bones [21], spine, and pelvis [22] until the patient is physiologically stable for conversion to definitive fixation [23]. The expert survey revealed that halo fixation is not the "gold standard" in damage control of unstable C-spine injuries. Initial immobilization is mainly performed by the application of hard cervical collars. Especially, the presence of intracranial bleeding and cranial fractures, need for a craniotomy, severe soft tissue injuries in the head, and severe chest trauma with pulmonary contusion may be contraindicated for halo fixation [24]. In thoracic and lumbar fractures, percutaneous techniques for dorsal spine instrumentation appear to be a possible approach well suited for DCO [25]. In pelvic fractures, anterior external fixation through the iliac crest or supraacetabular canal provides adequate temporary pelvic stability in most AO/OTA C-type injury patterns [26]. Biomechanically unstable posterior pelvic ring disruptions, such as vertical shear injuries, may require stabilization of posterior pelvic ring (e.g., C-clamp or sacroiliac screw fixation) [27].

### 27.3.1 Upper Versus Lower Extremity Injuries

In severe open fractures of the upper extremity, certain principles are different from those of the lower extremities. It is widely accepted that surgical management of lower extremities precedes the treatment of upper limb injuries. Moreover, the maintenance of correct length is less important in the treatment of upper extremity fractures. Severe upper extremity injuries, such as open fractures, compartment syndrome, and concomitant vascular injuries require immediate surgical management. In general, splinting or definitive fixation are more frequently performed in the upper extremity because soft tissue coverage is usually easier.

### 27.3.2 Fracture Care in Serial Extremity Fractures

The sequence of fracture care in patients with serial extremity injuries is important. Simultaneous treatment of extremity injuries can be achieved if the logistic conditions allow the surgeon to do so. The recommendations for the timing of fixation and are summarized as follows:

In serial injuries of the upper extremity, immobilization of humeral shaft fractures is an adequate option unless the injuries are open or if neurovascular injuries require surgical intervention. In forearm fractures, early fixation is advised due to limited soft tissue coverage.

In periarticular fractures, early fixation should be performed if the patient condition is adequate. If no definitive fixation can be performed and if the patient goes to the OR for other causes, transarticular external fixation (TEF) is preferred over casting. External fixation allows for better stability and assessment of soft tissues. This is of utmost importance due to the risk of compartment syndrome in these injuries.

In serial injuries of the lower extremities, definitive fixation should be achieved whenever possible. In floating knee injuries, retrograde femoral nails and an antegrade tibial nails can be placed using the same incision. In unstable patients, closed reduction and transarticular external fixation is performed for temporary fracture stabilization. Traction is not considered a "gold standard" for temporary long bone stabilization. However, this surgical technique can be used as a salvage procedure if external fixation is not applicable.

In metadiaphyseal and periarticular fractures, the priorities of care are dictated by the degree of soft tissue damage. The orthopedic emergencies that require operative care are:

- Compartment syndrome.
- Vascular injuries.
- Irreducible hip dislocation.
- Open fractures.

**Table 27.5** Classification system of complex extremity injuries [48]

| Fracture-associated injury | Points |
|---|---|
| Severe soft tissue damage | 2 |
| + hemorrhagic shock | 3 |
| ISS 16–25 | 1 |
| ISS > 25 | 2 |
| Neurovascular injury | 1 |
| Articular involvement | 1 |

| Type of complex extremity fracture | Points | Fracture care |
|---|---|---|
| Low risk | 1–2 | Definitive internal |
| Moderate risk | 3–4 | External |
| High risk | >4 | Consider amputation |

Among the higher priorities are femoral head fractures (Pipkin I–III) and fractures of the talus. Any other periarticular fracture is of lower priority, if no further complication is evident (compartment syndrome, pulse less extremity, or open fracture).

In the care of upper extremity fractures, similar principles are applied. In bilateral fractures, simultaneous treatment should be considered. Both extremities can be draped at the same time. Some parts of the procedure may require operative treatment of only one extremity at the time because of fluoroscopy, or handling issues. If the vital signs of the patient deteriorate during the operation, the second extremity may be temporarily stabilized using external fixation.

The classification system of complex extremity fractures is shown in Table 27.5.

## 27.4 Stages in Polytrauma

Initial fracture care of severely injured patients requires anticipation of potential problems and decision-making about the timing of interventions using a systematic approach [1]. Four time phases of the post-traumatic course are separated:

1. Acute phase (1–3 h): resuscitation (surgical, non-surgical).
2. Primary phase (1–48 h): stabilization (surgical, ICU care).
3. Secondary period (2–10 days): regeneration.
4. Tertiary period (weeks to months after trauma): reconstruction and rehabilitation.

### 27.4.1 Acute Phase (1–3 h After Admission): Resuscitation/ Hemorrhage Control

Initially, the focus of treatment lies in the control of acute life-threatening conditions. Complete patient assessment is required to identify all life-threatening conditions. This involves airway control, thoracocentesis, rapid control of external bleeding, and fluid and/or blood replacement therapy. Prioritization of the orthopedic injuries is crucial as well. The orthopedic fractures that require immediate surgery are listed above.

### 27.4.2 Primary Phase (1–48 h): Stabilization of Fractures

The primary phase is the usual time where major extremity injuries are managed. These include acute stabilization of major extremity fractures associated with arterial injuries and compartment syndrome. Fractures can be temporally stabilized by external fixation and the compartments released where appropriate. Systemic complications, such as development of systemic inflammatory response syndrome (SIRS) and acute lung injury (ALI), have to be considered if major musculoskeletal injuries are present.

### 27.4.3 Secondary Period (2–10 Days): Regeneration

During the secondary phase, the general condition of the patient is stabilized and monitored. In most cases, this implies days 2–4 after trauma. Surgical interventions should be limited to those absolutely required ("second look," debridement) and lengthy procedures should be avoided. Physiological and intensive care scoring systems help monitor the clinical progress.

### 27.4.4 Tertiary Period (Weeks to Months after Trauma): Reconstruction and Rehabilitation

During the tertiary phase, the patient is able to undergo further definitive fracture stabilization or conversation of initial "DCO" procedure. Intensive rehabilitation can help maintain range of motion and improve functional outcomes, social reintegration, and return to work.

## 27.5 Assessment of the Patient

Blunt injuries to extremities and trunk (thorax and abdomen) have been shown to be of immense importance to the clinical course of severely injured patients [4]. Patients with multiple blunt trauma have to be assessed for "four pathophysiologic cascades" (hemorrhagic shock, coagulopathy, hypothermia, and soft tissue injuries) in order to avoid life-threatening systemic complications (Fig. 27.1). These cascades have one

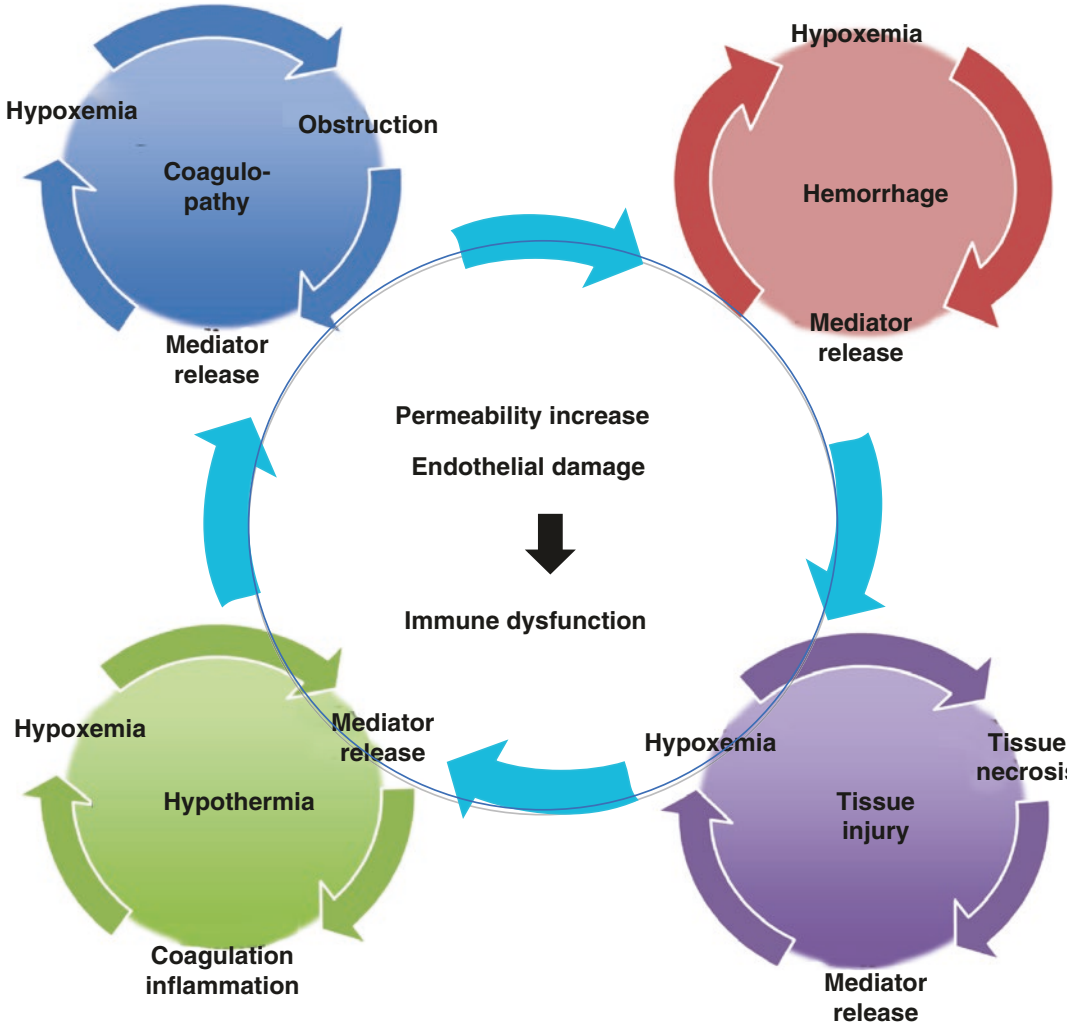


**Fig. 27.1** Four vicious cycles demonstrate the pathophysiological cascades. They are known to be associated with the development of post-traumatic immune dysfunction and endothelial damage. The exhaustion of the compensatory mechanisms results in development of systemic complications

common end point that results in endothelial damage [4]. The surgical management is based on the dynamic response to resuscitation rather than on initial snapshot of parameters at the time of presentation.

- Hemorrhagic Shock: The systolic blood pressure and dependence on vasopressors are reliable clinical marker of hypovolemia. Recent resuscitation strategies have changed towards permissive hypovolemia [28]. The aim is to reduce the amount of volume administered. Admission lactate threshold values of between 2.0 and 2.5 mmol/L were reported in large review publications [28]. Others reported a superiority of 24 h lactate clearance compared to initial lactate value [29]. In the interpretation of lactate level, certain preexisting conditions have to be considered: alcohol consumption, chronic renal failure, metabolic diseases, medication, sepsis, seizures, CO-poisoning, strenuous exercise, and respiratory or hepatic failure all influence baseline lactate levels and lactate clearance. Therefore, sole use of lactate value to guide management in polytrauma patients may not be advisable. Moreover, publications indicate that occult hypoperfusion (OH), defined as patients with normal vital signs and insufficient tissue perfusion and oxygenation, occurring in approximately one quarter of severely injured patients [30]. It must be kept in mind that younger patients are able to compensate to severe shock states by tachycardia and suddenly decompensate after a period without adequate resuscitation. OH is associated with the highest probability of poor outcomes in elderly patients, even worse than overt shock.
- Hypothermia: Several factors are known to affect the development of hypothermia in trauma patients; especially, hypovolemia with consecutive centralization of blood circulation and prolonged rescue time. Core temperature below 33 °C has been described to be a critical value [31]. Patients presenting with hypothermia are prone to develop coagulopathy, cardiac arrhythmias, and cardiac arrest.
- Coagulopathy: Low platelet count is a reliable screening marker for post-traumatic coagulopathy. It indicates an impending disseminated intravascular coagulation. Studies indicate that decreased systemic platelet count (below 90,000) on the first day is associated with multiple organ failure and death [32, 33]. More recent resuscitation strategies are mainly guided by restricted volume replacement and ROTEM/TEG controlled blood component transfusion therapy [34]. TEG and ROTEM provide some information to identify fibrinolysis phenotypes to stratify patients into different risk groups soon after trauma. Coagulopathic patients were associated with more severe injury, more severe base deficit, and lactate levels, as well as lower admission temperature, lower pH, and higher prehospital crystalloid volume [35] (see Chap. 10).
- Soft tissue injury: Major extremity injuries, crush injuries, severe pelvic fractures, thoracic and abdominal trauma (AIS >2) are included into this category. Severe soft tissue trauma may have additional systemic immunologic effects with consecutive stimulation of immune system and development of the systemic inflammatory response syndrome (SIRS).

The indication for damage control procedures in orthopedic trauma is not only made by physiologic parameters and hemodynamic stability. According to Roberts et al., the indication for damage control surgery is not only made according to patient physiology (57.6%) but also by focusing on injury severity (38.9%), injury pattern, and hemodynamic instability (14.3%) [36–38]. The presence of concomitant thoracic or abdominal injuries with a damage control indication indicate use of damage control surgery in musculoskeletal system as well. These indications might be difficult to access major vessel injuries; major liver or pancreaticoduodenal injuries; inability to control bleeding; need for staged abdominal or thoracic wall reconstruction; signs of an abdominal or thoracic compartment syndrome [36–38].

## 27.6 Physiology of Staged Treatment

The term "first hit" stands for the initial insult of trauma. The "second hit" is mainly affected by surgical procedures or clinical course. The "second hit" can enlarge the degree of damage leading to increased morbidity and mortality [39]. In order to reduce the secondary trauma load, the timing of fracture fixation in patient with multiple blunt injuries is based on physiological parameters. Patients can be placed into one of four categories (stable, borderline, unstable, in extremis) in order to direct the treatment approach. Figure 27.2 demonstrates the *safe definitive surgery* (SDS) concept in treatment of severely injured patient. This concept does not rule out the use of ETC or DCO, but rather put it in perspective of the clinical situation considering the dynamics of the clinical course. Due to repeated reevaluation and assessment of the patients regarding their physiology, dynamic classification, and adaptation of the treatment strategy is possible. Thus, advantages of both strategies (DCO or ETC) can be combined, which allow a safe definitive surgery in each situation. Another advantage of this approach is a better adaptation of the surgical strategy to regional differences and preclinical systems. Patients injured in an urban area are subjected earlier to a surgical intervention (e.g., ETC), than patients from sparsely populated regions. The physiological condition can worsen during the operation. The dichotomic approach (ETC versus DCO) do not respect these dynamics. Current strategies foresee that those major fractures that are associated with major hemorrhage should be in the focus of care. In patients responsive to resuscitation, this can be achieved by respecting the duration of initial surgery and associated blood loss. In the other hand, in a territorial state the rescue time might be prolonged. In this scenario, the initial assessment and further clinical evaluation require a special consideration of soft tissues and patients' physiology as well.

### 27.6.1 Stable Condition

Stable patients are hemodynamically stable and remain during the initial therapy. Moreover, there is no evidence of respiratory disorders, coagulopathy, hypothermia, and abnormalities of acid base status. Stable patients without comorbidities usually tolerate early definitive fracture fixation [40, 41].

### 27.6.2 Borderline Conditions

Borderline conditions are defined as indicated in Table 27.6. In this group of patients, a cautious operative strategy should be used. Additional invasive monitoring should be instituted preoperatively. A low threshold should be used for conversion to a "damage control" approach to the patient management, as detailed below, at the first sign of deterioration.

### 27.6.3 Unstable

Hemodynamically unstable patients demonstrating more than one high risk pathological change (Table 27.6) are classified as "unstable." These patients are at risk of rapid deterioration, subsequent multiple organ failure, and death. In these patients, a "damage control" approach is required. This entails rapid lifesaving surgery only when absolutely necessary and timely transfer to the intensive care unit for further stabilization and monitoring. Temporary stabilization of fractures using external fixation, hemorrhage control, and exteriorization of gastrointestinal injuries is advocated. Complex reconstructive extremity procedures should be delayed until stable conditions are achieved and the acute immunoinflammatory response to injury has subsided.

### 27.6.4 In Extremis Condition

These patients have ongoing uncontrolled blood loss. Despite extensive resuscitation, they remain

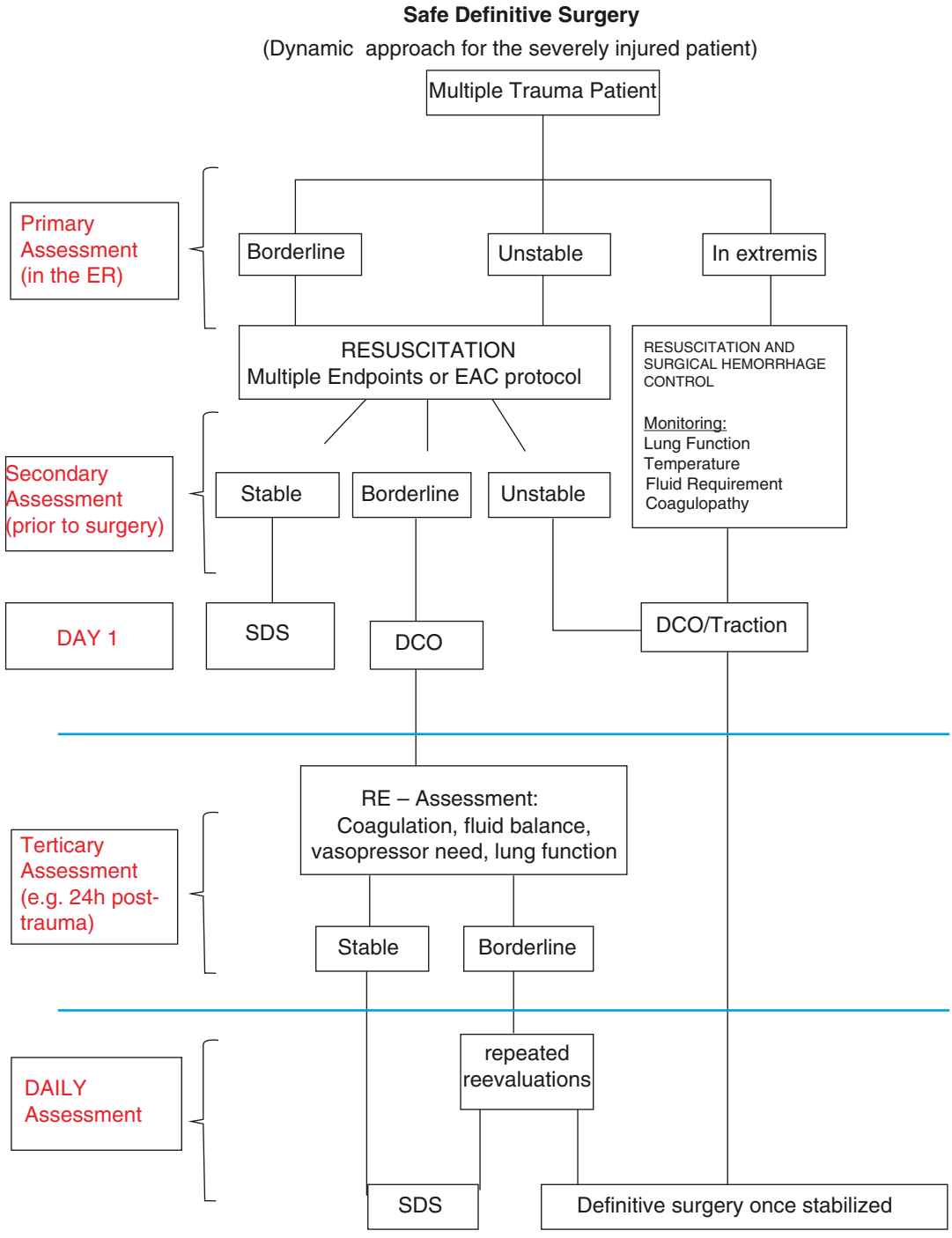


**Fig. 27.2** Polytraumatized patients are assessed according to the advanced trauma life support (ATLS) approach. Next, classification (stable, borderline, unstable, in extremis) of the patients is performed using clinical parameters. In "stable" patients, a safe definitive surgery (SDS) strategy can be applied. The patients "in extremis" should be transferred directly to the intensive care unit for invasive monitoring and advanced hematologic, pulmonary, and cardiovascular support. "Borderline" and "unstable" patients are brought to the ICU department for resuscitation. Thereafter, reevaluation of the clinical status is performed. "Unstable" patients and "borderline" patients with secondary deterioration should be treated according to the damage control orthopedics (DCO) concept. Patients with improving conditions can be subjected to safe definitive surgery [49]

**Table 27.6** Clinical parameters used to identify patients in uncertain condition, named "borderline." Usually, at least three of these have to be present to allow for classification as borderline [28]

| Factors to identify the borderline patient |
|---|
| • Multiple injuries (ISS > 20) in association with thoracic trauma (AIS > 2) |
| • Thoracic Trauma Score > Grade 2(>3 Rib Fractures, $paO_2/FiO_2$ < 200, Lung Contusion 1 lobe) |
| • Multiple injuries in association with severe abdominal or pelvic injury and hemorrhagic shock at presentation (systolic BP < 90 mmHg) |
| • Patients with bilateral femoral fractures |
| • Coagulopathy (ROTEM), Lactate (<2–2.5 mmol/L); Hypothermia below 35 °C; requirement >3 pRBC/h |
| • Massive transfusion (10 units RBCs per 6 h) initiates "goal directed therapy"(massive transfusion protocols) (ROTEM/FIBTEM); Lactate clearance <2.5 mmol/24 h |

severely unstable and suffer the effects of four vicious cycles: coagulopathy, shock, hypothermia, and tissue injury. The patients should then be transferred directly to the intensive care unit for invasive monitoring and advanced hematologic, pulmonary, and cardiovascular support. The treatment of life-threatening injuries is of importance. Orthopedic injuries can be stabilized rapidly in the emergency department or intensive care unit using external fixation.

## 27.7 Patient Assessment for Initial Definitive Surgery Versus Temporizing Orthopedic Surgery

The initial patient assessment usually is performed using scoring systems such as the ISS or NISS. For life threatening conditions, frequently due to penetrating trauma, the "triad of death" (blood loss, coagulopathy, and loss of temperature) approach has been used. In patients with blunt orthopedic injuries, it is important to account for soft tissue injuries as well and parameters of oxygenation to assess the clinical status of the patient [1].

Table 27.7 documents parameters and scoring systems that can be used to categorize a patient's condition. Three out of the four criteria should be present to qualify a patient for a specific category [4]. It is important to note that the combination of these parameters is a suggestion only and has a low level of evidence. Nevertheless, most of the components are scores that have been routinely used in the past and are widely accepted. For screening purposes, the following threshold levels have been used: pulmonary dysfunction ($PaO_2/FiO_2$ < 250), platelet count (<95,000), hypotension unresponsive to therapy >10 blood units per 6 h, and requirement for vasopressors. Several studies indicate that only one lactate measure is not reliable as a marker for defining the status of a patient [28].

Inflammatory parameters have also been described to have predictive power for the development of complications (multiple organ failure) [3]. An exaggerated post-traumatic dysregulation of the immune system may occur leading to immune paralysis [33]. Recent studies rather support the idea of simultaneous induction of innate ("genomic storm") and suppression of adaptive immune system with concomitant gene activation [5].

## 27.8 Special Situations

### 27.8.1 Surgical Priorities in the Presence of Additional Head Injuries

According to the pathophysiology of head injury, the brain loses the autoregulation of blood flow in zones of contusion. Also, an increase in the utilization of glucose occurs, adding to the susceptibility to ischemic injury [6]. Head trauma patients are at greatest risk for decreased cerebral blood flow during the first 12–24 h following injury. Intraoperative hypotension is an important risk factor for secondary brain injury ("second hit" to the brain) [7]. The primary goal of management for traumatic brain injury are the avoidance of secondary insults (hypoperfusion) [7].

The management needs to be performed in close cooperation with the neurosurgical team and sudden changes in the strategy can occur according to the degree of cerebral swelling, imminent herniation, or increase in bleeding.

**Table 27.7** Incorporation of existing classification systems for clinical patient assessment for patient assessment

| | Parameter | Stable (Grade I) | Borderline (Grade II) | Unstable (Grade III) | In extremis (Grade IV) |
|---|---|---|---|---|---|
| Shock | Blood pressure (mmHg) | 100 or more | 80–100 | 60–90 | <50–60 |
| | Blood units (2 h) | 0–2 | 2–8 | 5–15 | >15 |
| | Lactate levels | Normal range | Around 2.5 | >2.5 | Severe acidosis |
| | Base deficit mmol/L | Normal range | No data | No data | >6–8 |
| | ATLS Classification | I | II–III | III – IV | IV |
| Coagulation | Platelet count (µg/mL) | > 110,000 | 90,000–110,000 | <70,000–90,000 | <70.000 |
| | Factor II and V (%) | 90–100 | 70–80 | 50–70 | <50 |
| | Fibrinogen (g/dL) | >1 | Around 1 | <1 | DIC |
| | D-Dimer | Normal range | Abnormal | Abnormal | DIC |
| Temperature | | <33 °C | 33–35 °C | 30–32 °C | 30 °C or less |
| Soft tissue injuries | Lung function; $PaO_2/FiO_2$ | 350–400 | 300–350 | 200–300 | <200 |
| | Chest trauma scores; AIS | AIS I or II (e.g., abrasion) | AIS 2 or more (e.g., 2–3 rib fractures) | AIS 3 or more (e.g., serial rib fx. >3) | AIS 3 or more (e.g., unstable chest) |
| | Chest trauma score; TTS | 0 | I–II | II–III | IV |
| | Abdominal trauma (Moore) | < or = II | < or = III | III | III or > III |
| | Pelvic trauma (AO class.) | A type (AO) | B or C | C | C (crush, rollover abd.) |
| | External (AIS) | AIS I–II (e.g., abrasion) | AIS II–III (e.g., mult. >20 cm tears) | AIS III–IV (e.g., <30% burn) | (Crush injury, >30 per cent burn) |

Among the parameters belonging to a given category, at least 2 should be met to qualify for a specific Three out of the four categories must be met to classify for a certain category. It is of note that patients who respond to resuscitation qualify for early definitive fracture care, as long as prolonged surgeries are avoided [4]

The orthopedic surgeon and the neurosurgeon need to reveal how much operative time, blood loss, and temperature loss can be accepted for each individual case. General rules are currently not available. If in doubt, monitoring of the intracranial pressure (ICP) is safer and should be performed. During fracture fixation, secondary insults should be avoided by maintaining adequate cerebral perfusion.

### 27.8.2 Surgical Priorities in the Presence of Additional Chest Injuries

The pathophysiology in chest trauma is well described. A lung contusion is a separate entity than osseous injuries and has a higher association with ARDS than rib fractures alone [8]. In isolated rib fractures, a decrease in biomechanical (lack of rib cage motion) and pain-related hypoxemia is reversed by artificial ventilation. With lung contusion, intrapulmonary edema can develop despite ventilation. This is mediated by inflammatory cells and causes a local immunologic reaction [9]. The progressive nature of a pulmonary contusion can cause problems and is frequently underestimated. Early after injury, the blood gas parameters can still be within normal limits, and the chest X-ray may also present as a false negative. The immunologic mechanisms initiated by pulmonary contusions are comparable to those seen after severe injury [10]. Thus, the host response to pulmonary contusion is simi-

lar to non-pulmonary injury, resulting in an increased risk of ARDS.

Patient evaluation focuses on the following clinical criteria: presence of a lung contusion on the initial chest X-ray or CT scan, worsening oxygenation (requirement of increased $FiO_2 > 40\%$ or $PaO_2/FiO_2 < 250$), and increased airway pressures (e.g., > 25–30 cm $H_2O$). The pulmonary function can change within hours after the injury and repeated blood gases should be obtained.

### 27.8.3 Surgical Priorities in the Presence of Additional Pelvic Ring Injuries

The pathophysiology of systemic effects in severe pelvic injuries is dictated by the degree of local blood loss from the pelvic floor, the presacral venous plexus, and any arterial damage. Unlike other injuries, auto tamponade does not occur and retroperitoneal bleeding may mimic intra-abdominal injury. Soft tissue disruption can have more severe side effects than in the extremities since a higher degree of kinetic energy is required to cause substantial displacement. In open injuries with intestinal damage, a substantial increase in the risk of infection and late sepsis occurs [33].

Timing of pelvic fixation is based on the hemodynamic status and the presence of associated abdominal injuries. The decision to attempt definitive fixation within 24–48 h appears to be dependent upon the pelvic ring fracture pattern [42] and can be attempted in stable and borderline patients. In unstable patients, the use of sheets wrapped about the pelvis or a pelvic binder allows for rapid circumferential splinting of the pelvic ring most effectively at the level of the greater trochanter [43].

The paucity of studies in the literature seems to support early surgical management of such injuries. Favorable patterns may be treated by percutaneous fixation when several factors coincide: closed reduction can be achieved, the injury pattern is amenable to screw fixation alone, and the surgeon and operating team are available and experienced. In cases of exsanguinations from a pelvic ring injury, direct packing of the true pelvic space has been described [44, 45]. This technique is dependent upon achieving provisional stability of the pelvic ring with a binder, external fixation, or internal fixation. Patient with persistent arterial bleeding and hemodynamic and respiratory stability may be subjected to angioembolization of bleeding vessels [46, 47].

Current recommendations are to identify the source of pelvic hemorrhage and to stop the bleeding, followed by stabilization of the pelvic ring. The use of a binder is often successful for achieving a physiologic state that allows surgery unless a single artery is damaged. This may be treated by coiling.

## 27.9 Conclusion

The treatment strategies and management of fractures in critically injured have changed. Initial assessment includes the dynamic response to resuscitation and evaluation of the "Four Vicious Cycles" (*hemorrhagic shock, hypothermia, coagulopathy, and soft tissues*). "Safe Definitive Surgery" (SDS) concept has been introduced, which is a dynamic synthesis of both strategies (Early Total Care (ETC) and Damage Control Orthopedics (DCO)). This concept does not rule out the use of ETC or DCO, but rather put it in perspective of the clinical situation considering the dynamics of the clinical course. Moreover, the presence of concomitant injuries, such as soft tissue trauma, thorax injuries, abdominal trauma, and brain injuries need to be considered.

**Take-Home Messages**

- Proper diagnosis and assessment of the true degree of soft tissue damage in closed fractures is crucial.
- Staged management in a physiologically stable patients: "MusculoSkeletal Temporary Surgery" or "MuST Surgery."

- Staged management in a physiologically unstable patients: "Damage Control".
- Stages in Polytrauma:
  - Acute phase (1–3 h): resuscitation (surgical, non-surgical).
  - Primary phase (1–48 h): stabilization (surgical, ICU care).
  - Secondary period (2–10 days): regeneration.
  - Tertiary period (weeks to months after trauma): reconstruction and rehabilitation.
- Assessment of a polytrauma patient.
  - Hemorrhagic Shock/Acidosis.
  - Hypothermia.
  - Coagulopathy.
  - "Soft Tissue Injury"
- Physiology of staged treatment: Patients are classified.
  - Stable/Borderline/Unstable/In extremis.
- "Safe Definitive Surgery" (SDS) concept has been introduced, which is a dynamic synthesis of both strategies (Early Total Care (ETC) and Damage Control Orthopedics (DCO)).

**Conflicts of Interest** None of the authors has any conflicts of interests to declare.

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# 28 Mangled Extremity: Management in Isolated Extremity Injuries and in Polytrauma

Peter Kloen, Mark L. Prasarn, Craig Klinger, and David L. Helfet

## 28.1 Introduction

Clinical decision-making for trauma patients with extremity injuries is typically straightforward with resulting maintenance of viability and function of the involved limb. Damage control orthopaedics (DCO) has produced similar outcomes in the severely injured, unstable trauma victim with a relatively simple extremity injury. Numerous reports have described the beneficial effects of such temporizing measures that then allow the patient to be stabilized [1–5]. The decision process becomes much more clouded when dealing with trauma victims with severe extremity injuries, i.e., mangled extremities. There has been much debate as to whether limb salvage or amputation results in the best clinical outcomes in such a patient.

The emergent management of severe extremity trauma poses a difficult clinical decision for the entire treating surgical team. Resuscitation and management of all life-threatening injuries always must take precedence over any extremity injury. In a small subset of patients with complete traumatic disruption and clearly irreparable injuries an immediate completion amputation should be performed. Likewise, in the setting of prolonged limb ischemia, severe soft tissue loss that cannot be reconstructed, or concurrent life-threatening injuries elsewhere in an unstable polytrauma patient, a primary amputation is likely indicated. Also, patients with severe ipsilateral foot and ankle crush injuries may be better served with immediate amputation.

There exists a significant population of trauma patients in whom such clear indications for amputation are absent. It has been questioned whether or not attempted preservation of the limb in such patients is appropriate, or whether the patient would be better served with primary amputation. In many circumstances, the patient undergoes prolonged unsuccessful attempts at limb salvage only to be subject to great physical, psychological, financial, and social suffering. Various scoring systems have been devised to attempt to identify patients who should have limb salvage attempted versus those who should

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undergo primary amputation. The reliability of such scoring systems has been questioned, and the outcomes of limb salvage versus amputation debated. It still remains unclear in the literature as to which modality results in the optimal outcome, and in whom each should be performed. The treating surgeon and patient therefore still have no objective simple criteria to assist in making such a monumental decision.

## 28.2 Mechanism of Injury

The vast majority of injuries that pose the possible risk of amputation are due to blunt trauma. Motor vehicle crashes and industrial/farm accidents are the leading causes of such injuries in both the upper and lower extremities [6–16]. Falls from a height, high-velocity gunshots, and explosion injuries constitute the remainder of mechanisms [13, 17, 18]. The most significant factor involved with the injury mechanism is the amount of energy transferred to the extremity rather than the actual mechanism. The relative amount of energy absorbed directly translates into the amount of destruction to the bone and soft tissues. The concept of the "zone of injury" has been coined to define the area of the extremity affected by the injuring force. This zone may be defined by the fracture type, the amount of comminution, the area of crush, laceration, or shearing of the soft tissues, or devascularization of the entire limb [11].

## 28.3 Common Injury Patterns

Most studies have defined severe extremity trauma as those with associated complex fractures, dysvascular limbs, significant soft-tissue loss, neurological injury, and severe injuries to the distal extremity (hand, foot, and ankle). In all instances, there is a high-energy transfer to the involved limb that results in some combination of injuries to bone, arteries, tendon, nerves, and soft tissue. Complicated fractures are typically Gustilo grade IIIB and IIIC, but sometimes include select grade IIIA open fractures. These injuries often times have significant bone loss that requires either later bone grafting or bone transport using Ilizarov techniques. Dysvascular limbs can result from knee dislocations, internal amputation of the upper extremity, vascular injury secondary to a closed fracture, or penetrating wounds. Patients that have concomitant vascular disruption of the involved limb often constitute a great number of these injuries and are more likely to result in amputation [8, 19, 20]. Significant soft-tissue injuries are those secondary to crush mechanisms, those with degloving wounds, or avulsion injuries. Distal extremity injuries that result in consideration of amputation include Gustilo grade III pilon fractures, severe hindfoot or midfoot injuries, and loss of multiple digits in the hand.

## 28.4 Scoring Systems

Multiple scoring systems have been proposed by various authors to help guide in the management of complex extremity trauma. Even so, there is still much debate regarding the criteria that should be utilized in predicting which limbs can be successfully reconstructed versus those that should undergo amputation [21–25]. Most of these predictive indices have been criticized as being too subjective, complex, difficult to universally apply, derived retrospectively from small patient series, and not validated with functional outcome data [11, 26]. The four most commonly used systems are presented.

In 1987, Howe et al. proposed the Predictive Salvage Index (PSI) to use in the setting of combined orthopedic and vascular injuries involving the lower extremity. In this system, points are assigned for the level of arterial injury, the degree of bone and muscle injury, and the amount of time elapsed from injury to arrival to the operating room. In a small, retrospective analysis of 21 patients, all 12 patients with successful limb salvage had a PSI < 8, while 7 of the 9 who underwent amputation had a PSI of at least 8. They concluded that the PSI had a sensitivity of 78% and specificity of 100% for predicting amputation in this setting [22]. Other authors have reported much lower sensitivity and specificity of the PSI [26, 27].

In 1990, Johansen et al. introduced a system known as the Mangled Extremity Severity Score (MESS) after retrospectively reviewing 26 mangled lower limbs [23]. Under this system, the patient receives a numerical score for four different factors: skeletal/soft-tissue injury, ischemia, shock, and patient age. The scores are summated, and a value of <7 has been shown to be predictive of salvage [21, 23] (Table 28.1). The proposed advantages of this predictive index are that the information is readily available upon presentation, its relative simplicity, and its reproducibility. Others have criticized its subjectivity, and review of larger series of patients has shown lower sensitivity of the index than initially reported [26, 28, 29].

In 1991, Russell et al. proposed the Limb Salvage Index (LSI) based on the review of 70 limb-threatening injuries. The index predicts the likelihood of limb salvage based on ischemia time and injury severity to six types of tissue that may be involved [25]. In order to specifically quantify each of these categories, extensive examination during an operation is necessary. The system is therefore very detailed and difficult to use in the acute decision-making process [26]. Another detailed scoring system, known as the NISSSA (Nerve injury, Ischemia, Soft-tissue contamination, Skeletal injury, Shock, and Age), was introduced by McNamara et al. in 1994. This system is a more complex modification of the MESS that separates the skeletal and soft-tissue injury, and adds a score for nerve injury. In a small retrospective series (24 patients), the authors concluded that the system is more sensitive and specific than the MESS [30].

## 28.5 Management

Initial management of the patient with a limb-threatening injury begins with ATLS protocol emphasizing a primary survey with immediate assessment of ABCs. (Table 28.2) Following this, the field dressing should be removed and any significant bleeding immediately controlled. This should be done with direct pressure, tourniquet, a compressive dressing, or proximal clamping (in that order of preference). Once the resuscitative effort is underway, further assessment of other injuries should be undertaken as well as a thorough neurovascular examination. If there is disruption to the arterial flow to the extremity, and salvage is being considered, an intraluminal shunt may be used. Wound dressing, gross alignment, and splinting should be performed. Following this, any radiographic studies may be obtained (including vascular studies if necessary), and intravenous antibiotic and tetanus prophylaxis administered. We always calculate a MESS for each patient at the onset of treatment.

If an early amputation is deemed necessary, it is often advantageous to take medical record photographs to document the severity of the injury. We also recommend keeping a photographic record throughout the course of treatment if reconstruction is performed, to document both progress and decline. Our indications for early amputation include: unreconstructable osseous or soft-tissue injuries, irreparable vascular injuries, and loss of the plantar soft tissue. Previous authors have recommended amputation if plantar sensation is absent. Recent evidence has suggested that initially absent plantar sensation does not predict a poor functional outcome, and that it may return in more than half of patients followed out to 24 months [31]. We therefore do not use absent plantar sensation as criteria for a primary amputation alone.

The amputation should be performed at the most distal level possible, but should not include clearly nonviable tissues. Examining color, consistency, contractility, and bleeding determine tissue viability. It has been shown that transtibial amputations have significantly better functional outcomes and lower energy expenditure than more proximal levels of amputation [11, 32]. A thorough irrigation and debridement should be performed without any attempt to close the wound at this time. A sterile dressing or wound VAC can be applied, and a splint placed if the amputation is below the level of the knee or elbow (Fig. 28.1). Return to the operating room with repeat surgical debridements should be performed as deemed necessary. In most instances, several irrigation and debridements are undertaken prior to closure of the stump site.

**Table 28.1** Criteria of mangled extremity severity score

| Type | Characteristics | Injuries | Points |
|---|---|---|---|
| **Skeletal/soft tissue** | | | |
| **Group** | | | |
| **1** | Low energy | Stab wounds, simple closed | **1** |
| | | Fractures, small-caliber | |
| | | Gunshot wounds | |
| **2** | Medium energy | Open or multiple level | **2** |
| | | Fractures, dislocations, | |
| | | Moderate crush injuries | |
| **3** | High energy | Shotgun blast (close range) | **3** |
| | | High-velocity gunshot | |
| | | Wounds | |
| **4** | Massive crush | Logging, railroad, oil rig | **4** |
| | | Accidents | |
| **Shock** | | | |
| **Group** | | | |
| **1** | Normotensive hemodynamics | BP stable in field and in OR | **0** |
| **2** | Transiently hypotensive | BP unstable in field but | **1** |
| | | Responsive to | |
| | | Intravenous fluids | |
| **3** | Prolonged hypotension | Systolic BP <90 mmHg in | **2** |
| | | Field and responsive to | |
| | | Intravenous fluid only in OR | |
| **Ischemia** | | | |
| **Group** | | | |
| **1** | None | A pulsatile limb without | **0**[a] |
| | | Signs of ischemia | |
| **2** | Mild | Diminished pulses without | **1**[a] |
| | | Signs of ischemia | |
| **3** | Moderate | No pulse by Doppler, | **2**[a] |
| | | Sluggish capillary refill | |
| | | Paresthesia, diminished | |
| | | Motor activity | |
| **4** | Advanced | Pulseless, cool, paralyzed | **3**[a] |
| | | And numb without | |
| | | Capillary refill | |
| **Ischemia** | | | |
| **Group** | | | |
| **1** | <30 years | | **0** |
| **2** | >30, <50 years | | **1** |
| **3** | >50 years | | **2** |

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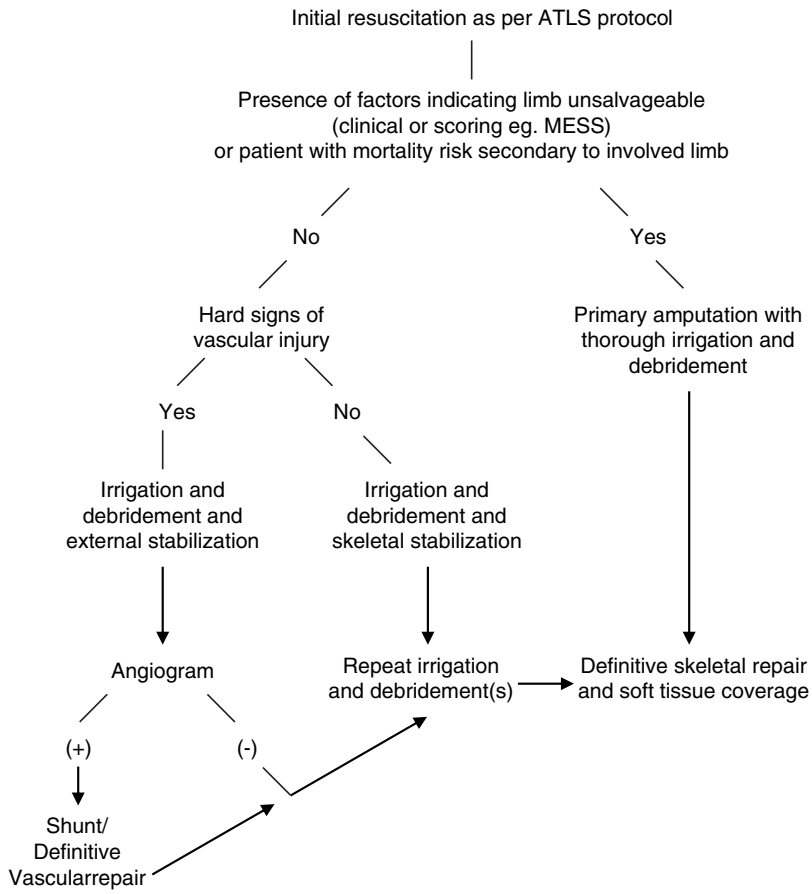
*OR* operating room, *BP* blood pressure
[a]Points X 2 if ischemic time exceeds 6 h

If the need for amputation is not clear upon initial examination, then limb salvage should be attempted. Once again a thorough irrigation and debridement with removal of any contaminants and nonviable tissue performed emergently. External fixation to gain stability of fractures and to aid in wound care is typically performed at this time. If necessary, a definitive vascular repair should be performed following skeletal stabilization. Ex-fix pins should be placed strategically away from the zone of injury and based on future incisions for definitive ORIF. Compromise of formal ORIF after DCO using external fixation is generally not an issue [5]. Fasciotomies should be performed as

**Table 28.2** Algorithm for the management of the patient with severe extremity trauma




necessary. Antibiotic bead pouches and negative pressure wound therapy can be used to help decrease infection and assist with wound care [33–38]. The extremity is closely monitored over the next 24–72 h for soft tissue viability and sensorimotor function. Wounds should be regularly inspected, and repeat irrigation and debridements performed based on wound appearance (tissue viability, presence of contaminants, infection, etc.). VAC dressings are changed every 48–72 h.

If at any point the limb is deemed unsalvageable of the patient's life is in jeopardy secondary to the extremity amputation should be performed. If the extremity remains viable for reconstruction and the patient condition permits, then definitive skeletal stabilization and early soft tissue coverage should be performed [39, 40]. The use of BMP-2 has been approved in complex open tibia fractures. It was shown to accelerate fracture healing, reduce infection rate, and decrease the need for secondary procedures to obtain union in a randomized, prospective study involving 450 open tibia fractures [41]. Further research involving a larger cohort of patients with longer follow-up is necessary to confirm these results and analyze the long-term complications and outcomes. Until more data is available, the utility and safety of BMP in the setting of open fractures is still uncertain. Various modalities are available for surgical fixation including: uniplanar external fixators, hybrid external fixators, thin-wire ring external fixators, plate and screw constructs, and intramedullary nails. There are pros and cons of each modality. It is beyond the scope of this chapter to recommend the type of fixation to use in the setting of complex extremity trauma. Many patients with require further surgery to achieve osseous union, and this should be discussed along with possible complications with each patient thoroughly [8, 19, 42] (Figs. 28.2 and 28.3).

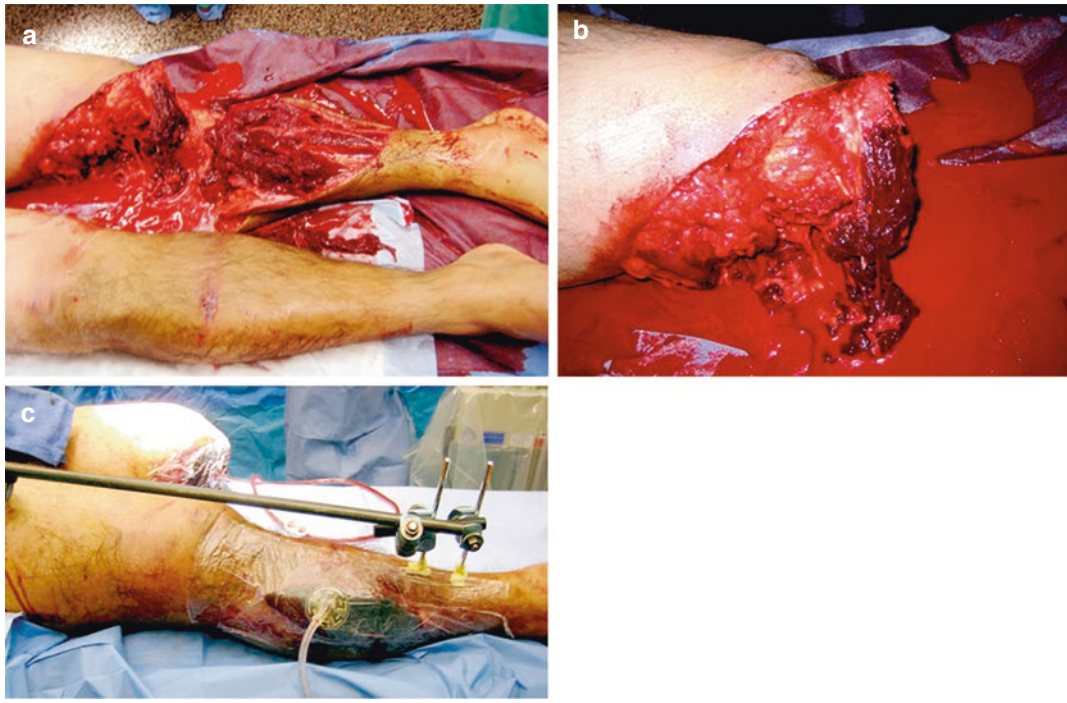
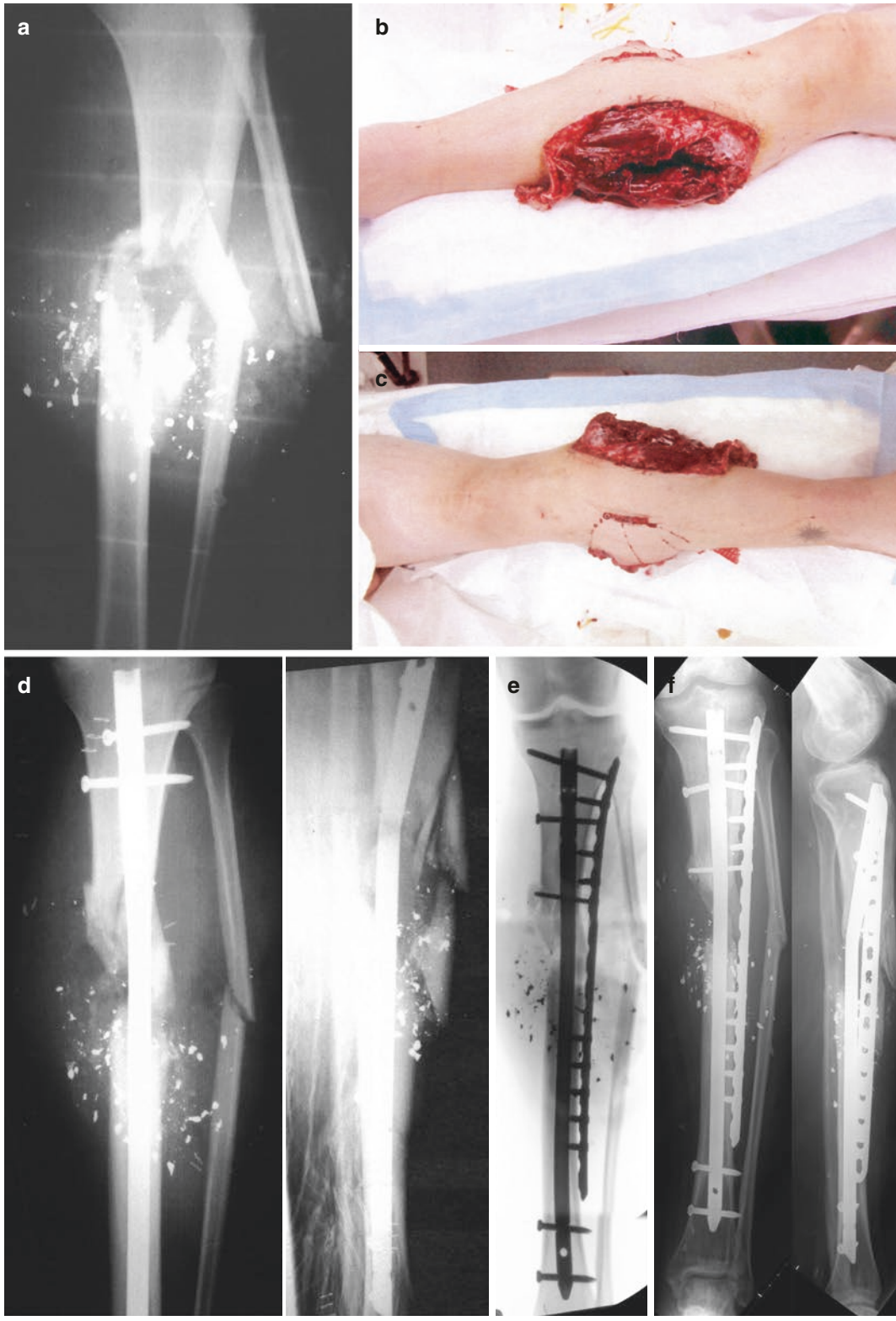



**Fig. 28.1** A 21-year-old male presented to the emergency department following a motorcycle collision with bilateral lower extremity injuries. (**a**) Left-sided pulse-less (Grade IIIC) "mangled" knee/lower extremity injuries and a right-sided bicondylar closed tibial plateau fracture with compartment syndrome (top image). (**b**) Left-sided completion of the above knee amputation retaining as much viable soft tissue as possible (middle image). (**c**) Application of negative pressure wound therapy dressing to left-sided amputation site, as well as external fixation of right bicondylar tibial plateau fracture and leg fasciotomies for compartment syndrome (bottom image)

**Fig. 28.2** A 36-year-old male was accidentally shot in the leg with a shotgun during a hunting trip. (**a**, **b**, **c**) He suffered an open, left-sided grade IIIC tibial shaft fracture with marked comminution. He also presented with complete functional deficit to his anterior compartment. He was taken to a local trauma center for irrigation and debridement (I&D), stabilization with and external fixation, and a saphenous vein revascularization of the popliteal artery. Subsequent multiple I&D procedures were performed (including compromised bone). A negative pressure wound therapy dressing was placed over the wound sites. An Inferior Vena Cava (IVC) filter was also inserted. (**d**) On day 3 a reamed, locked tibial intramedullary nail was inserted. (**e**) At 2 weeks following the injury, the patient was transferred to our institution for definitive management of his injuries. Repeat I&D was performed, the proximal interlocking screw was then removed to allow some correction of alignment and a percutaneous locking plate and screws was placed along the lateral surface of the tibia and a VAC dressing was applied. (**g**) Radiographs at 19 months illustrate some callus formation and a broken proximal interlocking screw. (**h**, **i**) Exchange IM nailing was planned and performed with placement of Demineralized Bone Matrix (DBM) and a Bone Morphogenetic Protein-7 (BMP-7) supplement. (**j**) At the latest follow-up visit at 29 months following revision surgery, he presented with good radiographic and clinical findings including increased callus formation and consolidation of the fracture, well-healed soft tissues, resolution of most pain symptoms, a return to activities of daily living and some recreational activities including weight training and skiing. A slight dorsiflexion lag was still present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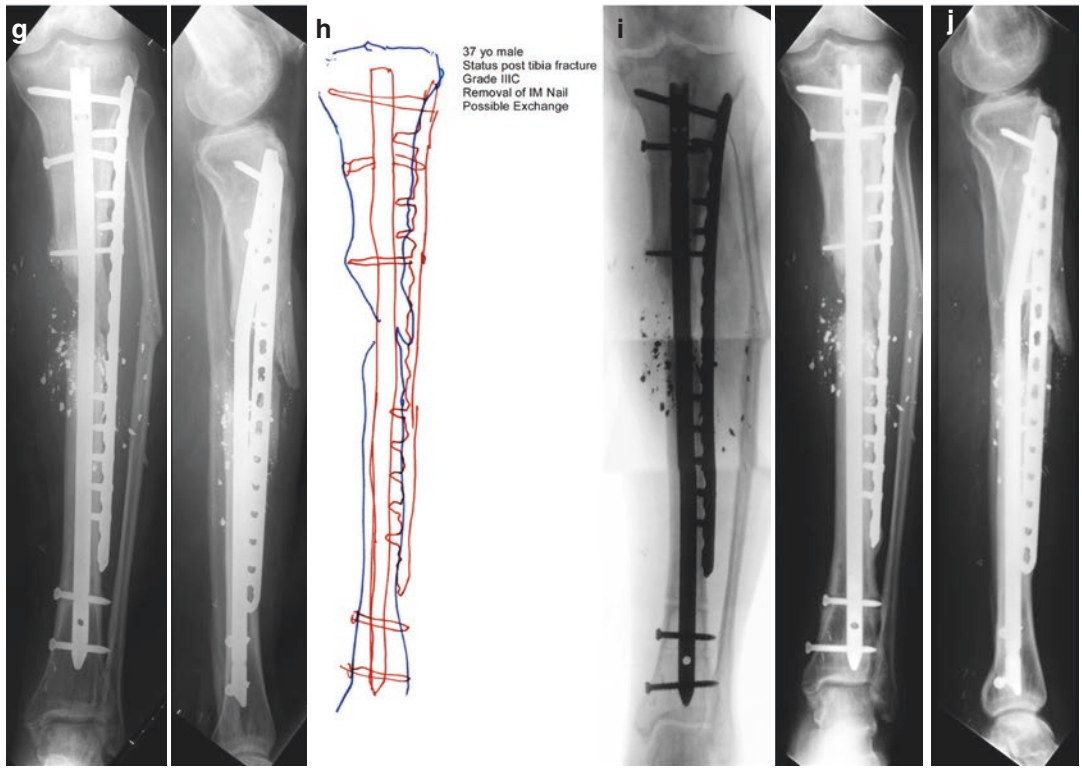
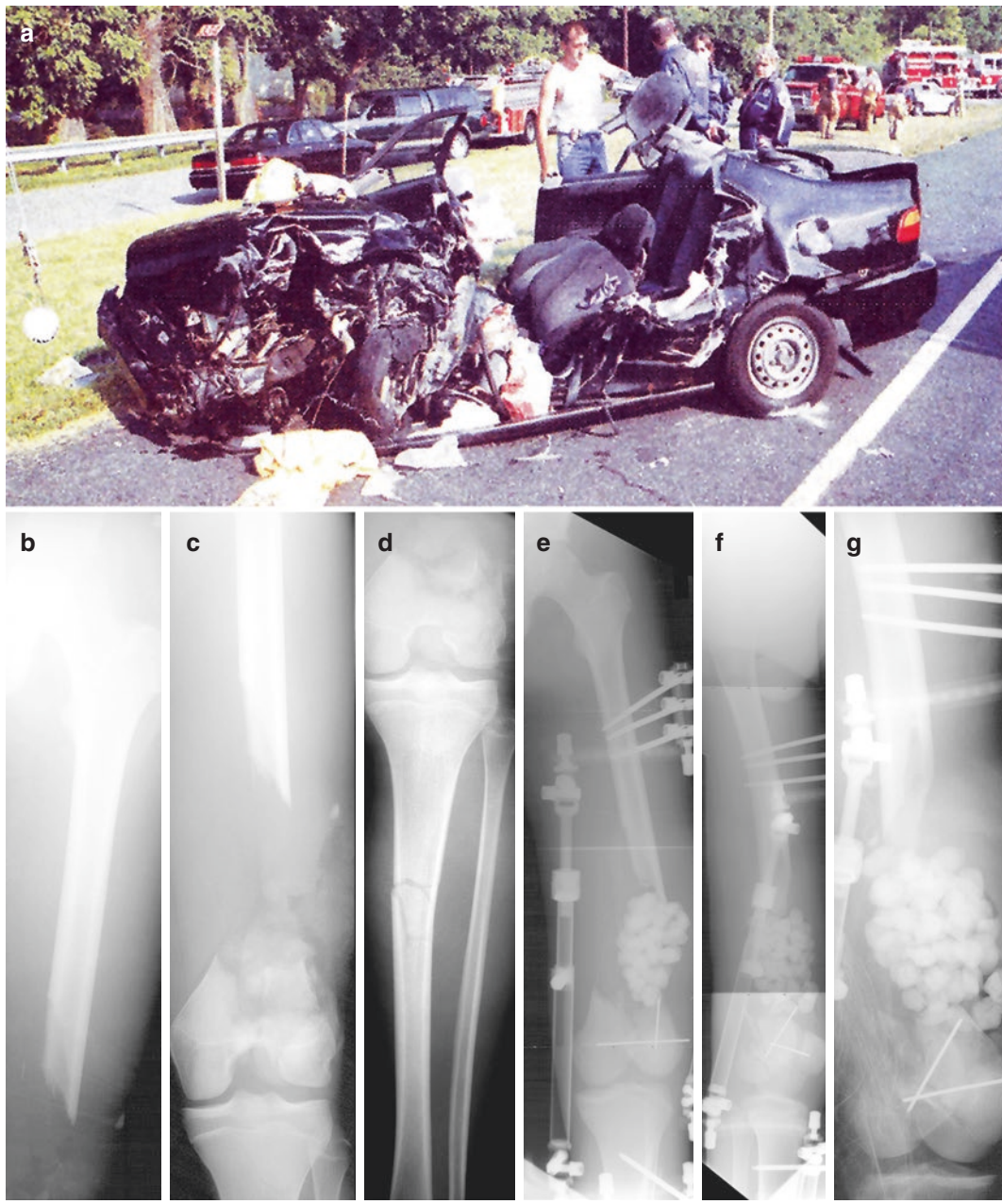



**Fig. 28.2** (continued)

**Fig. 28.3** A 17-year-old male was involved in a head-on collision with a tractor trailer. After being trapped inside the vehicle for approximately 1 h, he was extricated and flown to a local trauma center. He was diagnosed with an open, Grade IIIC left-sided AO/OTA Type C3.3 distal femur fracture with segmental defect and an ipsilateral tibial shaft fracture. External fixation was placed for initial stabilization and antibiotic beads were subsequently placed in the defect at 3 days following injury. Open Reduction and Internal Fixation (ORIF) was performed with placement of an intramedullary (IM) locked nail for treatment of the tibial shaft fracture and then ORIF of the distal femur fracture with placement of a Less Invasive Stabilization System (LISS) locking plate and screws. One week later, the antibiotic beads were removed and the defect was prepared for bone graft placement. A second incision was made along the lateral border of the ipsilateral fibula and a free vascularized fibula bone graft was harvested for transplant to the femoral defect. It was docked in a double barrel fashion and stabilized using screw fixation. Following surgery, he returned for regular follow-up visits. Three months after surgery all of the fractures were healing with incorporation of bone graft. The LISS plate was removed 4.5 years following the initial surgery. The clinical and radiographic follow-up illustrated excellent results with bony union, full range of motion, and complete resolution of pain and return to pre-injury activities. (**a**) Photograph of the vehicle and the scene following the accident. (**b**, **c**, **d**) Anteroposterior (AP) X-rays illustrating an AO/OTA Type C3.3 distal femur fracture with segmental bone defect and an ipsilateral tibial shaft fracture. (**e**, **f**, **g**) AP and lateral radiographs following placement of external fixation and antibiotic beads at the site of the segmental bone defect. (**h**) Counterclockwise from top-left; preoperative plan, fluoroscopic images showing placement of intramedullary nail for the tibial shaft fracture and locking screws and open reduction and internal fixation (ORIF) of the distal femur fracture with placement of an LISS locking plate and screws. (**i**, **j**, **k**) Immediate postoperative radiographs demonstrating adequate fixation and alignment. (**l**) AP radiographs illustrating preparation of distal femoral bone defect for placement of vascular bone graft. (**m**) AP x-radiograph following free vascularized fibular bone and placement of screw fixation. (**n**, **o**, **p**, **q**) AP and lateral X-rays 3.5 years following ORIF showing healed a distal femur fracture with incorporation of the fibular bone graft and a healed tibial shaft fracture. (**r**, **s**) AP and lateral X-rays 8 months following removal of LISS plate and screws and 4.5 years following fracture surgery

## 28.6 Complications

A major factor in the decision-making in the treatment of the mangled extremity is the possible major complications associated with each treatment arm. Harris et al. reported the nature and incidence of major complications for patients enrolled in the LEAP study group. Their cohort consisted of 545 patients with severe lower extremity injuries followed prospectively for 24 months. A physician examined each patient at 3-, 6-, 12-, 24-month intervals and major complications recorded. The two most common complications were wound infection (28.3%) and nonunion (23.7%), and the majority of each of these required operative intervention and inpa-



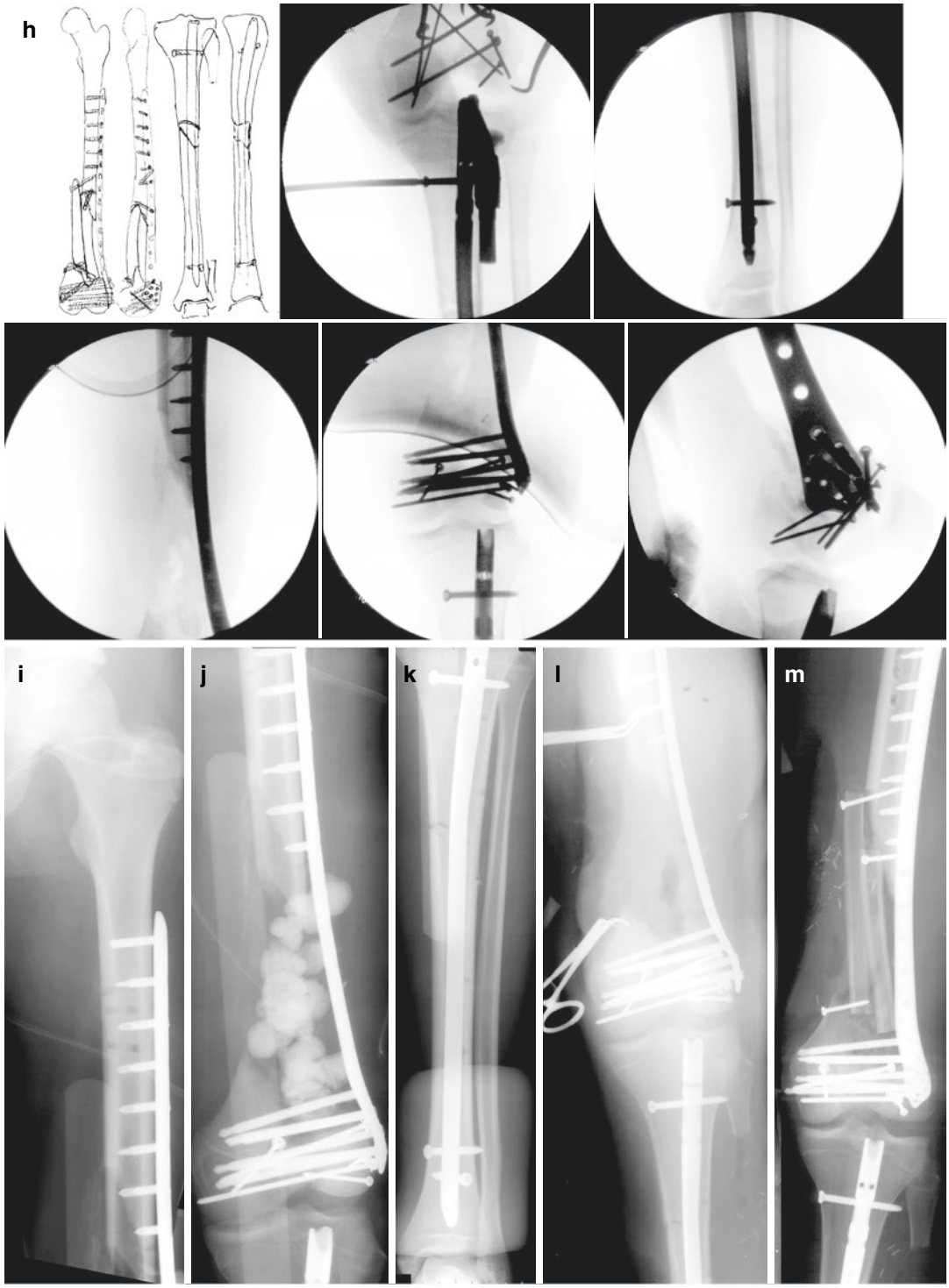



**Fig. 28.3** (continued)

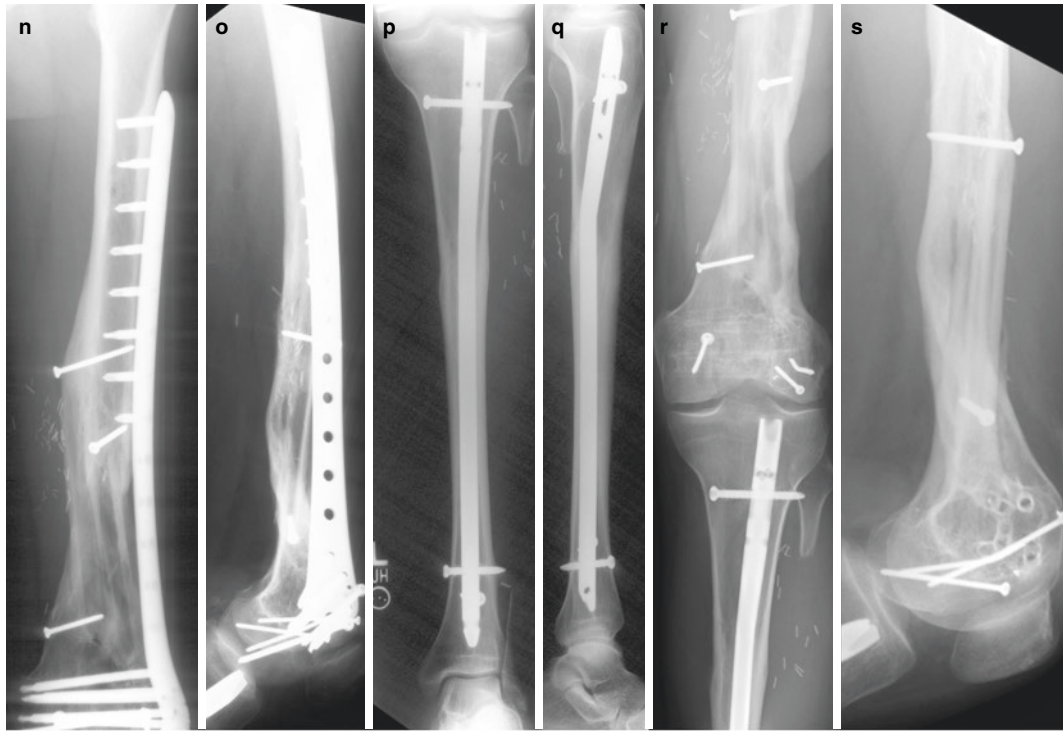



**Fig. 28.3** (continued)

tient care. Approximately a quarter of each of these complications were considered severe enough to compromise long-term function. The overall incidence of wound dehiscence was 8.6% and that of osteomyelitis 7.7%. There was also a 5.3% incidence of symptomatic hardware [19].

The complication data from the cohort was further examined based on treatment arm in the study. A total of 149 patients underwent amputations, and the revision amputation rate was 5.4%. The most common complications in this group were wound infection (34.2%), followed by stump revision (14.5%), phantom limb pain and wound breakdown (13.4% each), and stump complications (10.7%). In the limb reconstruction group, the most common complication was nonunion (31.5%), followed by wound infection (23.2%). Of these infections 8.6% developed into osteomyelitis. There was an incidence of post-traumatic arthrosis of 9.4% and wound necrosis or breakdown of 6.5%. The late amputation group (patients amputated after initial discharge) experienced the highest rate of major complications (85%) [19].

This fact clearly highlights the need for appropriate decision-making in the patient with a mangled extremity at the onset of treatment. Although there were no late mortalities reported, an incidence of up to 21% has been reported in the literature. Bondurant et al. undertook an investigation looking at the effects of delayed versus primary amputation. There was a significant increase in length of hospital stay (22 versus 53 days) and number of surgical interventions (1.6 versus 6.9). The cost was almost double ($28,964 versus $53,462), and there was a 21% mortality rate in the delayed amputation group [43]. It is quite evident that every effort should be made to avoid a late amputation given such high costs for all involved.

In a prospective cohort study (using LEAP study patients), Castillo et al. examined the specific effect of smoking on complication rate in severe open tibia fractures. A total of 268 patients with

unilateral injuries were followed prospectively. Nonunion rates were significantly higher in both the current and previous smoking groups (37% and 32%, respectively). The authors were able to demonstrate that current smokers were more than twice as likely to develop an infection, and 3.7 times more likely to have osteomyelitis. Previous smoking history was detrimental as well, and this group was 2.8 times as likely to develop osteomyelitis than nonsmokers. Their recommendation was that orthopedic surgeons should encourage patients to enter smoking cessation programs [44].

## 28.7 Predictive Ability of Scoring Systems to Predict Final Outcome

Some authors have examined the ability of the previously discussed scoring systems to predict functional outcome following treatment. Durham et al. performed a retrospective analysis of upper and lower severe extremity injuries to determine the validity and ability to predict outcome of the above discussed predictive indices. For each of the four systems analyzed, there were no significant differences between patients with good or poor functional outcomes [45]. Ly et al. reported on the ability of the five most commonly used predictive indices (above plus Hannover Fracture Scale-98) to determine functional recovery following limb salvage in a cohort of 507 patients (LEAP study group). The authors showed that none of the scoring systems analyzed were able to determine outcome based on the SIP out to 24 months following injury [46]. One can conclude, based on these two studies, that the commonly applied predictive indices may be useful in early decision-making, but are unable to predict functional recovery.

## 28.8 Outcomes Following Limb Salvage Versus Amputation

Recent medical and surgical technological advances have dramatically improved the surgeon's ability to salvage severely injured extremities. Limbs that historically would have been amputated can now be managed with complex reconstruction techniques. Although the limb remains viable, it is often questioned whether or not the patient would have been better served with an amputation. Limb salvage patients often still complain of edema, pain, decreased sensation, difficultly with footwear and ambulation [20]. The end result is often a physical, psychological, financial, and social cripple with a useless salvaged limb [21, 47].

Hoogendorn and van der Werken looked at the long-term outcome and quality of life of patients treated with reconstruction versus amputation following Grade III open tibia fractures. A total of 64 patients were assessed, including 43 with successful limb salvage and 21 who underwent amputations (including both primary and delayed). Lower extremity impairment was determined using "Guides to the Evaluation of Permanent Impairment" of the American Medical Association. Quality of life was measured using the Nottingham Health Profile (NHP), the SF-36, and a questionnaire the authors specifically designed for the study examining pain, daily function, psychological factors, and handicap with working. Patients who underwent amputations had more severe injuries and had a higher number of vascular injuries (77% versus 17%). The limb salvage group underwent more operations and had more complications [20].

Delayed amputations were performed in eight patients, most commonly secondary to persistent infection and poor soft tissues. They were hospitalized twice as long as those who underwent primary amputation. Others have shown that delayed amputation results in poorer functional outcome versus primary amputation [43, 48]. From the reported health surveys, the authors found low scores in both groups but no significant differences. In both groups, over half the patients considered themselves disabled, with a slightly higher percentage of patients who had amputations reporting difficulty with practicing a profession (60% versus 40%). Of particular interest was that the mean lower extremity impairment score was significantly worse for amputees (73.5%) as compared to the limb salvage group

(17.6%). These patients therefore perceived a higher level of function than those who were amputated [20].

The LEAP study group recently examined the functional outcome following limb salvage versus amputation. A total of 569 patients with severe leg-threatening injuries were studied in this multicenter, prospective, observational study. Eight level I trauma studies participated in this investigation. Functional outcome was measured using the Sickness Impact Profile (SIP) and follow-up at 24 months was 84.4%. Comparisons of outcomes for the SIP were adjusted for potential confounding variables of the patient characteristics as well as their specific injuries [8]. It was noted that patients who underwent amputation had more severe injuries, but otherwise did not differ from those who had reconstruction [8, 49].

Upon examining final functional outcome, there were no significant differences in scores between either treatment group although 42% of the patients had scores greater than 10 indicating severe disability. Patients who underwent limb salvage were more likely to have been rehospitalized than those who had amputation performed (47.6% versus 33.9%, $p = 0.002$). Multivariate analysis reveals several factors that were significant factors for a poor outcome including: rehospitalization for a major complication, having less than a high-school education, low household income, having no insurance of Medicaid, being nonwhite, smoking, having a poor social-support network, having a low-level of self-efficacy, and being involved with the legal system for injury compensation. At final follow-up, approximately 50% of patients had returned to work and this rate did not differ between the two groups [8].

Patients with bilateral mangled extremities were excluded from the initial above analysis in the LEAP study but were followed prospectively and reported on separately. There were a total of 32 bilateral injuries, of which 14 had bilateral salvage, ten had bilateral amputation, and eight had unilateral salvage/amputation. Forty six percent of patients were severely disabled at 24-month follow-up as demonstrated by SIP scores >10. Once again, the groups where salvage procedures were performed had higher rehospitalization rates for complications than the bilateral amputation group. The return-to-work rate was higher in the unilateral amputation/salvage group, and they had faster walking speeds. Examination of all three combinations of treatment of bilateral limb-threatening injuries demonstrated similar outcomes at 2 years. The evidence from this study suggested that the disability for bilateral limb-threatening injuries is high, but no more so than the unilateral group described above. The authors therefore concluded that treatment strategies for bilateral mangled extremities should be derived from the results from the larger cohort study of unilateral injuries [50].

MacKenzie et al. later reported on the long-term follow-up of the original patients included in the LEAP study. The main goals of the study were to determine if the previously reported outcomes improved after 2 years, and whether there were any late differences between the treatment groups. Of the 569 patients from the original cohort, 397 were contacted by phone at an average of 84 months post-injury (range 70–90 months). On average, most of the patients reported physical and psychosocial functioning that had deteriorated since their 24-month follow-up ($p < 0.05$). This increase in SIP scores was consistent across both treatment groups. It should be noted thought that patients who underwent through knee amputations were at the highest risk for a poor outcome. More than a third of patients in both groups had been re-hospitalized between 2 and 7 years post-injury. At final follow-up, almost all of the patients indicated severe disability, with SIP scores >10. Only 34.5% of the cohort had a physical SIP subscore typical of the general population (<5) [32].

## 28.9 Cost of Care

There have been conflicting reports in the literature over the long-term health care costs of limb salvage versus amputation. Hertel et al. calculated a 15% higher hospital cost for the reconstruction patients over those who underwent amputation over the first 4 years post-injury

[51]. Georgiades also showed that patients who undergo reconstruction have higher hospital charges over those with primary amputations [48]. Bondurant et al. demonstrated a substantially higher hospital cost for patients who had delayed amputations over those who had primary amputations [43]. The LEAP study group found that the average 2-year costs for amputation versus reconstruction were very similar. When the cost of prosthetic devices was included, health care costs were significantly higher for patients who had amputations. The projected lifetime health care cost was three times higher for patients in the amputation group ($509,275 versus $163,282). The large number of patients in this particular study (545 patients), and the fact that this study is much more recent than the other mentioned reports, make this data more valuable [52].

## 28.10 The Mangled Upper Extremity

Of note are the differences between the mangled upper and mangled lower extremity, which must be carefully considered by the treating surgeon. Critical time for reperfusion is longer in the upper (8–10 h) versus the lower extremity (6 h) [16]. A transtibial amputation carries a much better functional prognosis than a transradial amputation. This is due to the fact that upper extremity prostheses do not work as well as lower extremity prostheses. Shortening of the humerus to reduce soft tissue defects is tolerated well up to 5 cm, in contrast to the lower extremity that does not tolerate shortening of more than 2 cm. Nerve reconstruction in the upper extremity is done with reasonable success, whereas in the lower extremity many consider major nerve injury an indication for primary amputation. The rehabilitation process is also more imperative when the upper extremity is involved [13]. One consistency to both is that the MESS has also been shown to be useful for predicting amputation following mangled upper extremities [53].

## 28.11 The Mangled Extremity and Polytrauma

Severely injured patients that would not have survived their trauma in the past now survive because of improved resuscitation. Mangled limbs that used to be considered beyond reconstruction can now be salvaged. However, the decision of whether to reconstruct or amputate a mangled extremity in a polytrauma today still requires complex and careful decision-making. An undisputed rule in polytrauma is "life before limb," meaning life-threatening issues are always addressed first. Orthopedic efforts in the initial resuscitation of the severely injured patient with extremity injury often involve Damage Control Orthopaedics (DCO) [4, 5, 15]. DCO polytrauma patients are typically categorized into stable, borderline, unstable, and in extremis. The goal of DCO is to minimize subsequent stresses after the first hit (=injury) and its effectiveness in the context of major orthopaedic fractures has been shown [5, 54, 55].

The question whether amputation of a mangled limb is advisable for a severely injured patient cannot be answered [56]. There are no clear guidelines with respect to the *isolated* mangled extremities, let alone the polytrauma patient. As an exception, utilizing DCO guidelines, salvage of the *stable* polytrauma patient's mangled limb is possibly the most relevant. For these, techniques involving early free tissue transfer and internal fixation as proposed by the "fix-and-flap" technique might be successful, but require a highly specialized trauma center [40]. Still, for these the patients, the decision whether to salvage or amputate faces the same dilemmas as for the patient with the isolated mangled limb as described elsewhere in this chapter.

*Borderline* patients that stabilize after resuscitation can undergo early total care (ETC), but reconstructive efforts need to anticipate potential deterioration. Long procedures (e.g., "fix-and-flap") are not justified in these patients. Wound debridement, revascularization, and external fixation are all that can be done while a rapid turn for the worse should be anticipated. In the *unsta-*

*ble* or in extremis polytrauma patient, there might be a role for primary amputation as prolonged revascularization and stabilization procedures add to the patient's catabolic state and will increase the second hit enormously. Any other reconstructive efforts for the extremities are not justified.

Next steps in limb salvage in should not be undertaken until the patient has stabilized and is beyond the systemic inflammatory response syndrome (SIRS) stage. As a rule, timing of second and subsequent major procedures (longer than 3 h) should be at least after 4 days [3]. If the limb develops evidence of sepsis, early amputation should still be considered. The use of fresh warm blood, plasma, and recombinant factor VII defined as Damage Control Resuscitation before surgery help to optimize the physiologic parameters and theoretically allows for more prolonged surgical procedures such as revascularization [57].

## 28.12 Conclusions

The combination of osseous, vascular, soft-tissue, and nerve injury present following severe trauma to an extremity make such injuries a challenge to treat. Unfortunately, the data regarding the management of the mangled extremity are conflicting, and the literature is without Class I studies. It is therefore imperative that an experienced surgical team at a trauma center that cares for such patients with some regularity care for the patient with a complex extremity injury [58]. The treating team must always keep in mind the high prevalence of associated multisystem trauma and systemic problems related to these injuries. Even though the treatment goal is limb salvage, it must be kept in mind that in many instances a primary amputation might provide the best outcome. New insights, therapies, and techniques will improve outcomes in even the most severely injured patients with complex extremity injuries. As for the mangled limb in these patients, it is unlikely a scoring system will allow a clear cut-off point for amputation versus salvage. What has become clear is that primary amputation should not be considered a treatment failure but rather a means of meeting goals of treatment [59]. As Hansen pointed out long ago, we should not let heroism triumph over reason [47].

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# 29 Surgical Management: Elderly Patient with Polytrauma

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**Learning Objectives**

- Recognizing and appreciating the prevalence of geriatric polytrauma and the unique physiologic response of the elderly polytraumatized patient.
- Understanding the mechanisms and most common injury patterns sustained by geriatric polytrauma patients and their unique characteristics in this generally osteoporotic population.
- Building a framework for the appropriate initial triage, resuscitation, and pain control for the geriatric trauma patient.
- Understanding the role of geriatric and palliative care specialists in the care of these patients, and the importance of shared decision-making about the choice and timing of operative intervention.
- Recognizing the importance of secondary prevention in this high-risk population.

**Key Concepts**

- Geriatric polytrauma is an underrecognized public health issue and is not always handled in a systematic, appropriate manner.
- Injury severity, physiologic reserve, preexisting conditions, time to definitive care, and aggressiveness of resuscitation all play an important role in outcomes following trauma in the elderly.
- The impact of this decreased physical reserve on morbidity and mortality is substantial, with an emphasis limited stress response.
- Osteoporosis can lead to devastating fracture patterns due to weakened bones.
- Blunt trauma accounts for most geriatric polytrauma injuries, namely falls and motor vehicle collisions.
- Pelvic ring, acetabular, hip, and spine fractures are among the most commonly injuries in this population.
- Undertriage is common in the geriatric population and can have significant ramifications in the appropriate level of care of these patients.
- Early and aggressive monitoring and resuscitation is paramount in the geriatric trauma patient.

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- Appropriate pain control is important given the elderly propensity for delirium. Use of non-opioid pain management such as regional blocks (i.e., fascia iliaca) can prove quite useful.
- Patients who are co-managed with geriatric specialists have improved outcomes.
- The need to manage according to damage control orthopedic principles should be balanced against the ability to perform single surgery in the frail elderly patient.
- Secondary prevention of fractures through fracture liaison services and fall prevention programs.

## 29.1 Introduction

Trauma is a serious public health issue and accidents are the third leading cause of death in the United States. According to 2017 CDC statistics, accidents were the leading cause of death in all age groups from birth to age 44 [1]. While trauma, especially polytrauma, is commonly thought of as affecting younger patients, there is a growing recognition of the geriatric polytrauma patient. In 2017, accidents were the seventh leading cause of death in those over the age of 65, when only 10 years earlier accidents ranked ninth in leading causes of death [1]. Some recent studies have shown up to 35% of trauma patients being older than 65 years of age [2]. This is due in part to both an aging global population and a more active elderly population. Globally, the population aged greater than 60 is expected to increase from 287 million in 2013 to 417 million by 2050 [3], with the 2030s set to be a transformative decade for the population of the United States. By 2030, the entire baby boomer generation, comprising 20 percent of the population, will be older than 65 [3].

Several authors have noted the lack of literature focused on high-energy trauma in the elderly population and have advocated for more investigation and review of these increasingly important injuries, both due to their heightened mortality and economic impact [4–6]. Part of the difficultly with defining these injuries comes in the inherent confusion around the definition of both "geriatric" and "polytrauma" leading to a significant heterogeneity within the literature. Many studies use an age of greater than 65 to define geriatric patients but the age cut-off can range from 50 to 70 in different studies. To complicate matters further, polytrauma itself is not well defined. Historically defined as an Injury Severity Score (ISS) greater or equal to 16 [7], this definition of polytrauma has been called into question, with a recent working group defining polytrauma as significant injuries of three or more points in two or more different anatomic Abbreviated Injury Scale (AIS) regions in conjunction with one or more additional variables from five physiologic parameters [8, 9]. It is difficult to isolate trends and outcomes in geriatric polytrauma due to the paucity of available literature. Some of the trauma data used comes from the geriatric hip fracture literature, which is quite robust. While hip fractures, often an isolated injury, do not fall into a definition of polytrauma, there is much that can be extrapolated from this data and applied to other geriatric traumas, and Bergeron et al. argue that low-energy falls must be included in these discussions to fully appreciate the societal and economic impact of these injuries [10].

Injury severity, physiologic reserve, preexisting conditions, time to definitive care, and aggressiveness of resuscitation all play an important role in outcomes following trauma, and these are all important points of consideration when approaching the case of a geriatric trauma patient as treatment decisions on data based on younger cohorts [11].

## 29.2 Physiologic Differences between Younger Adults and Older Adults in the Trauma Situation

### 29.2.1 Physiologic Differences

When considering the elderly trauma patient, there are certain factors that must be considered

that set them apart from their younger counterparts. With aging comes the inevitable decline in efficiency of individual organs and the overall function of the body. With the aging body also comes the development of underlying medical comorbidities. These two factors together lead to an overall decrease in the physical reserves of a patient that can be uncovered in settings of high stress upon the body such as polytrauma [12]. The impact of this decreased physical reserve on morbidity and mortality is substantial. Giannoudis et al. reported a mortality rate as high as 42% in patients aged greater than 65 compared to 20% in younger patients, with a mortality rate of close to 50% in those patients over 75 [13]. While these rates of mortality (often cited as in-hospital mortality) exhibit a wide range in the literature (4–44%), it is clear that older patients are more at risk than their younger counterparts [14].

One key feature of these reduced reserves is that older adults do not tolerate hypotension and hypovolemia as well as younger adults. The cardiovascular and nervous systems play an important role in the autoregulation of blood pressure. Studies have shown the cardiac stroke volume of 80-year-old patients to be half of that compared to 20-year-old controls [15]. The catecholamine response, which aids in a robust tachycardia secondary to pain and blood loss is also blunted [16]. These factors together yield a decreased stress response to shock. Osler et al. reported a 17% mortality rate in those aged over 65 compared to 3% in younger controls, with the presence of shock increasing mortality significantly among those patients [17]. In a single institution study conducted by Henry et al. investigators found that older patients were almost three times more likely to receive transfusions than younger pelvic trauma patients [18]. While the physiologic changes in the cardiac system may be the most crucial in the initial stages of presentation, most elderly organ systems lead to increases in morbidity and mortality.

Not only is the stress response to shock blunted, but so too is the ability of the lungs to effectively oxygenate the tissues. Decreased lung capacity secondary to changes in collagen structure as well as weak intercostal muscles lead to decreased ability to compensate for hypoxia [19]. These collagen changes also lead to weaker tensile strength of skin which predisposes to more significant soft tissue injuries and increases the likelihood of open fractures [20]. These soft tissue injuries paired with aberrations in the immune system, effecting mainly the innate system, lead to increased rates of infection and significant wound complications [21].

The impact of neurodegenerative changes cannot be overemphasized. Elderly patients may have significant issues with cognition which can both limit their ability to give accurate medical history as well as identify and report pain [22]. This can also lead to missing significant occult injuries [23]. Decreased visual, auditory, and proprioceptive inputs can also lead to increased rates of falls, the leading cause of geriatric trauma [19].

Some authors postulate that it is truly the reduced physiological reserves of the elderly that put them at such a high risk when encountering severe injury, regardless of their other medical comorbidities [24].

### 29.2.2 Medical Comorbidities

While the inherent physiologic differences between the young and old increase the baseline mortality risk for all elderly patients, the treating physician must also consider preexisting medical comorbidities as well. Comorbid conditions have been shown to increase mortality as well, with one study by Milzman et al. demonstrating a 9.2% mortality compared to 3.2% in patients without comorbid conditions. Their study also showed in increasing mortality rate as the number of preexisting conditions increased, 15.5% with two or more, and 24.9% with three or more. The comorbidities found to contribute the highest to mortality were renal and cardiac disease [25].

In fact, even when controlling for vital signs, GCS, and ISS in a study by Grossman et al., comorbidities had a significant effect on mortality on these elderly trauma patients [26]. Clement et al. showed that it is often the medical comorbidities that attribute to the late mortality, often in

patients initially with lower injury severity scores [27], and some authors have postulated that this contributes to underreporting deaths secondary to trauma as it is the complication, rather than the trauma that is cited as the cause of death [28].

Another key comorbidity to assess in the geriatric trauma patient is malnutrition. Multiple studies have shown high rates of malnourishment in elderly hospitalized patients up to 25–65% [29, 30]. Lack of proper nutrition has been associated with prolonged hospital stays as well as increased rates of mortality [31] with some studies showing 55% higher mortality rate in geriatric patients [29]. Beyond its effect on overall health, malnourishment has also been shown to significantly effect wound healing [32] and has even been linked as an underlying cause for weakness, falls, and subsequent fracture [33].

A discussion of orthopedic injuries of the geriatric polytrauma patient would be incomplete without addressing the impact of osteoporosis. The aging musculoskeletal system is affected by both deconditioning (i.e., muscle atrophy) and osteoporosis, which together can lead to more significant injuries even with lower energy. Once peak bone mass is reached in the young adult, it declines slowly over the life of the patient, slowly changing the bony structure, that when fractured may demonstrate a high-energy pattern in a low-energy trauma scenario [34]. A common problem, osteoporosis has been shown to be present in 45% of women and 15% of men over the age of 50. Osteoporosis can also be exacerbated by other medical conditions including malabsorption, thyroid and parathyroid conditions, insufficient calcium or vitamin D, and certain medications [34]. Osteoporosis weakens both the bone's cortex and the medullary bony trabeculae.

With numerous medical comorbidities comes the burden of polypharmacy. Polypharmacy is defined as five or more medications on the medication list. Polypharmacy can affect both the cause of trauma and resuscitation after trauma. As the number of prescriptions increases, so too does the risk of falls, with greater than five prescription medications linked to an increase in falls [35, 36]. The resuscitation phase of a trauma activation can also be complicated by polypharmacy. Drugs that play a significant role include beta blockers, due to their effects on heart rate and blood pressure, and anticoagulants. Neideen et al. showed that beta blockers increase the risk of mortality, presumed to be secondary to their shock-altering response [37]. Older adults are commonly prescribed some form of oral anticoagulation, which may contribute significantly to post trauma bleeding. In the trauma patient, these oral anticoagulants should be stopped and replaced by more easily reversible medications (such as low molecular weight heparin) [34]. While the reversal of warfarin is well documented, some of the newer anticoagulants (e.g., dabigatran, rivaroxaban) do not have specific reversal agents and may take longer to metabolize [34].

## 29.3 Common Mechanisms of Injury

In some ways, the elderly polytrauma patient does not differ from the young polytrauma patient; when involved in high-energy injuries, many organ systems may be affected. However, it has been shown that it takes less energy to cause equivalent injuries in the elderly compared to the young patient. A simple fall in an older adult may create an injury pattern similar to a high-energy injury in a young person [38]. Falls are the leading cause of injury-related mortality in the elderly population [39]. Falls from height are the most common cause of polytrauma along with motor vehicle collisions [13]. Geriatric polytrauma is less well understood and researched than that of geriatric trauma, and many registry-based studies exclude "simple" hip fractures and injuries caused from ground level falls [5]. Blunt trauma, and not penetrating trauma, makes up almost all geriatric trauma cases (96–99%) [12, 17].

Motor vehicle collisions (MVCs) are the second most common cause of non-fatal injury in the elderly second to falls. While MVCs are commonplace, their frequency can be increased by medical issues common in the elderly such as confusion/dementia, reduced senses (vision,

hearing), or syncope. Pedestrians struck by a motor vehicle also represent significant source of polytrauma, particularly in an urban setting [40]. An older multicenter trial investigating injury mechanism in patients older than 65 showed falls (40.6%), motor vehicle collision (20.2%), and pedestrian struck (10%) made up greater than 70% of all injuries [41].

The greatest predictor of accidental injury in older adults remains the participation in high-risk activities, including simple tasks such as climbing a ladder or driving a car.

## 29.4 Frequent Patterns of Injury

When considering the polytraumatized patient, there are often many organ systems that are injured, which can occur in an unpredictable manner. Some systems most frequently injured in the elderly trauma patient include the pelvis and extremities [42].

### 29.4.1 Pelvic Ring Injuries

In young adults, a large amount of energy is necessary to injure the pelvis and disrupt its ring. With the geriatric population, both low and high-energy mechanisms can cause significant pelvic injuries. Older pedestrians struck by a motor vehicle have high rates of pelvic ring and intracranial injuries [43]. The characteristic fracture patterns seen in geriatric pelvic ring injuries also differ, with lateral compression (LC) fractures occurring 4.6 times more frequently than anterior-posterior compression (APC) [18]. In the younger population, APC injuries generally are more significant, but in the elderly even minor lateral compression fractures were four times more likely to require blood transfusion [18].

#### 29.4.1.1 Representative Case: Non-op Pelvic Fracture Can Have Significant Bleeding Risk

This is a 70-year-old female with history of rheumatoid arthritis on adalimumab presented following a motor vehicle collision versus tree as an restrained driver with positive loss of consciousness. There was a prolonged extrication at the scene, and she was found to be somewhat mentally altered. On arrival she was mildly hypotensive 90/60 mm hg in the trauma bay, and her blood pressure responded well to a fluid bolus. Focused Assessment with Sonography for Trauma (FAST scan) was negative, but subsequent CT showed active bleeding into the pelvis as well as a left lateral compression (LC1) pelvic ring injury. She was also noted to have a subarachnoid hemorrhage, left-sided rib fractures [3, 4, 11, 12], small left pneumothorax, and left-sided thoracic T3–5 fractures. She became acutely hypotensive while waiting to be transferred to Interventional Radiology (IR) and was sent emergently to the operating room for exploratory laparotomy (ex-lap) and pelvic packing. She then went to IR for embolization of the left anterior internal iliac artery and massive transfusion protocol was initiated. Her hemoglobin dropped from 12.4 on admission to 7.2, while her lactate rose to 4 and her base excess dropped to −7.4. Patient spent significant time in the ICU, required multiple transfusions, thoracentesis for pleural effusion, left hand fasciotomies due to compartment syndrome from IV infiltrate. Hospitalization complicated by acute hypoxic respiratory failure requiring intubation, hemorrhagic shock requiring multiple transfusions. After ICU, patient did well and was discharged to inpatient rehab and then subsequently discharged home, seen in follow-up and is walking with only support of cane (Fig. 29.1).

### 29.4.2 Acetabular Fractures

Acetabular injuries in the elderly present an interesting historical perspective. When the fracture patterns of the acetabulum were described by Letournel, the mainstay of treatment for those over the age of 60 was non-operative management, however, this is longer standard of care [44]. Not only have the treatment options evolved, but so too have the demographics of the injury with the average age of those sustaining acetabular fractures increasing [45]. A large proportion

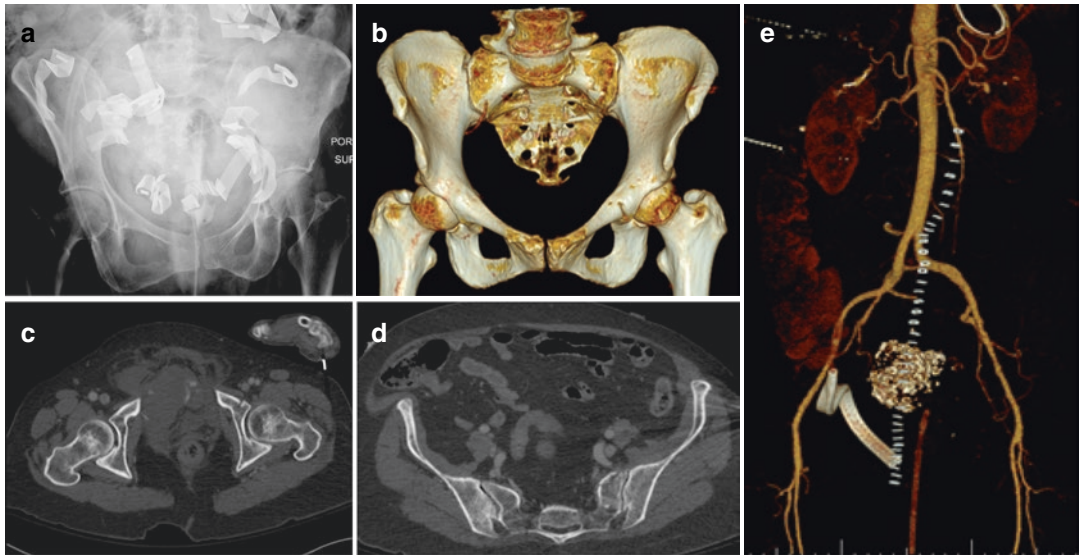


**Fig. 29.1** (**a**–**e**). (**a**) Pelvis x-ray status post initial ex-lap and pelvic packing with evidence of minimally displaced bilateral para-symphyseal fractures. (**b**) Three-dimensional reconstruction of CT pelvis with left-sided high pubic root fracture and left sacral ala fracture. (**c**) Axial CT cut demonstrating left superior pubic root fracture. (**d**) Axial CT cut with left-sided sacral fracture. (**e**) Three-dimensional reconstruction of CT abdomen status-post IR embolization, removal of packing, and drain placement

of acetabular fractures occur secondary to ground level falls; however, MVCs are becoming a more common injury mechanism [4]. These high-energy fractures of the acetabulum have worse outcomes when compared to their low-energy counterparts, with increased rates of arthritis, heterotopic ossification, and infection [46]. In addition, impaction and comminution is more commonly seen in the geriatric patient [47].

High-energy fractures are also less amenable to non-operative treatment [48]. Research has shown that non-operative management has significantly higher mortality rates than operative fixation.

#### 29.4.2.1 Representative Case: Medium Energy Injury, High-Energy Fracture

This 77-year-old male fell from a ladder. Patient was not anticoagulated but took a daily aspirin. He sustained significant traumatic injuries including a right-sided rib fractures (second through fifth), pulmonary contusions, and a pneumothorax, for which a chest tube was inserted in the trauma bay. Head computed tomography (CT) demonstrated both subdural and intraparenchymal hemorrhages. The pelvic x-ray and CT demonstrated a comminuted, right-sided associated both column (ABC) acetabular fracture along with left-sided inferior and superior pubic rami fractures. Laboratory values demonstrated a climbing serum lactate from 2.6 to 3 mmol/L. The patient was placed in skeletal traction in keeping with the principles of DCO. The patient was seen and assessed by the geriatric medicine team within hours of arrival, and he was determined to have lower than average risk of serious complication according to the National Surgical Quality Improvement Project calculator (10.2% compared to average of 13.7%). The patient was judged to be in average health and functionally was a baseline ambulator who took care of his own Activities of Daily Living. Even with lower than average risk, this patient had a calculated 56% chance of being discharged to a nursing facility. The patient was admitted to the intensive care unit (ICU) and started on multimodal pain control regimen including scheduled acetaminophen, low-dose oxycodone, lidocaine patches, and a lidocaine drip. He required placement of a second right-

sided chest tube for persistent pneumothorax and underwent repeat head CT without worsening of the subarachnoid or intraparenchymal bleeds. He remained in the ICU with a tenuous pulmonary status requiring high flow oxygen not requiring intubation. Surgery was delayed by poor respiratory status, exacerbated by difficulty with mobilization. A decision was made to place an epidural catheter for pain control and remove patient from skeletal traction to allow for mobilization. He remained non-weight bearing on the right lower extremity but was able to get up and around with assistance, which significantly aided in his respiratory status. Eventually, he was stable enough to undergo open reduction and internal fixation of his acetabular fracture, allowing for toe-touch weight bearing, and he was discharged to an inpatient rehab facility from which he was discharged home. He progressed well from toe-touch weight bearing, to 50% weight bearing, to full weight bearing without complication (Fig. 29.2).

### 29.4.3 Spine Fractures

Due to the changing rigidity and biomechanics of the spine, spinal fractures are more common in the elderly population [49]. Low-energy trauma or simple falls are both common causes of cervical spine injury [50]. In the elderly population, these injuries can be devastating given the increased risk of high (C1-2) cervical spine injuries due to a stiff, degenerative spine [51].

### 29.4.4 Hip Fractures

Hip fractures present an interesting dilemma when considering geriatric trauma. As addressed earlier, much of the prospective data on geriatric trauma patients comes from study of hip fracture patients. Many trauma registries and researchers do not include hip fractures from low-energy falls within qualifying injuries [5]. Reported

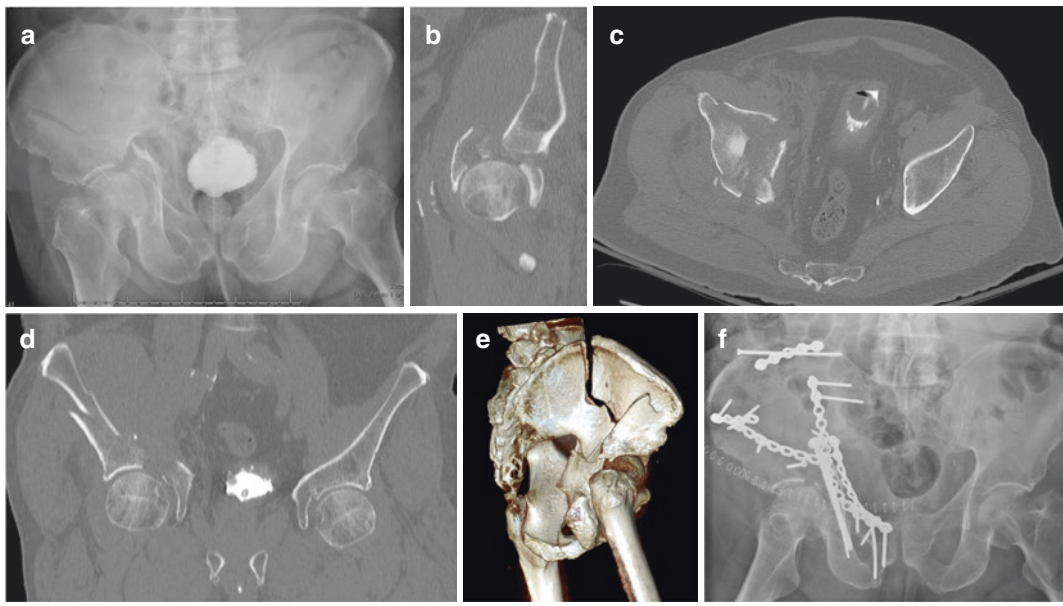


**Fig. 29.2** (**a**–**f**): (**a**) Antero-posterior (AP) radiograph of the pelvis demonstrating fractures of both the anterior and posterior columns of the acetabulum. (**b**) Sagittal cut of pelvic CT scan demonstrating significant comminution of the weight bearing dome of the acetabulum. (**c**) Axial cut of pelvic CT scan again showing significant comminution of the weight bearing dome. (**d**) Coronal CT cut with significant gapping of the articular surface of the acetabulum. (**e**) 3D reconstruction of the pelvis CT demonstrating fractures of both columns of the acetabulum and dissociation of the (**f**) Post-operative AP radiograph following open reduction and internal fixation of the associated both column acetabular fracture

mortality after hip fractures that are surgically treated is 9% at 30 days, 19% at 90 days, and 30% at 12 months [52].

### 29.4.5 Traumatic Brain Injury

Along with pelvic and extremity injuries, traumatic brain injuries (TBI) are among the most common in a geriatric population [43]. Elderly patients diagnosed with TBI and presenting GCS of 8 or lower have been correlated with poor prognoses [53]. While many of the injuries caused by trauma can have significant implications on morbidity and mortality, TBI is the most common cause of traumatic death [24].

### 29.4.6 Rib Fractures

Chest injuries are frequently present in trauma patients; however, it is the sequelae of the injury that often is the most devastating. Rib fractures cause both hyperventilation and pain, which predisposes the patient to the development of pneumonia. These patients often require intensive level of care, and frequently are intubated [24]. Bulger et al. found that in this population, each additional rib fracture increases the risk of pneumonia by 27% and the risk of mortality by 19% [54]. There has been an increase in the operative treatment of rib fractures, with studies showing mortality benefit in geriatric trauma patients undergoing surgical stabilization. Rib fixation has been shown to decrease ICU length of stay (LOS), total hospital LOS, and rates of ventilator pneumonia. Early rib fracture fixation may be associated with improved outcomes in the geriatric trauma population with multiple rib fractures [55].

## 29.5 Relevance of Scoring Systems

Both in the clinical and research setting it is useful to define standard scores that might be used to predict outcomes. Standard scores help trauma teams make informed decisions about treatment plans especially in scenarios where pressure of time requires accurate and easily procured predictors of elderly trauma mortality [56]. The injury severity score (ISS) is perhaps the most widely used scale within the trauma literature. However, issues arise when considering geriatric patients, as ISS doesn't take into account medical comorbidities, and some authors have disputed the accuracy of the ISS for predicting in-hospital mortality [57]. Other injury scores have also been developed including the New Injury Severity Score (NISS), the Revised Trauma Score (RTS), the Abbreviated Injury Scale (AIS), and the Trauma Score and the Injury Severity Score (TRISS). Specifically, for geriatric trauma are the Geriatric Trauma Outcome Score (GTOS) and the Geriatric Trauma Survival Score (GTSS). The GTOS is calculated by the patient's age + (ISS*2.5) + 22 (if blood transfused within 24 h) whereas the GTSS combines age, ISS, sepsis, and cardiac complications. The GTSS was developed in 1987 and was shown to predict survival better than any other single variable; however, it was not widely employed and its presence in the literature is scarce [58]. Both the GTSS and the GTOS are they are reliant on the ISS. Recently, Morris et al. developed a novel outcome score known as the Elderly Mortality after Trauma (EMAT) score that uses data points available at admission to help predict hospital mortality [56]. The qEMAT (quick) and fEMAT (full) accurately estimated the probability of in-hospital mortality and can be easily calculated on admission, whereas the ISS is a retrospective score. This information could aid in deciding transfer to tertiary referral center, patient/family counseling, and palliative care utilization [56].

## 29.6 Appropriate Triage of the Older Adult Involved in Trauma

One of the most important factors during a traumatic injury is the time from injury to assessment at a trauma center. Often referred to as the "golden hour," the underlying principle is that a

traumatically injured patient has roughly 1 h to be assessed and aggressive resuscitation started, before the rates of morbidity and mortality increase significantly [59]. This process begins at the scene, when emergency responders first assess the patient and make decisions about the appropriate hospital destination for the patient. This triage is a crucial step, but is one that often falls short, as we are slow to recognize the significance of these injuries in the elderly [60]. This concept is known as "undertriage" and is defined as a failure to take a trauma patient to a state-designated trauma center [61]. Undertriage has been shown to occur in close to half (49.9%) of patients over the age of 65, compared to just 17.8% in those younger than 65 [61]. Numerous studies have shown that geriatric trauma patients are significantly less likely to be admitted to a level 1 or level 2 trauma center [62, 63]. These differences have been attributed to inadequate training, inherent age bias, mechanism of injury (i.e., simple fall), and because older patients often do not exhibit the typical hypotension or tachycardia of a traumatically injured patient [19, 61]. Studies out of Maryland, Florida, and Washington support this as well, demonstrating that physiologic parameters for triage to a trauma center were less likely present in patients over the age of 55. During the initial field evaluation of the geriatric trauma patient, it is crucial to recognize that these vital signs may not accurately reflect injury severity [64]. These aberrant vitals are often due to underlying comorbidities (such as hypertension that can mask hypotension) or certain medications (beta blockers) [19]. These vitals are heavily utilized as markers for resuscitation, but in the geriatric population can be unreliable and so laboratory values for lactate and base deficit should be employed [64]. Due to the unreliability of these classic signs of instability, some centers have added age to their trauma activation criteria, with any patient over the age of 65–70 being alerted when involved in a minor or major trauma [65]. Hammer et al. showed that patients greater over age 70 had decreased mortality when trauma-alerted to the highest level, regardless of mechanism or vital signs [66]. Other groups have investigated the use of different cut-off values for vitals when considering geriatric trauma patients (i.e., heart rate of 90 bpm and systolic pressure less than 110 mm Hg) [16]. Demetriades et al. suggested a new protocol for trauma team activation with similar vital alterations and showed that those patients who received early invasive monitoring and resuscitation, as well as early ICU admission had significant reduction in mortality [65]. The takeaway is that older patients have high risk of death even in the absence of physiologic disturbance and should be treated more aggressively.

## 29.7 Initial Evaluation and Resuscitation

Triage isn't the only time that missteps are commonly taken in the treatment of geriatric polytrauma patients. There is often a delay in recognition of critically ill patients and a corresponding delay in the initiation of aggressive resuscitation and implementation of invasive monitoring [67]. Recognition of shock in this vulnerable population is imperative as multiple studies support that the early initiation of invasive monitoring, goal directed resuscitation, and admission to appropriate units (often intensive care) decreases both the morbidity and mortality associated with elderly trauma [16, 64, 65, 67]. Scalea et al. demonstrated an impressive decrease in mortality (93 to 47%) when invasive monitoring was used to drive more efficient delivery of tissue oxygen, similar to results seen by Demetriades et al. who showed a reduction from 53.8% to 34.2% mortality [65, 68]. In these scenarios, the goal is to avoid the lethal triad of hypothermia, coagulopathy, and acidosis [69]. Efficient gathering of information is paramount to survival in these patients. According to the American College of Surgeons Trauma Quality Improvement Project (ACS TQIP) recommendations, base deficit should be calculated early to identify patients in occult shock [70]. Both base deficit and serum lactate serve as markers for tissue oxygenation, with high levels representing poor peripheral perfusion, with a study by Callaway et al. demonstrating a 4.1 and 4.2 times

increased odds ratio of mortality in patients with a severely increased base deficit and lactate level, respectively [71].

## 29.8 Pain Control/Anesthesia

Traumatic injuries are painful, and appropriate and adequate pain control is important both for patient well-being, but also for beginning the process of mobilization and recovery. Specifically, pain control in the older adult requires a balanced and often multi-modal approach as both too much and too little pain control has been associated with delirium, decreased mobility, and development of complications and extended lengths of stay [72]. Morrison et al. demonstrated that even in cognitively intact patients, the undertreatment of pain increased the risk of developing delirium nine-fold [73]. The scenario is complicated further by the multiple medical comorbidities, polypharmacy, and physiologic changes often present in the elderly [74]. While opiate narcotics certainly play an important role in pain control after traumatic injuries, their use in elderly patients has been controversial as they have been shown to contribute to delirium, decreased respiratory drive, and other serious complications [75]. For this reason, there has been extensive research on other modalities of pain control for the elderly including a multimodal approach as well as regional anesthesia. Similar to other topics in geriatric trauma, much of this research has been on hip fracture patients. Spinal and epidural analgesia have been introduced as superior methods of pain management in geriatric patients, and epidurals are also useful in the setting of multiple rib fractures. The use of spinal and epidural pain control is not always simple and may be complicated by use of anticoagulants [34].

A more recent development in pain control, specifically for extremity injuries, is the fascia iliaca block, which has been shown to be effective at decreasing preoperative pain in patients with hip and femur fractures. Mangram et al. demonstrated lower pain scales than those treated with standard pain control regimens and a higher percentage of patients were discharged to home rather than facility although no difference in rates of morbidity or mortality was seen [76]. The fascia iliaca block fills the plane underneath the iliac fascia with local anesthetic, desensitizing the obturator, femoral, and lateral femoral cutaneous nerves. Fascia iliaca block has shown to reduce opioids preoperatively and improve pain scales post-op and shorter length of stay [77].

## 29.9 Co-Management with Geriatrics and Palliative Care Specialists

In continuation of a previous theme, co-management of the elderly patient by both orthopedic surgeons and geriatric medicine specialists has been well described in the hip fracture literature and has been shown to decrease perioperative complications and decrease mortality [74, 78]. The development of protocols and agreements between surgical and medical services when considering the geriatric patient has been expanded to many surgical disciplines. Many institutions have developed specific teams dedicated to the care of the geriatric trauma patient consisting of medical hospitalists, physiatrists, physical therapists, occupational therapists, respiratory therapist, dedicated nursing supervisors, pharmacists, and palliative care team members [79]. The preponderance of literature on this topic has demonstrated that this interdisciplinary team-based approach is the standard of care. It is important to have these teams and agreements in place as these patients often benefit from early operative intervention but also benefit from medical evaluation before surgery which has been shown to decrease complications, total length of stay, readmissions, and mortality [80]. Early involvement by the medicine or geriatric team is crucial as their training focuses directly on understanding the comorbidities of the elderly and how to manage potentially adverse outcomes and complications. In fact, centers with automatic hospitalist consults placed for older adult patients, have demonstrated a decreased time to surgery and decreased length of stay [81].

Geriatricians should direct the patient's overall care as they are most knowledgeable as to when to involve the consultation of other services (i.e., cardiology) and how to best provide expeditious care [34, 80]. These physicians in consult are also key in helping to manage the common polypharmacy that accompanies older adult. An accurate medication reconciliation is paramount and then any unnecessary medications should be stopped, taking care to continue all those medications that could cause deleterious side effects or withdrawal if stopped [34]. Along with consultation of geriatric medical providers, The American College of Surgeons Trauma Quality Improvement Program geriatric trauma management guidelines put forth that palliative care should be provided in these cases regardless of prognosis and that involvement of a palliative care team can both aid in informed patient decision-making and improved outcomes such as length of stay [82].

## 29.10 Timing of Surgery

Much of the evidence supporting the protocols and practices for geriatric polytrauma find their root in studies of low-energy trauma mainly looking at isolated hip fractures [64]. The geriatric hip fracture literature is robust and has provided at least some insight into the appropriate timing of surgical intervention through a number of retrospective and prospective trials. Moran et al. found that those patients with significant medical comorbidities necessitating a delay in surgery had 2.5 times the risk of 30-day mortality [52]. The same study showed that a delay of 4 days in surgical care without acute medical comorbidities did not increase morbidity or mortality in hip fracture patients [52]. Sexson et al. showed that patients with relatively few medical comorbidities (1-2) had improved 1-year mortality if operated on within the first day of admission, but those with more complex medical problems (3+) had increased rates of mortality [83]. In an extensive metanalysis, Klestil et al. showed that those patients operated on after 48 h had an increased risk of death within 1 year, but if within the window of the first 2 days there was no significant difference [84]. In a study looking specifically at mortality in relation to surgical timing in elderly polytrauma patients, Tornetta et al. found no difference in mortality between early and late surgery. Mortality was 11% in those treated within 24 h, compared with 18% in those who had later surgery [85]. While there is still need for further research on the subject, it seems to make sense that early stabilization likely prevents complications secondary to prolonged immobilization. In a recent study of elderly patients with operative traumatic injuries, those who underwent surgery within 48 h after admission had improved mortality rates [27].

### 29.10.1 Representative Case: Timing of Surgery and Appropriate Team-Based Clearance

This 81-year-old male with history of partial blindness experienced a two-story fall resulting in a subarachnoid hemorrhage (SAH), cervical spine fractures (C2 bilateral lamina fx, C6 & C7 lamina fx), dorsal cervical epidural hemorrhage, right-sided rib fractures [1, 3–7, 9, 10] and left-sided rib fractures [2–12]. He also sustained a right peri-implant femur fracture and a left-sided displaced femoral neck fracture. His right lower extremity was placed in traction, and he was admitted directly to the ICU with orthopedics, neurosurgery, geriatrics, and acute pain service following in consult. In coordination with all teams, and after appropriate clearance, the decision was made to proceed to the operating room the following morning for fixation of the right peri-implant femoral shaft fracture, with plan for left hip hemiarthroplasty the following day. Post-op from right femur open reduction and internal fixation he had increased oxygen requirement, required blood transfusion, and left hip surgery postponed. A change in mental status prompted a repeat head CT, which showed interval improvement in SAH. Again after input from geriatric, neurosurgical and intensive care teams, patient was cleared for surgery and went for left

hip hemiarthroplasty. After both procedures, he was bearing weight on bilateral lower extremities and progressed well with rehabilitation and was discharged to a skilled nursing facility. Seen in follow-up and was back to all baseline activities of daily living (Fig. 29.3).

## 29.11 Initial Operative Management

There are certain organ systems that when injured, must be dealt with swiftly in order to save the patient's life. A chest injury with large

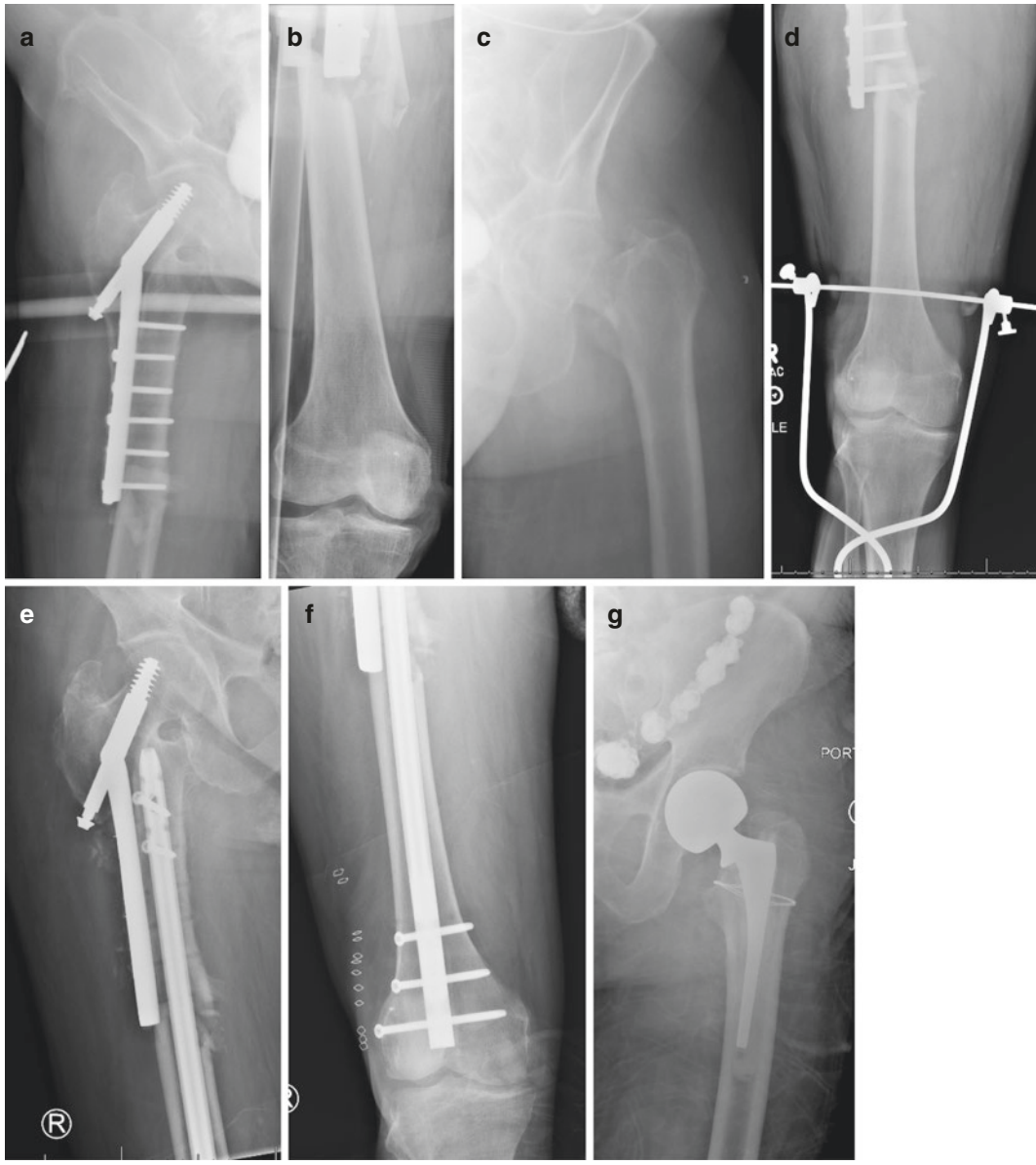


**Fig. 29.3** (**a**–**g**): (**a**) AP radiograph of right hip and proximal femur demonstrating a peri-implant fracture just below the previous six-hole sliding hip screw. (**b**) Lateral/oblique of the distal femur and knee with displaced peri-implant fracture. (**c**) AP radiograph of the hip with a displaced femoral neck fracture. (**d**) AP of the knee and femur status post initial stabilization with a distal femoral traction pin. (**e**) AP of the hip and femur status post retrograde intramedullary nailing of the femur. (**f**) AP of the knee and distal femur status post retrograde intramedullary nailing of the femur. (**g**) AP of the left hip status post left hip hemiarthroplasty

hemothorax or pneumothorax must be quickly treated with a chest tube. High grade injuries to abdominal organs such as the liver or spleen must be addressed before the patient dies from hemorrhagic stroke, often treated through laparotomy with packing and/or splenectomy [86].

When considering the operative plans for a patient and their orthopedic injuries, it is vitally important to obtain and understand the patient's specific medical history, with an emphasis on baseline functional status. Not only must the team take into account the physical function of the patient (ability to perform activities of daily living, ambulatory assist devices), but also the cognitive function as this can play a significant role not only in preoperative discussions, but also in determining the ability to participate in rehabilitation [28].

There have been a number of pendulum swings in the last 50 years when considering the principles of damage control orthopaedics (DCO) and early total care (ETC). While this is still a debated topic when considering the young trauma patient, there is not a significant amount of literature available on the role of DCO in the elderly polytrauma patient. While there is literature that shows ETC has been associated with a high incidence of complications, especially in those with high injury severity scores such as polytrauma patients, there may be a stronger role for ETC in stabilized geriatric patients [87]. This debate of early total care (ETC) versus damage control orthopaedics (DCO) is especially relevant to fractures of the pelvis, acetabulum, spine, and femur which most commonly require bedrest until surgical stabilization [88]. Early stabilization for each of these injuries has been extensively supported with the primary goal to allow for early mobilization which has been shown to decrease complication rates [89–91]. This may be even more true in the polytraumatized patient [90]. Early Appropriate Care (EAC) in fractures of the axial skeleton and femur has been shown to have similar results and complication risk in elderly patients when compared to young patients [88].

In these patients, the principle of postponing definitive care to later operative phases is also sometimes employed, when physiologic disturbances have been corrected by intensive care therapy. There is evidence that DCO can help to offset these physiologic disturbances of hypothermia, acidosis, and coagulopathy [92]. As mentioned previously, there are characteristic injuries associated with geriatric polytrauma, with musculoskeletal injuries the most frequently seen. Along with controlling the blossoming lethal triad, the main goals from an orthopedic perspective are to control instability thereby reducing pain and easing the care needed for turns and other patient care. This should ideally be done through the quickest available procedure.

The need to manage according to DCO principles should be balanced against the ability to perform single surgery in the frail elderly patient. For example, an external fixator may cut out of osteoporotic bone. Definitive fixation in some instances may be preferred if the patient's condition permits it. The topic of DCO in the elderly requires future research to better define its benefits and risks.

As one of the most common, and most deadly injuries in the geriatric polytrauma patient is high-energy pelvic trauma which requires surgical intervention [93]. These injuries lend themselves to some form of DCO, as ETC is often not possible given the patient's condition. External fixation can serve to both stabilize the pelvic ring and reduce blood loss [94]. Pelvic injuries may also require pelvic packing as a last resort if pelvic binder or external fixator does not stabilize the patient, but mortality rates are quite high with this procedure [95]. These injuries may also benefit from angiography and selective embolization for better control of intrapelvic arterial bleeding [96].

## 29.12 Secondary Operative Management

Return trips to the operating room following a recent trauma must be well orchestrated among all involved teams. Operative sequence must take into account the individual urgency of the proce-

dure and the affected organ system. Return to OR following exploratory laparotomy or pelvic packing and debridement and irrigation of open wounds must take precedent. Again, understanding the complex medical history of the patient is crucial because information within these histories has an impact on surgical options and potential for rehabilitation [28]. From the orthopedic perspective, weight bearing considerations are of utmost importance as the goal is always to facilitate early motion and weight bearing if possible.

### 29.12.1 Open Fractures

Open fractures in the geriatric patient are treated by the same algorithm as young patients: aggressive debridement of bone ends and soft tissue, fracture stabilization, and assuring soft tissue coverage. Open fractures are known to have higher rates of infection and complication than closed fractures, in all populations. With the added aspect of decreased immune response, fragile soft tissues, and other medical comorbidities, the geriatric population may be at increased risk of these complications. While there are many challenges to treating open fractures in the elderly, there is evidence to support aggressive management of severe open fractures which can lead to low rate of infection and amputation [97]. However, all significant open fractures in the elderly should be treated as limb-threatening conditions.

### 29.12.2 Osteoporotic Fractures

With a high rate of osteopenia and osteoporosis within the geriatric population, it must be considered with the planning of each fracture, as the altered architecture and biomechanics of osteoporotic bone make for difficult fixation. Osteopenic bone has poor screw purchase and increased risk of screw pullout, leading to fixation failure [28]. Failure of hardware in osteoporotic bone typically occurs at the bone-implant interface, resulting in cutout, fracture subsidence, or pull-off of the plate. In this osteoporotic bone, load-bearing, as opposed to load sharing, devices are preferred in these patients [34].

### 29.12.3 Peri- and Intra-Articular Fractures

Primary joint arthroplasty may be considered in certain fracture types when there is substantial destruction of an osteoporotic joint such as with comminuted fractures of the femoral neck, proximal humerus, and elbow [34]. Primary total hip arthroplasty is indicated in certain displaced femoral neck fractures, and comminuted proximal humerus fractures may be treated with arthroplasty. A reverse arthroplasty is often required based on fracture pattern or previous rotator cuff disease.

### 29.12.4 Periprosthetic Fractures

When a previous orthopedic implant is present such as a joint replacement or other implant, it almost always alters the fracture pattern and treatment for a given injury. A large review of joint arthroplasty found that 5-year periprosthetic fracture rates are 0.9% after primary total hip, 4.2% after revision total hip, 0.6% after primary total knee, and 1.7% after revision total knee [98]. Principles of periprosthetic fractures are early mobilization and preserving mechanical axis of the limb [28].

#### 29.12.4.1 Representative Case: Open Fractures and Osteoporotic Bone (High Energy Leads to Devastating Injury Complex)

This 71-year-old female with history of hypertension, asthma, and obesity who was involved in a high-speed motor vehicle collision who sustained significant traumatic injuries including a grade 3 splenic laceration, grade 1 hepatic laceration, multiple rib fractures with bilateral pneumothoraces and pulmonary contusions, a sternal fracture, a three-column thoracic spine injury at T7-8 as well as a multitude of orthopedic injuries. She sustained

a right proximal humeral shaft fracture, bilateral distal radius fractures, left grade 3 open pantalar fracture dislocation with extrusion, left grade 1 open tibial plateau fracture, right grade 1 lateral compression pelvic injury, left grade 3 open calcaneus fracture, left foot fractures of the navicular and 2-5 metatarsals, left 2-4 metacarpal fractures, right grade 2 open thumb distal phalanx fracture. She was seen by orthopedics, neurosurgery, and trauma surgery for initial stabilization and management in the trauma bay (irrigation, splinting, chest tube, etc.) and then admitted directly to the ICU. Post-injury day 1 underwent ex-lap and splenectomy due to hypotension. Seen by geriatrics consults. Patient was not cleared for operation until hospital day (HD) 2. She went for initial I&D and external fixation of her left ankle with placement of antibiotic beads, I&D and ORIF of her tibial plateau, and transiliac-transsacral screw fixation. Went HD4 for upper extremity fracture fixation. Followed the next day by fixation of her spine by neurosurgery. She underwent multiple I&Ds of her ankle. Her post-operative course was complicated by ventilator acquired pneumonia, and bilateral pleural effusions with near collapse of right lung. Underwent tibiotalar-subtalar arthrodesis with a ring fixator 1 month into hospitalization, but later after extensive discussions, decided that she wanted to proceed with below knee amputation instead of the arduous process of limb salvage. She continued to work towards discharge and after 2 months of hospital stay was discharged to rehabilitation facility. Unfortunately, the patient transferred all of her follow-up care to her home state, and while there is record of her living at least 6 months post-discharge, there are no further follow-up records (Fig. 29.4).

## 29.13 Post-op Complications

It should come as no surprise that post-operative complications significantly increase the risk of mortality in elderly trauma patients [42]. These complications are often brought on by alterations in normal physiology in a body system already worn down by the tides of time. Commonly the heart, lungs, brain, kidneys, and soft tissues are particularly susceptible to insult. Cardiac arrythmias and myocardial infarctions are both devastating to the already weakened system. Geriatric patients, who are more susceptible to post-op infection (UTI, pneumonia, surgical site infection); and nosocomial infections result in longer stays in the hospital and ICU and increased mortality. Geriatric patients are also at a higher risk of soft tissue infection due to their fragile skin and often malnourished state.

## 29.14 Secondary Fracture Prevention and Fracture Liaison Services

Many orthopedists think of themselves more as surgeons than as medical doctors, yet they will often be the first healthcare professional that interacts with patients who develop a fragility fracture. A recent study reported that orthopedists regularly come in contact with fragility fractures, however they do not have a good foundation in the screening and medical treatment of osteoporosis [99]. The orthopedic surgeon should feel competent to start patients on calcium and vitamin D to correct vitamin D deficiency and improve fracture healing in osteoporotic patients. Barton et al. suggest that the implementation of a Fracture Liaison Service fits well within the practice and preferences of many orthopedic surgeons, acting to identify at risk patients, but referring definitive osteoporosis care to other providers within the system. The treatment gap for osteoporosis is so vast that it is crucial that orthopedists contribute to the identification of these patients and ensuring they receive the appropriate bone health evaluation. In 2009, the American Orthopaedic Association launched the Own the Bone program to provide a simple tool for hospital systems and orthopedic practices to establish their own Fracture Liaison Services.

Prevention of falls represents the other aspect of secondary prevention of fractures. Falls are the leading cause of fracture of the forearm, hip, and pelvis in geriatric patients. Controlling risk factors for falls is crucial, such as limiting the use of sedatives (benzodiazepines, phenothi-

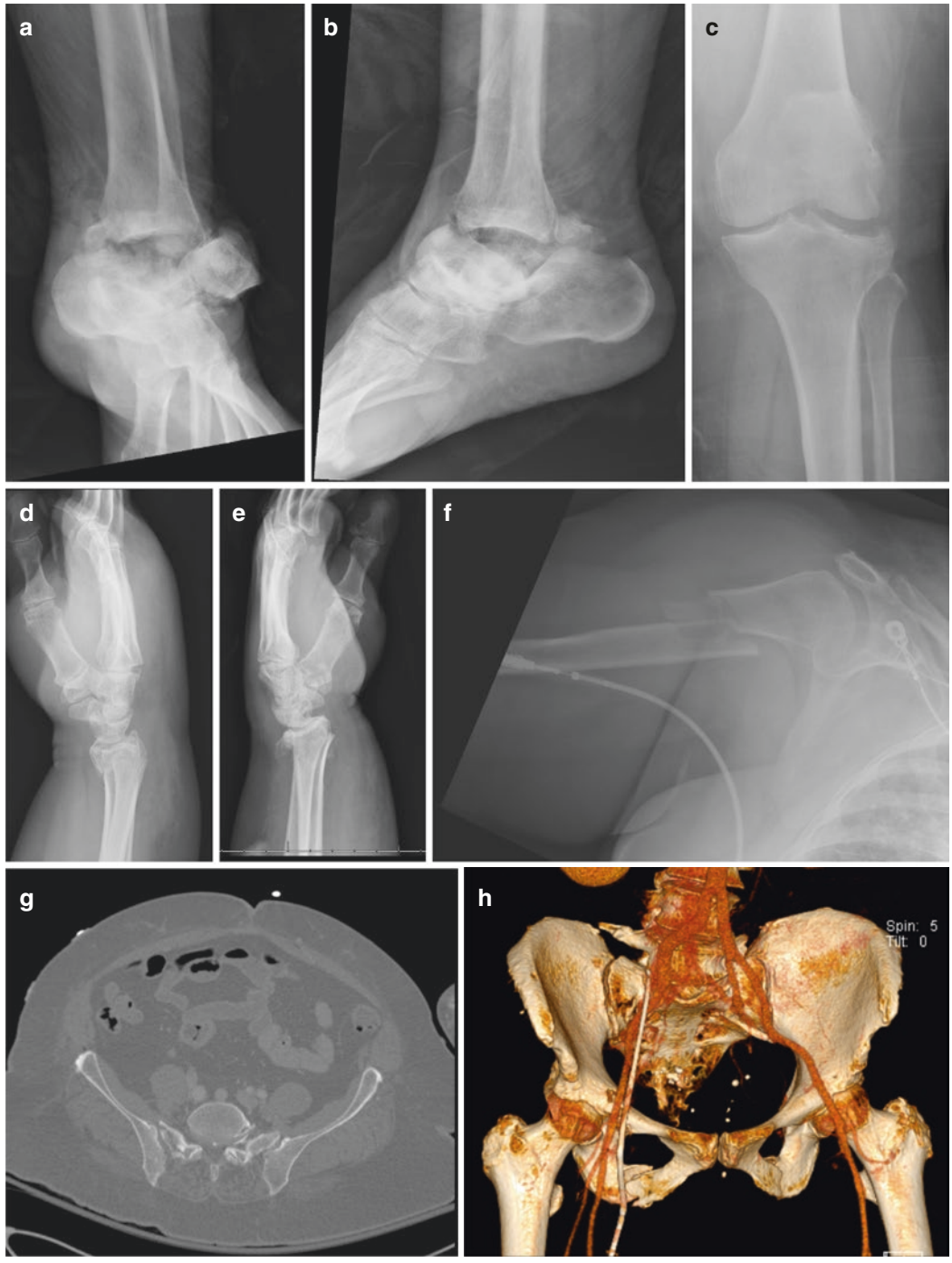


**Fig. 29.4** (**a**–**q**): (**a**) Oblique of the ankle with talar extrusion. (**b**) Lateral of the ankle with talar extrusion. (**c**) AP of knee with lateral tibial plateau fracture. (**d**) Lateral of a right displaced distal radius fracture. (**e**) Lateral of a left displaced distal radius fracture. (**f**) AP of the humerus with a proximal humeral shaft fracture. (**g**) Axial CT with fracture of the right sacrum. (**h**) 3D of pelvic CT with multiple fractures. (**i**) AP of the ankle status post external fixation. (**j**) AP of the ankle status post tibiotalar-subtalar arthrodesis with a ring fixator. (**k**) AP of the leg with eventual below the knee amputation. (**l**) AP of the tibial plateau status post ORIF. (**m**): AP of the pelvis status post transiliac-transsacral screw. (**n**) Lateral radiograph of the thoracic spine status post four level posterior instrumented fusion. (**o**) AP of the humerus status post IMN. (**p**) PA of the right wrist status post ORIF. (**q**) PA of the left wrist status post ORIF

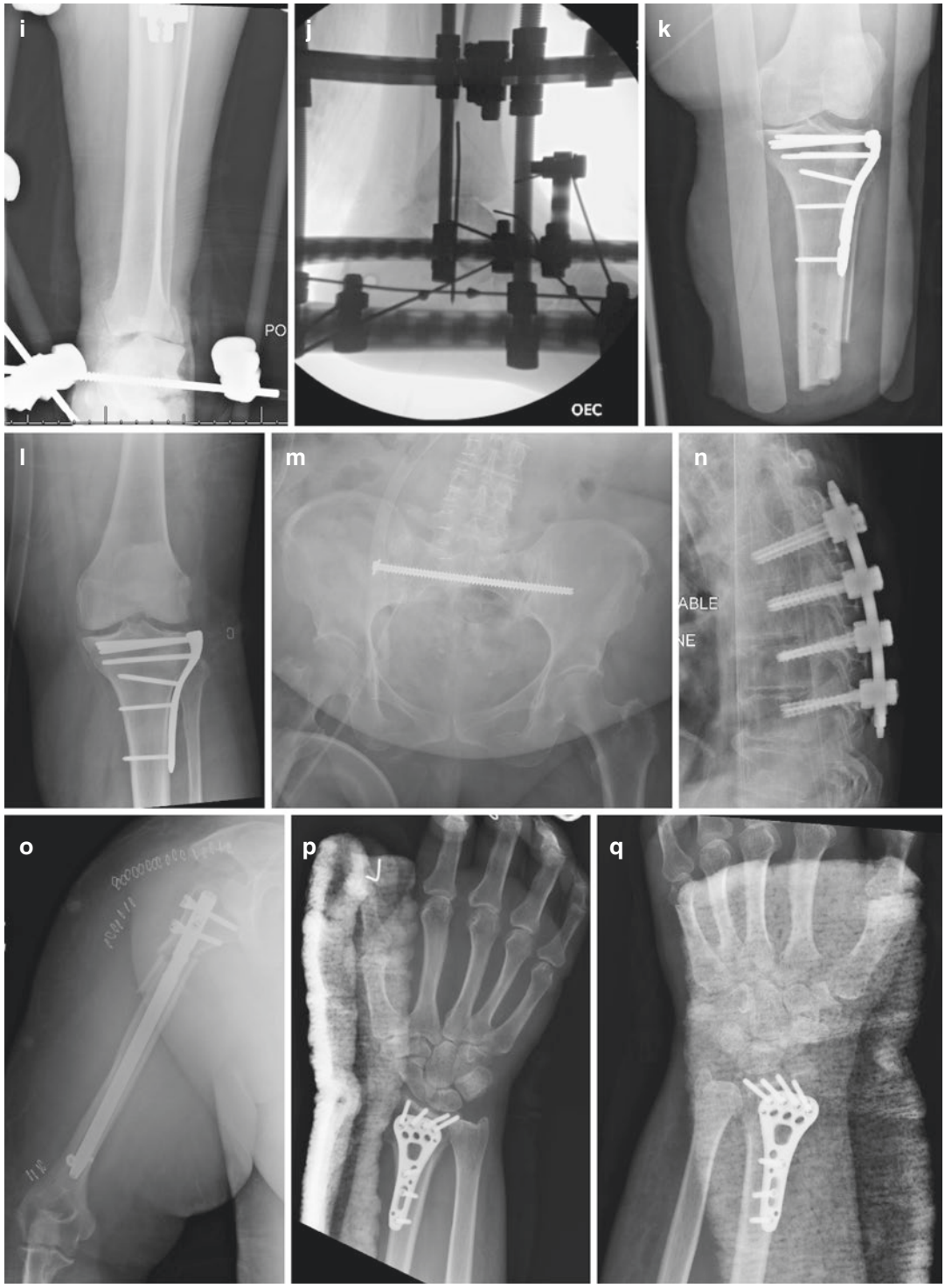


**Fig. 29.4** (continued)

azines, antidepressants). Other factors that lead to falls include cognitive or visual impairment, lower extremity disability, foot problems, balance or gait abnormalities, and neurologic conditions [39].

## 29.15 Outcomes of Care and Expectations for the Patient and Family

We must rely somewhat on the hip fracture literature to look at outcomes for geriatric trauma patients as there are limited studies reporting outcomes data in critically ill and multiply injured elderly trauma patients. As discussed earlier in this chapter, one thing we are confident in is that a team-based approach to geriatric trauma patients is critical, and that outcomes including complications and mortality are improved with this model. A polytrauma event is a lifechanging event at any age, especially in those aged greater than 65 [56]. Medical comorbidities, decreased physiological reserves, and already declining functional status set the stage for an uphill and sometime Sisyphean effort for the geriatric patient. Even in those patients who experience simple fragility fractures, few will recover their pre-injury functional level [34]. Magaziner et al. demonstrated that one quarter of hip fracture patients living independently required long-term nursing at discharge [100]. One of the most important goals in treatment of older adult patients is to get them moving again as soon as possible. Ceder et al. protocolized immediate weight bearing and intensive physical therapy and showed a decreased length of stay and higher functional level at discharge with fewer patients requiring a skilled nursing facility [101]. Berry et al. found similar results, that with 5 years of aging there was a 30% increase in mortality [102]. Regardless of ISS, age has been shown to be an independent predictor of mortality, and mortality rates from 5% to 42% in the elderly have been recorded [13, 103].

## 29.16 Conclusions

Due to their limited physiologic reserves morbidity and mortality of elderly patients after high-energy trauma are higher than in younger adults. Specific triage criteria must be applied for the elderly trauma patient and resuscitation must be aggressive. Low-energy falls are the most common cause of geriatric trauma, however high-energy polytrauma is a notable cause of morbidity and mortality in the elderly. Within the geriatric population, osteoporosis is common and it can significantly influence the pattern and necessary treatment of musculoskeletal injuries. Co-management between surgical and medical (geriatric) teams are key for improving outcomes in elderly trauma patients. Even though they are at higher risk for complications, older patients can still survive trauma if treated with appropriate and timely care. The Eastern Association for the Surgery of Trauma (EAST) Practice Management Guidelines for Geriatric Trauma revealed a significant lack of investigation in this field and called for future studies to better analyze the geriatric response to trauma and to continue working towards protocols to improve outcomes further.

**Take-Home Messages**

- Geriatric polytrauma patients have high mortality rates, and there is a significant economic impact associated with these injuries.
- While there are some similarities with younger trauma patients, geriatric polytraumatized patients are largely a unique entity, due to physiologic changes and the build-up of other medical comorbidities.
- More research through systematic review and prospective trials are needed to better understand this injury population.

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# Pediatric Polytrauma Management

# 30

Thomas Lustenberger and Ingo Marzi

**Learning Objectives**

- Anatomic and physiologic differences in children as compared to adults.
- Types and patterns of injury in the pediatric patient.
- Differences in the acute management of the polytraumatized child compared to adult patients.
- Key concepts in the management of critical injuries of the head, chest, abdomen, pelvis, spine, and extremities in the pediatric patient.

## 30.1 Initial Assessment and Resuscitation

The Advanced Trauma Life Support (ATLS)-based primary survey with simultaneous resuscitation addresses life-threatening injuries that compromise oxygenation and circulation. Upon arrival at the hospital, the child's airway, breathing, and circulation are evaluated. The Broselow Pediatric Emergency Tape is helpful for determining height, weight, the appropriate size for resuscitative equipment, and correct drug doses and drip concentrations in a child [1, 2].

Airway control is the first priority for any trauma patient, but a child's airway is anatomically distinct from that of an adult. A child's neck is shorter, the epiglottis is large and floppy, and the vocal cords are located higher and more anterior. In a child, intubation might be easier with a straight laryngoscope blade, and the endotracheal tube size can be estimated using the child's fifth digit. The subglottic trachea is the narrowest portion of the pediatric airway and provides a physiological cuff; thus, traditionally, uncuffed endotracheal tubes are used in children less than 8 years of age to avoid subglottic edema and injury. The tube position should always be checked with a chest X-ray since a high incidence of right mainstem intubation is found in emergency intubations. Surgical cricothyroidotomy should be avoided in children younger than 6 years of age due to a frequent association with secondary subglottic stenosis.

Assessment of the patient's breathing follows establishment of the airway. Infants and small children are primarily diaphragmatic breathers; consequently, any compromise of diaphragmatic excursion significantly limits the child's ability to

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ventilate. Severe gastric dilation due to the swallowing of air may cause respiratory difficulties or complicate the abdominal examination. Gastric decompression with insertion of a naso- or orogastric tube should be performed in appropriate cases.

Children are known to have an amazing cardiovascular reserve; therefore, initial normal vital signs should not impart any sense of security with regard to the status of the child's circulating volume. Obvious signs of shock, such as hypotension or a decrease in urinary output, may not occur until more than 30% of the blood volume has been lost.

Evaluating the level of consciousness in infants and young children is difficult. Therefore, a modified verbal and motor version of the Glasgow Coma Scale (GCS) score has been developed (Table 30.1).

As in adults, a focused assessment sonography in trauma (FAST) is performed during the primary evaluation of the injured child. In children in particular, a lack of free intraperitoneal fluid does not exclude significant organ injuries. On the other hand, the majority of children with hemoperitoneum do not necessarily require operative intervention.

Computed tomography (CT) scanning of the head, chest, abdomen, spine, and pelvis is the preferred technique for imaging the polytraumatized child. However—in particular in the awake patient—a thorough physical examination and evaluation of the trauma mechanism may permit the avoidance of a complete CT diagnostic. Reducing the radiation dose as much as possible and thereby reducing its associated risks in children is essential if a CT scan is performed ("ALARA" concept: as low as reasonably achievable) [3]. This is done by adjusting the CT technique to the age and size of the child, to the body region of interest and the clinical question. The amount of i.v. contrast media required is determined based on the child's weight. Multiplanar sagittal and coronal reconstructions are helpful in assessing the spine, the pelvis, as well as the skull and fascial bones for possible fractures or instabilities.

## 30.2 Head Injuries

Head injuries are common in children with polytrauma; they represent the leading causes of mortality among children and adolescents and are the most common causes of long-term disability (Fig. 30.1). After initial resuscitation to ensure adequate airway, ventilation and hemodynamic stability, early neuroimaging is required to look for intracranial pathologies requiring surgical intervention and neuroprotection. Compared to adults, children are more prone to suffer from severe traumatic brain injury (TBI): the skull is more pliable and thinner and therefore provides less protection to intracranial contents. The weak cervical musculature and the proportionally increased head mass also bias the pediatric popu-

**Table 30.1** The pediatric Glasgow Coma Scale (GCS) (adapted with permission from Orliaguet et al. [28] and Jakob et al. [12])

| Score | Eye opening | Best verbal response | | | Best motor response |
|---|---|---|---|---|---|
| | | <2 years | 2–5 years | >5 years | |
| **6** | – | – | – | – | Normal spontaneous movement |
| **5** | – | Cries appropriately, coos | Appropriate words | Oriented | Withdraws to touch |
| **4** | Spontaneous | Irritable crying | Inappropriate words | Confused | Withdraws to pain |
| **3** | To voice | Inappropriate screaming/crying | Screams | Inappropriate | Abnormal flexion (decorticate) |
| **2** | To pain | Grunts | Grunts | Incomprehensible | Extension (decerebrate) |
| **1** | None | No response | No response | No response | No response |

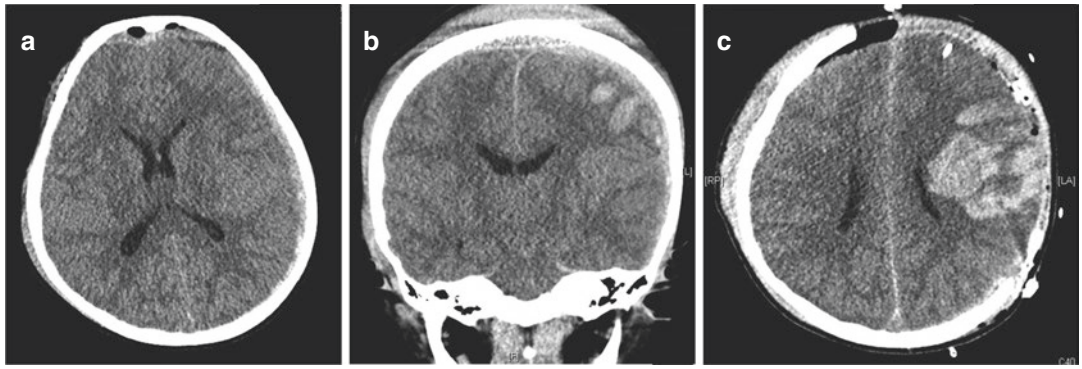


**Fig. 30.1** A 5-year-old boy with severe TBI after fall from the third floor of a building. The admission CT scan of the head demonstrates intracerebral bleeding and bilateral subdural hematomas with midline shift and obliteration of the ventricles (**a**, **b**). Left-sided hemicraniectomy was performed on the day of admission (**c**)

lation toward head injuries. Myelination occurs between 6 and 24 months of age, making the brain very soft and prone to disruption prior to the completion of this process.

Injuries of the brain can be classified as a primary or secondary damage. Primary injuries are the result of the trauma itself, while secondary injuries are from hypoxia, hypotension, hypercarbia, anemia, hyperglycemia, infections, seizures, or increased intracranial pressure (ICP) in addition to the primary injury. All of these have the potential to cause subsequent brain damage during the days and weeks subsequent to the initial injury. The mass effect due to a hematoma or a cerebral edema secondary to the injury can result in a rise of the ICP. Acute management of severe TBI focuses on minimizing secondary injury or preventing secondary insults to the brain.

The incidence of increased ICP is higher in children and the cumulated duration of elevated ICP episodes directly correlates with the outcome measured by the Glasgow Outcome Scale in TBI patients. In children, the tolerated burden of an increased ICP is less than in adults. While in adults the tolerance for an ICP >20 mmHg is 37 min, it is only 7 min in children [4, 5]. Keeping the ICP <20 mmHg is therefore the standard in the management of severe TBI in children [4, 6]. With regard to the cerebral perfusion pressure (CPP), keeping it above a recommended threshold (60 or 70 mmHg) is associated with improved clinical outcomes in adults [6, 7]. For children, the current guidelines support maintaining a minimum CPP of 40–50 mmHg [6].

General neuroprotective measures include:

- Head in midline prevents kinking and obstruction of the jugular veins, thus assisting venous drainage from the cranium.
- Elevating head of the bed, typically 30 degrees.
- Minimizing unnecessary stimuli.
- Sedation and analgesia (e.g., barbiturates administration titrated to ICP and blood pressure).
- Rare, and only transient use of hyperventilation.
- Osmotic therapy (e.g., Mannitol, hypertonic saline).
- Cerebrospinal fluid drainage (if ventriculostomy catheter in place).
- Moderate hypothermia can be considered to control elevated ICP.

Intracranial pressure monitors are frequently placed and are recommended in children with a GCS score of ≤8, particularly in children with closed cranial sutures. Intracranial hematomas—subdural as well as epidural bleedings—resulting in intracranial hypertension should be evacuated within the first 3 h following injury, as long-term results significantly worsen thereafter [8]. A decompressive craniectomy with duraplasty is

often considered for pediatric TBI patients with medically refractory intracranial hypertension or signs of herniation [9, 10]. This procedure should always be considered in children with a high ICP and as early as possible since this is the only option to improve the perfusion of the brain.

## 30.3 Chest Injuries

Pediatric chest injuries are relatively uncommon (5–12% of admissions); however, they are associated with a significantly higher mortality rate than other type of injuries. In isolated chest trauma, the mortality has been reported with 5%, which increases up to 40% when combined with intra-abdominal and head injuries [11].

The pediatric chest wall is more compliant with a greater cartilage content and incomplete rib ossification, making fractures of the rib and sternum less common. However, this leads to a direct transmission of the force to the underlying lung parenchyma resulting in pulmonary contusions. These severe parenchymal injuries may be present with minimal or even no signs of external trauma and with a normal chest X-ray on admission. The mediastinum and heart are more mobile in children resulting in a higher risk of heart dislocation and transection or angulation of the great vessels [12]. Furthermore, a pneumothorax may more quickly develop into a tension pneumothorax (three times more common in children than in adults) and obstructive shock [13].

The most common thoracic injuries in the pediatric patients are pulmonary contusions, rib fractures, and pneumo−/hemothorax. Far less common but more devastating injuries include lacerations to the heart and aorta, the diaphragm, the esophagus, and the tracheobronchial tree.

Pulmonary contusions represent the most common thoracic injury in children with blunt chest trauma, reaching an incidence of more than 50%. The contusions develop over the hours after injury, typically become symptomatic within 48–72 h and usually resolve within 7 days of the injury. Pulmonary contusions may lead to atelectasis and progressive inflammation, possibly resulting in pneumonia, ventilation-perfusion mismatch, and respiratory insufficiency. The treatment should focus on maintaining adequate gas exchange; in contrast to adults, kinetic therapy is in general not required.

Pneumo- and hemothorax are the second most common injuries in pediatric chest trauma and are mainly managed by chest tube placement. Small volume hemothorax and occult pneumothorax identified on CT scan with a normal chest X-ray, should, however, not receive a thoracostomy tube and may be safely observed first as almost all resolve spontaneously without intervention.

Mediastinal injuries are rare injuries in children with blunt chest trauma and include lacerations to the great vessels, to the tracheobronchial tree, cardiac injuries, or esophageal rupture. Tracheobronchal injuries are usually located in the lower trachea or the upper bronchus. If the injury involves less than one-fourth of the bronchus diameter, nonoperative treatment with frequent bronchoscopic examination may be suitable [12].

Indications for operative intervention in pediatric chest trauma:

- Cardiac tamponade.
- Hemodynamically compromising, persisting thoracostomy tube output.
- Massive air leak from the thoracostomy tube.
- Open injuries of lung parenchyma.

## 30.4 Abdominal Injuries

Abdominal injuries are diagnosed in 8–12% of blunt pediatric polytrauma patients. Due to the fact that children are in general healthy, having good physiological reserves, they may initially present clinically stable despite significant injuries. The earliest and probably only sign of hemorrhagic shock with imminent hemodynamic decompensation is tachycardia (Fig. 30.2).

There are several anatomic differences between children and adults making children more vulnerable for major abdominal injuries:

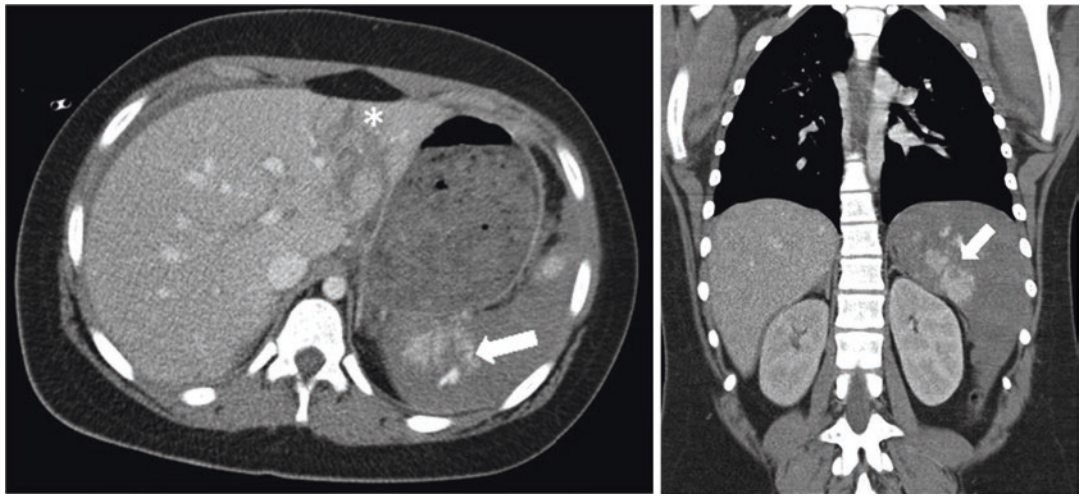

**Fig. 30.2** Polytraumatized 14-year-old girl after motorcycle accident as pillion rider. The polytrauma CT scan demonstrates severe abdominal injuries with Moore Type IV splenic laceration (arrow) and multiple liver lacerations (asterisk)

- The children's intra-abdominal organs are proportionally larger and in closer proximity to each other.
- The pliable rib cage, the thin abdominal wall with the weak and undeveloped abdominal musculature provides less protection to intra-abdominal organs.

High risk injury mechanisms for intra-abdominal injuries include blunt trauma involving lap belts (hollow viscus injury) and handle bars (pancreatic injury).

In the hemodynamically unstable patient and in the patient with peritonitis, emergent laparotomy is indicated following primary or secondary survey. The hemodynamically stable child allows further diagnostic evaluation for intra-abdominal injuries, which is generally performed by CT scan with intravenous contrast. As in adults, the FAST examination is part of the primary survey and aims to detect intraperitoneal (blood, bowel content, bile, or urine) or pericardial fluid. Although having high specificity rate to diagnose a hemoperitoneum, it has a low sensitivity to rule out significant intra-abdominal injuries.

Indications for emergent laparotomy in pediatric patients:

- Hemodynamic instability despite volume resuscitation.
- Free intra-abdominal air.
- Rupture of hollow viscus organ.
- Signs of peritonitis.

### 30.4.1 Liver and Splenic Injuries

The liver and the spleen are the two most commonly injured solid organs in blunt abdominal trauma, with an incidence of approximately 33% each [14]. The vast majority of these injuries, even high-grade liver lacerations Moore IV and V, can be successfully managed nonoperatively [15]. In fact, numerous prospective studies support management based on hemodynamic status rather than severity of injury detected on CT scan [16]. A selective, nonoperative management (NOM) requires hemodynamic stability and the absence of peritoneal signs. These patients then require close monitoring with serial vital signs and clinical examination, as well as serial hemoglobin measurements. Failure of NOM usually occurs early within the first few hours after admission. In a large multicenter study, the median time to failure of NOM

in pediatric solid organ injuries was 2 h, with 76% of failures occurring within 12 h after injury [17]. However, very few children with blunt solid organ injuries fail NOM (rate of failure of NOM of isolated injuries at pediatric trauma centers: approx. 3% for liver and kidney injuries each, 4% for splenic injuries) [16, 17]. Children with contrast extravasation from splenic injury, which is seen in approximately 5–15%, may benefit from angioembolization if conservative treatment fails [16, 18].

Children with hemodynamic instability despite transfusion and volume management require surgery for hepatic and splenic injuries. Organ-preserving techniques are preferred: Splenorrhaphy and partial splenectomy are techniques to control bleeding while preserving splenic parenchyma. Splenectomy may be required in the critically ill child or in the case of a completely shattered spleen.

The operative management of liver injuries follows the "damage control" concept. In case of surgically uncontrollable bleeding due to major hepatic lacerations, perihepatic packing is performed. Definitive operative treatment is carried out when hemodynamic stabilization is achieved and coagulopathy is reversed. Hepatorrhaphy or suture ligation of bleeding vessels is preferred instead of extensive hepatic resections [12].

### 30.4.2 Hollow Viscus Injuries

Hollow viscus injuries are much less common in blunt abdominal trauma compared to solid organ injuries. Following motor vehicle accidents, the "seatbelt sign" (abdominal wall ecchymosis) might be a clinical finding, indicating a sudden increase in the intraluminal pressure resulting in a "blowout" or perforation of the intestine. CT findings suspicious for hollow viscus injuries include:

- Free fluid without solid organ injury.
- Bowel wall thickening or enhancement.
- Extraluminal air.
- Mesenteric stranding.
- Bowel wall discontinuity.

Close monitoring and serial physical examinations should be performed in patients with suspicious findings. Once diagnosed, surgical management is required. Injuries to the stomach and the small bowel can typically be repaired during the initial operation [14]. Injuries of the stomach and small bowel can usually be primarily repaired. Stomach injuries are typically seen at the greater curvature; in these cases, debridement and primary repair is adequate. Small bowel injuries involving greater than 50% of the circumference usually require segmental resection and primary anastomosis, whereas lacerations of less than 50% of the circumference might be primarily sutured. Only in cases of severe abdominal contamination, a two-stage procedure with creation of a temporary colostomy is indicated [12].

### 30.4.3 Pancreatic Injuries

Pancreatic injuries are rare, occurring in around 3–12% in children with blunt abdominal trauma. The diagnosis is frequently delayed and is mostly based on an elevated amylase level combined with the clinical sign of severe epigastric pain. The treatment remains controversial: while some pediatric centers report nonoperative management for almost all cases of pancreatic injuries, others describe distal pancreatectomy for distal injuries and endoscopic retrograde cholangiopancreatography with stent placement for pancreatic duct injuries [14].

## 30.5 Pelvic Injuries

Injuries of the pediatric pelvic ring and the acetabulum are rare and usually present after high energy trauma and in the setting of polytrauma. The immature pelvis has greater elasticity at the sacroiliac joints and the pubis symphysis, which is explained by a higher proportion of cartilage, making it far more deformable than an adult pelvis. Furthermore, the ligaments present higher stability and the periosteum of all pelvic bones is thicker. A flatter orientation of the pediatric pel-

vis provides less protection for intra-abdominal organs [19].

The following are typical clinical signs of pelvic fractures:

- superficial hematomas above the inguinal ligament in the groin, over the scrotum or perineum, or in the upper thigh (Destot's sign),
- decreased distance between the greater trochanter and the pubic spine compared to the contralateral side in patients with a lateral compression fracture (Roux's sign),
- a large hematoma or a palpable fracture line discovered on rectal examination (Earle's sign),

### 30.5.1 Pelvic Ring Fractures

The classification system of Tile and Pennal combines the mechanism of injury and pelvic ring stability and differentiates between stable (type A), rotationally unstable (type B), and vertically unstable (type C) pelvic fractures. Unlike pelvic fractures in the adult, pediatric pelvic fractures are generally not hemodynamically relevant [20].

Type A fractures are mostly treated conservatively, aiming at pain relief and early mobilization. Avulsion fractures of secondary ossification centers (avulsion of sartorius muscle, rectus femoris muscle, and proximal hamstrings) are in most cases managed nonoperatively [21].

Type B and C fractures are treated depending on the mechanical instability of the pelvis and the need for intervention due to hemodynamic instability. While in partially stable fracture (type B) the choice between conservative and surgical treatment depends on the deformity and the expected residual instability, unstable fractures (type C) will in most cases require surgery. Emergent options to achieve mechanical pelvic stability include a pelvic binder or simply bounding the patient's knees and ankles loosely together to reduce the volume of the small pelvis. The C-clamp for emergent external posterior stabilization has no role in the acute management of pelvic fractures in children. The anterior external fixator can be used initially, but can also be a definitive approach in children. Open reduction and internal fixation with a plate can be performed in the acute or delayed setting, however, needs adapted operative techniques and modified implants up to the age of about 12 years [19].

Indications for operative intervention in fractures of the pediatric pelvic ring:

- displacement of large fragments of more than 1 cm,
- diastasis of the pubis symphysis >2 cm,
- open pelvic ring fractures,

Anatomical reduction should be the primary goal to minimize the risk of functional impairment. Most articles report poor results if an unstable pelvic fracture heals in malposition [19].

### 30.5.2 Acetabulum Fractures

Fractures of the acetabulum are rare and evidence-based studies regarding the treatment are sparse. Injury of the triradiate physis, which closes between 12 and 14 years of age, might result in growth arrest and subsequent subluxation of the femoral head. In children with a posterior hip dislocation, an MRI is highly recommended to diagnose a posterior wall dislocation requiring operative fixation. The indications for surgery follow those for adult fractures: unstable fractures or those that result in an incongruent relationship between femoral head and the acetabulum benefit from operative management. Interfragmentary displacements of >2 mm or a joint instability should be surgically treated [22]. Screws and/or small fragment plates are the implants of choice, ideally not crossing the triradiate physis. If the implants however cross the physis, implant removal as early as possible may be indicated in young children to allow for continued growth of the acetabulum. Nondisplaced fractures of the acetabulum and crush injuries of the triradiate physis are managed nonoperatively [19].

### 30.5.3 Associated Injuries

Most patients with a pelvic fracture are polytraumatized, sustaining associated injuries to the head, chest, abdomen, and/or extremities). Urogenital injuries should receive specific attention during the initial clinical examination, as those injuries are often missed and may lead to serious complications in the further course. Bladder injuries may require urgent repair in the case of an intraperitoneal rupture, or delayed intervention versus observation for extraperitoneal bladder injuries [23].

## 30.6 Spine Injuries

Spine fractures are rare injuries in children, representing approximately 1–2% of all pediatric fractures; in the polytraumatized child, however, the incidence is significantly higher (8–30%). The disproportionately large head size and the relatively weak neck muscles, the horizontal orientation of the upper cervical facet joints, and a ligamentous laxity place the upper cervical spine (C0-C2) at higher risk for injury in children younger than 12 years of age [12, 24]. However, compared with the adult spine, the pediatric spinal column is less likely to suffer fractures and ligamentous injuries because of its increased flexibility; on the other side, children are more likely to sustain spinal cord injury with purely ligamentous injury. Therefore, children are more prone to spinal cord injury with normal radiographs, the so-called SCIWORA (spinal cord injury without radiographic abnormality), compared to adults.

The developing pediatric spine contains several anatomic differences from the adult spine that can make interpretations of radiologic imaging difficult and may be mistaken as pathology:

- incomplete ossification of the vertebrae and synchondrosis,
- increased anterior displacement of C2 on C3 (pseudosubluxation) and less frequently of C3 on C4,
- increased distance of dens and anterior arch of C1,
- anterior wedging of vertebral bodies,
- pseudospread of the atlas,

### 30.6.1 Cervical Spine Fractures

Most cervical spine injuries do not require surgical management and can be managed with external orthoses [25]. The *atlanto-occipital dislocation* is a rare and often fatal injury in the polytraumatized child. Significant neurological deficits may be present, ranging from cranial nerve dysfunction to varying degrees of quadriplegia and complete loss of neurological function below the brain stem. Early reduction and stabilization, preferably using a halo fixator or a Minerva cast, should be performed. In the adolescent patient or in younger children with persisting instability and neurological deficit, internal fixation, and posterior occiput-C1/C2 fusion might be necessary.

*Atlanto-axial dislocations* are relatively common lesions in the C1/C2 segment and may present as a translational or a rotational instability between atlas and axis. Acute rotational atlanto-axial dislocations are in most cases reducible and are subsequently immobilized using a halo device for 2–3 months. A traumatic translational atlanto-axial dislocation, a non-reducible rotational instability, or a rupture of the transverse atlantal ligament usually require a fusion of C1-C2.

*Odontoid fractures* are rare in children under the age of 7 years and are usually resulting from high energy trauma with a flexion mechanism. These fractures are among the most frequently seen pediatric cervical spine injuries; neurological deficits are rare. In young children, odontoid peg fractures usually occur through the synchondrosis between the body of C2 and the peg [24]. They usually demonstrate an anterior displacement with the dens angulated posteriorly. Most displaced pediatric odontoid fractures can be reduced with mild extension and are adequately treated using a halo device for 6–12 weeks.

*Fractures of C3–C7* are mostly seen in older children and adolescents. These fractures typically present as compression fractures of the vertebral body, which can be sufficiently treated with a cervical orthosis. Persistent instability, neurologic deficits, or increasing kyphosis represent indications for posterior cervical fusion.

### 30.6.2 Thoracolumbar Spine Fractures

The majority of thoracolumbar spine fractures are minor, stable, and without neurological deficits [26]. Type A compression fractures, mostly occurring in the thoracic spine, are seen in 90% of the cases and are treated in the vast majority of cases conservatively. Surgical treatment may be indicated if the sagittal compression of the vertebral body is >50% or the lateral compression is >15% (increased risk of scoliosis). Type B and C injuries are rare in children below the age of 12 years. Up to 50% of these cases are associated with severe chest and abdominal injuries. Surgical treatment aiming to reduce retropulsed fragments by ligamentotaxis with posterior distraction and instrumentation is recommended, but the treatment for concomitant chest or intra-abdominal injuries takes priority. Neurologic deficits due to a narrowed spinal canal require—as in adults—a posterior decompression by laminectomy and a posterior stabilization by internal fixation.

The goal of the surgical management of pediatric spine fractures is a stable osteosynthesis, allowing early mobilization, facilitating the care of the severely injured child, and avoiding secondary spinal cord damage.

## 30.7 Extremity Trauma

Extremity fractures are common in polytraumatized children (in up to 76%) and must be viewed in the context of the overall status of the multiply injured child [27]. Clinical suspicion of associated vascular injury requires a diagnostic investigation with color flow Doppler imaging and/or (CT-) angiography.

Emergent intervention is necessary for

- open fractures,
- fractures with associated vascular injuries,
- acute compartment syndrome,
- amputation injuries.

Open fractures and open joint injuries are primarily washed out, debrided, and subsequently stabilized. Severe, open articular fractures may require a two-stage management procedure. An acute compartment syndrome is treated by decompression of the afflicted compartment by incision of the fascia. Stabilization of fractures is performed thereafter. Vacuum-assisted closure devices or artificial skin are used to temporarily cover soft tissue defects or fasciotomy sites.

### 30.7.1 Principles of Care

Fractures of the *epiphysis*, *epiphysiolysis*, and fractures of the *metaphysis* are mostly treated by K-wire osteosynthesis. Some cases require additional or alternative application of an external fixator. Depending on the fracture pattern, as well as the age of the child, open reduction and internal fixation using screw and/or plate osteosynthesis or closed reduction and cast retention may be an option. Fractures of the *diaphysis* are predominantly addressed using flexible intramedullary rods, such as elastic stable intramedullary nailing (ESIN). In the polytraumatized child, in multi-fragment fracture situations, in cases with severe soft tissue injuries and in long and unstable oblique fracture patterns, the external fixator may be the best treatment modality. Plate osteosynthesis of diaphyseal fractures during adolescence should, at most, be considered as temporary stabilization and using minimally invasive techniques.

*Early definitive osteosynthesis of extremity fractures should be a goal in the pediatric patient management.* Children often recover remarkably well from severe injuries to the central nervous system

or to other organ systems. Consequently, optimal fracture care must be undertaken with the assumption that the injured child will completely recover.

Early fracture stabilization reduces the systemic effects of fractures, including systemic inflammatory response syndrome, sepsis, multiple organ failure, and acute respiratory distress syndrome. Early stabilization also reduces pain, the risk of secondary neurovascular damage, and promotes mobilization of the patient. In general, initial definitive surgical care should be undertaken in fractures of the humerus, forearm shaft, femur, and tibia.

Important early, postoperative and long-term complications of the different injury patterns are outlined in Table 30.2.

**Table 30.2** Early and late complications after trauma in the pediatric patient (adapted with permission from Jakob et al. [12])

| | |
|---|---|
| Traumatic brain injury | – Diffuse brain edema<br>– Coagulopathy<br>– Thromboembolic events<br>– Appallic syndrome<br>– Posttraumatic epilepsy<br>*Postoperative complications*:<br>– Increase of intracranial pressure (ICP)<br>– Ongoing intracranial bleeding<br>Increased risk of complications with GCS < 8 |
| Chest trauma | – Pneumonia<br>– Acute respiratory distress syndrome (ARDS)<br>– Abscess, empyema |
| Abdominal trauma | – Postinjury organ failure due to abdominal malperfusion during hemorrhagic shock<br>– Secondary hemodynamic instability in cases of nonoperatively treated liver and splenic injuries<br>– Peritonitis due to hollow viscus injuries or intestinal wall necrosis<br>– Delayed solid organ rupture<br>*Postoperative complications:*<br>– Re-bleeding<br>– Infections/wound dehiscence (abdominal wall)<br>– Abscess<br>– Adhesions, posttraumatic ileus<br>– Abdominal wall hernia<br>*Late complications:*<br>Mainly due to missed injuries following blunt abdominal trauma (missed hollow viscus injuries) |
| Spine trauma | – Growth disturbance / deformity in cases of injured growth plate<br>– Progressive deformity in case of persisting instability<br>– Posttraumatic paralysis<br>– Fusion of spinal segments following damage of end plates<br>*Postoperative complications:*<br>– Progression of neurological deficits<br>– Re-bleeding<br>– Implant dislocation |
| Pelvic trauma | *Early complications:*<br>– Blood loss due to intra-abdominal or retroperitoneal injuries (fracture, injury of presacral venous plexus)<br>– Peritonitis following disruption of the pelvic floor, rectal injuries<br>– Urinary incontinence<br>*Late complications:*<br>– Growth disturbance (fusion of pubic symphysis or iliosacral joint)<br>– Acetabular dysplasia with hip luxation<br>*Postoperative complications:*<br>– Re-bleeding<br>– Neurovascular injury<br>– Implant dislocation |

**Table 30.2** (continued)

| | |
|---|---|
| Extremity trauma | Compartment syndrome<br>Infection<br>Soft tissue defect<br>Implant failure<br>Premature growth-plate closure, growth arrest<br>Non-union<br>Leg length discrepancy<br>Nerve injury, motoric dysfunction |

## 30.8 Pediatric Critical Care

In the severely head-injured pediatric trauma patient, optimizing the CPP is of utmost importance, either by decreasing the ICP or augmenting the mean arterial pressure (MAP). ICP management may include sedation, osmotic therapy (including mannitol and hypertonic saline solutions), and pentobarbital coma for refractory cases. Adequate CPP may also be maintained through MAP support, using norepinephrine if the central venous pressure is adequately high, or epinephrine in case of insufficient myocardial contraction. The use of a PiCCO system allows the monitoring of intravascular volume and catecholamine therapy.

To avoid secondary lung damage (pneumothorax or acute respiratory distress syndrome), ventilation is based on pressure control, which provides peak inspiratory pressure throughout inspiration. Initially, relaxation may be required to reach the therapeutic target of arterial pO2 > 100 mmHg. In brain-injured patients, the positive end expiratory pressure should be minimized to allow sufficient drainage from the cervical venous system; however, the pressure should not fall below 3 cm $H_2O$. Again, PiCCO monitoring may be a valuable tool in patient management.

## 30.9 Conclusion

Treating pediatric trauma patients requires the understanding of the distinct anatomy and pathophysiology of the pediatric population. Head injuries are the principal determinants of outcome and mortality in polytraumatized children. However, children often recover remarkably well, even after apparently devastating injuries. Therefore, maximal care should be undertaken with the assumption that a complete recovery will occur.

**Take Home Messages**

- The unique characteristics of pediatric injuries is based on anatomic and physiologic differences compared to adults.
- The initial assessment and management of the polytraumatized child follows the ATLS principles.
- Nonoperative management of abdominal injuries requires close monitoring and frequent clinical reevaluation; this should only be performed in experienced trauma centers.

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# 31 Surgical Management: Management of Traumatic Bone Defects

Nikolaos Patsiogiannis and Peter V. Giannoudis

**Learning Goals**

- Definition and epidemiology of traumatic bone defects.
- Initial management of the polytrauma patient.
- Reconstruction versus early amputation for the severely injured limp.
- Treatment principles for skeletal fixation and soft tissue coverage.
- Definition of "critical"-sized bone defect.
- Options for managing traumatic bone defects.

## 31.1 Introduction

Segmental bone defects can be the result of either severe trauma, infection, or malignancy. Traumatic bone defects can occur either during the initial injury (high energy impact, penetrating trauma, blast injuries) or following debridement of devitalized bone fragments related to open fractures or infected non-unions.

Currently, there are reliable methods to successfully reconstruct large defects that in the past were treated even with primary amputation. Reconstruction of large bone defects can cause significant disabilities and represent a challenging situation for the surgeon. They carry a substantial burden of disease, a high rate of complications and reoperations, as long as a significant economic impact.

Autologous bone grafting remains the gold standard for the reconstruction of small defects, while distraction osteogenesis, acute shortening, vascularized grafts, the induced membrane technique, titanium mesh cages, and arthroplasty—in selected cases—are useful alternatives for the management of the larger bone defects.

### 31.1.1 Epidemiology

Only a small minority of all fractures are associated with bone loss and critical size bone defects, and these are mostly open injuries. In a prospective audit of admissions to the Edinburgh Orthopaedic Trauma Unit in 10 years, fractures with bone loss accounted only for 0.4% of all fractures. Bone loss, though, was present in 11.4% of open fractures. The most common ana-

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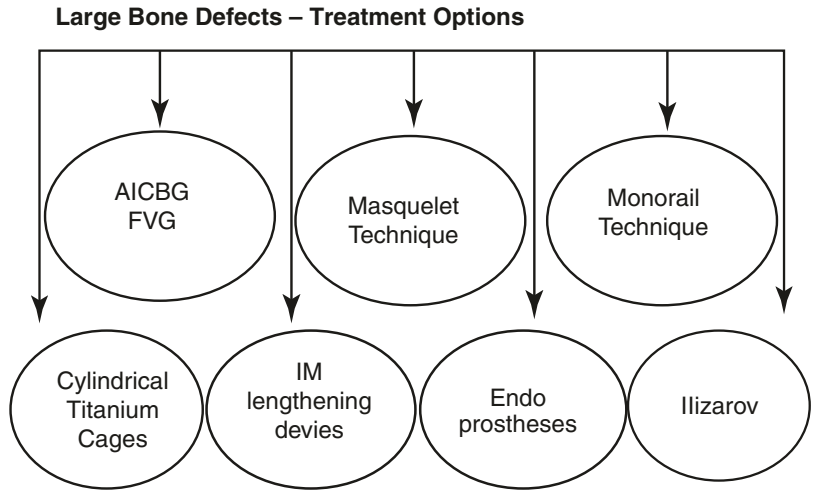



**Fig. 31.1** Treatment options for large bone defects. **AICBG* Autologous iliac crest bone graft; **FVG* Fibula vascularized graft

tomical site sustaining bone loss following trauma was the tibia [1] (Fig. 31.1).

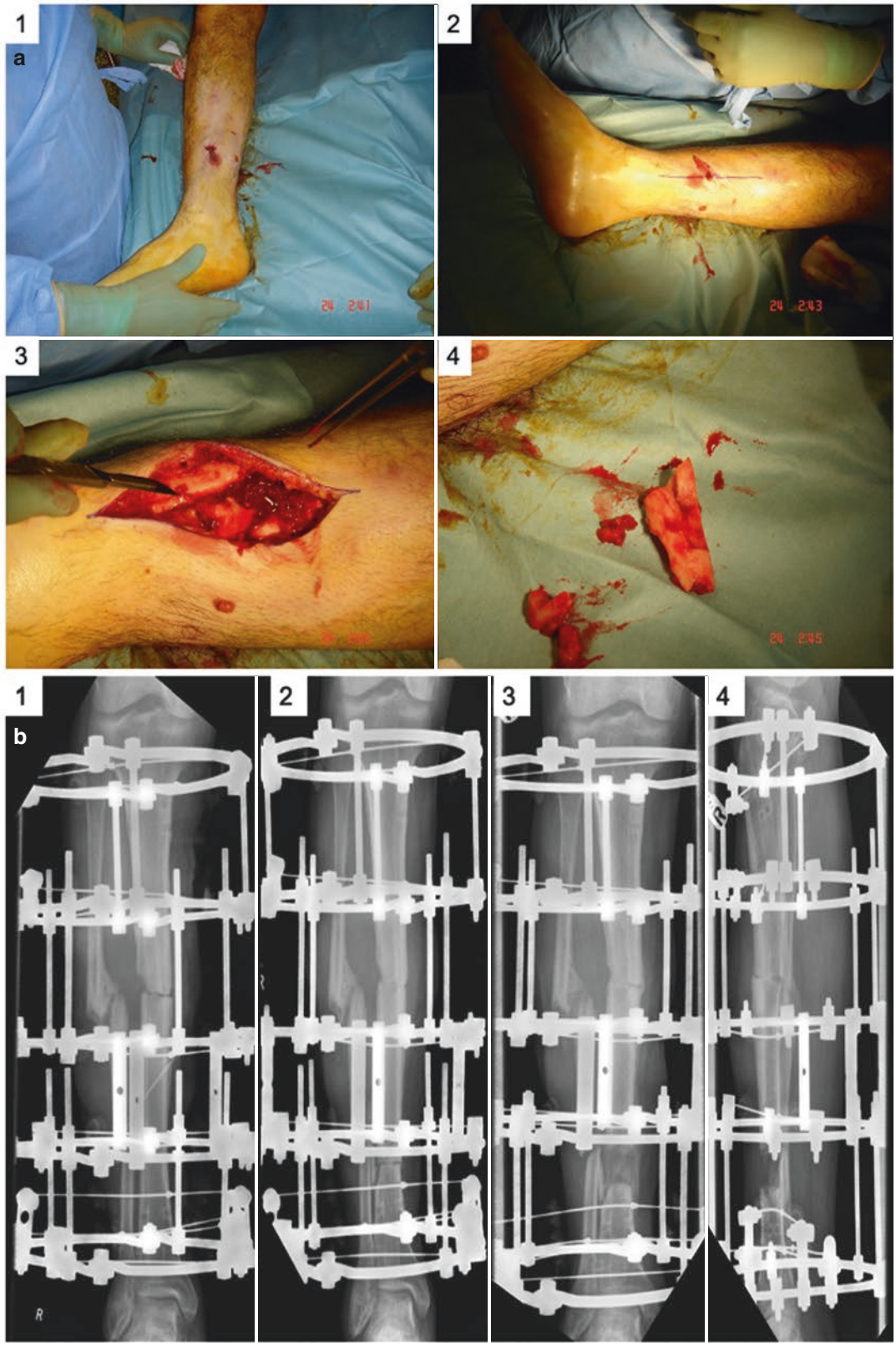
### 31.1.2 Initial Patient Management

Early evaluation of the patient according to the ATLS protocol is mandatory [2] in all trauma cases. Initial procedures in the context of polytrauma must be of life-saving nature in order to maintain the function of vital organs such as the brain, heart, and lung. Volume replacement and interventions to stop the bleeding, restoring haemodynamic stability are essential. The dogma save life, save the limb, limit disability continues to dictate the management of patients presenting with multiple injuries.

Once the primary assessment has been completed, and the patient is physiologically stable, a detailed assessment of any open wound should take place, and all findings documented. Photography is also beneficial for documentation and for multidisciplinary team communication. The wound should not be explored in the emergency setting and handled only for gross contamination removal; it must then be covered until formal exploration occurs in the operating room and under sterile conditions. A detailed neurovascular examination and documentation of the findings are also of paramount importance (Fig. 31.2).

When necessary and within the concept of "damage control orthopaedics", a spanning external fixation can be applied to stabilize orthopaedic injuries avoiding additional physiological stress-related insults to the patient [3]. Pin site and implant placement should be carefully selected to allow for definite fixation and stabilization of the defect at a later stage.

**Fig. 31.2** A 38-year-old male patient presented with a pelvic, spinal, and right tibia open fracture following a motorbike accident. After resuscitation and restoration of physiology, the patient was taken to the operating theatre. (**a**) 1: Open wound of the right tibia. 2: Wound was extended as shown. 3: Wound inspected underneath and debrided. 4: Non-vital fragments removed. (**b**) 1: AP right tibia radiograph showing bone shortening occurred and compression of fracture at the injury site. 2: AP right tibial radiograph showing distal corticotomy performed 7 days later for bone transport to address the bone loss incurred. 3: AP radiograph showing bone transport. 4: Lateral radiograph showing the degree of bone transport. (**c**) 1: AP radiograph; 2: Lateral radiograph showing the formation of regenerate bone at the distraction site at 4 months. 3: AP radiograph; 4: Lateral radiograph demonstrating osseous healing at 6 months following the injury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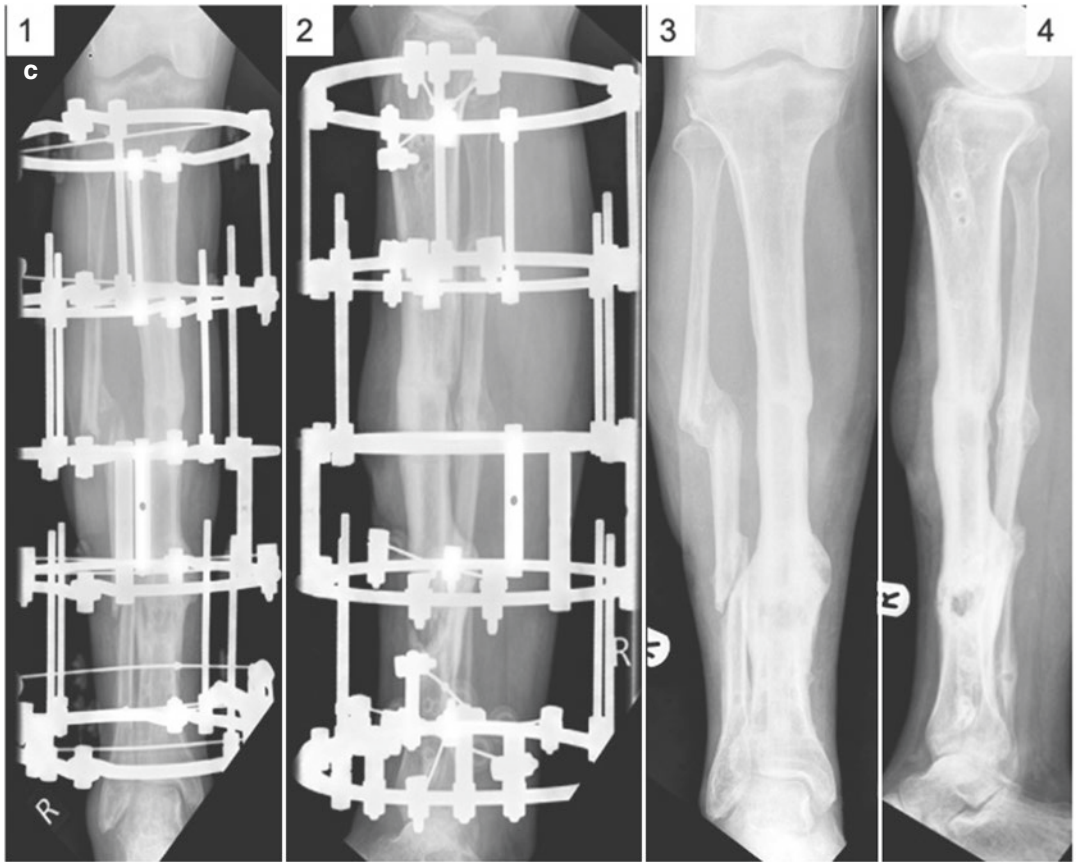


**Fig. 31.2** (continued)

### 31.1.3 Reconstruction Versus Amputation

In these complex injuries, a decision whether to proceed with salvage procedures or primary amputation should take place early in the process. Several algorithms have been proposed to guide the management [4–6] and scoring systems such as the mangled extremity severity scale (MESS); the limp salvage index (LSI), and the predictive salvage index (PSI) [7–9] are useful but need to be interpreted with caution as such a decision is always difficult and rarely clear. The Lower Extremity Assessment Project (LEAP) a multicenter study for severe lower extremity trauma in the US population, investigated the functional outcomes of a salvaged versus amputated-prosthetic lower extremity. The Sickness Impact Profile Score was used to evaluate the outcomes of prospectively collected data from patients with Gustillo grade IIIB and IIIC fractures. It was concluded that at 2- and 7-year follow-up; there was no difference in functional outcome between patients who underwent either limb salvage surgery or amputation. Long-term outcomes following major limp trauma were poor for both groups, and approximately 50% of patients in each group were able to return to work. Patient characteristics predicting poor outcome included older age, non-white race, lower level of education, poverty, smoking, poor self-reported preinjury health status, and involvement in disability compensation litigation.

Indications for early amputation in adults include significant nerve and vascular injury beyond the limits of repair. Relative indications are severe soft tissue damage, absence of plantar sensation, warm ischemia of more than 6 h and

life-threatening trauma. Noteworthy, the extend of bone loss that prevents limb salvage is yet to be determined.

Finally, it is also vital that the patient understands the potential need for future surgical procedures and prolonged rehabilitation, and his compliance needs to be carefully evaluated to the degree that this is possible within the limits of an acute major trauma situation.

## 31.2 Skeletal Fixation and Soft Tissue Coverage

Traumatic bone defects are often associated with open fractures with potential severe soft tissue involvement, so successful management requires collaboration from several specialities (orthopaedics, plastics, vascular) to optimize the outcome. Wound debridement, stabilization, defect reconstruction, and soft tissue coverage must all be planned in conjunction.

The aim of treatment is skeletal stabilization, soft tissue management, restoration of length and alignment, and preservation of limp function.

The initial debridement or serial debridements, if required, are of paramount importance to reduce the bacterial load and remove necrotic tissue. The defect can be provisionally filled with a PMMA-antibiotic spacer or antibiotic-impregnated PMMA beads [10]. This can be exchanged during debridements, and it is aiming to reduce infection rates and create a clean aseptic environment for future bone reconstruction procedures. Alternatively, it can be maintained for a period of 4–6 weeks if the induced membrane technique is planned.

In the presence of temporary spaning fixation (external fixator), conversion to definite fixation should take place as soon as possible to minimize the risk of pin site infection (ideally within the first 10–14 days) [9].

Managing the soft tissues in conjunction with the bone defect is crucial, and the reconstruction ladder, as described in the literature, provides the plan of action for this challenging situation [11, 12].

For the treatment of diaphyseal bone loss, interlocking nails have become the treatment of choice. They offer excellent stability; the soft tissues can be easily addressed over a nail, and joints can be early mobilized. Nails are not the treatment of choice when distraction osteogenesis is planned unless an intramedullary lengthening device is used. Plates have biomechanical disadvantages in the presence of bone loss due to cantilevering, but they are useful for metaphyseal or articular defects. External fixators can be used in almost any location and offer the advantage of deformity correction and bone lengthening (distraction osteogenesis) [1].

## 31.3 Management of Bone Defects

### 31.3.1 Definition of "Critical"-Sized Bone Defect

There is no single definition of a "critical"-sized bone defect. In general, defects that are not expected to heal without intervention and despite stabilization are considered as "critical". In the literature bone defects of more than >1–2 cm, greater than twice the diameter of the diaphysis or >50% loss of the circumference, are considered "critical" [1, 13–15]. Parameters that could impact the outcome of the defect reconstruction include biomechanical related issues, the potency of local biology, the overall state of the soft tissue envelope, the age and comorbidities of the patient, nutrition, glycemic control, smoking habits, and development of infection [16, 17].

The anatomical location of the bone defect is also related to the overall prognosis as some areas display better vascularity and osteogenic potential [1, 14]. Poor outcomes have been reported for defects in the tibia more than 1–2 cm and >50% circumference [14]. Interestingly, spontaneous healing of traumatic segmental defects of the femur up to 15 cm long has been reported in the literature [18].

### 31.3.2 Autologous Bone Grafts

For small defects <5 cm, with adequate soft tissue coverage, autologous bone graft remains the gold standard [13]. Autograft is the only material that possesses all three properties of osteogenesis, osteoinduction, and osteoconduction [19]. Other advantages are its low cost and the fact that it carries no risk of disease transmission and immunologic rejection. The graft can be harvested from several sites, such as the ilium, the femur, the tibia, the radius, and the ribs. The iliac crest remains the most common harvesting source. The ilium can provide both cancellous and cortical bone as well as a vascularized graft; the technique is well familiar by most surgeons and can take place in the supine position, which makes it accessible in most trauma-related scenarios. Disadvantages of autologous bone grafting are donor site morbidity and the limited volume that can be obtained in cases of large defects. Both the anterior and the posterior crests can be harvested with the anterior being the most common. Anterior crest harvesting has been associated with higher rates of infection, haematoma, fractures, and hypertrophic scar whereareas donor site pain and sensory disturbances were lower when compared to the posterior iliac crest harvesting [20].

Autologous bone graft can also be obtained from the long bone intramedullary cavity and particularly the femur. The "reamer-irrigator-aspirator" (RIA) is a recent development that was originally designed to address the issues of fat emboli and thermal necrosis associated with reaming during long bone nailing procedures. Although clinical evidence is still lacking to support that fully, RIA indications have expanded to include bone graft harvesting for the management of non-unions and bone defects as it can provide a significant volume of bone graft up to 25–90 $cm^3$ [21]. Reamings obtained with RIA have been shown to have greater enrichment in mesenchymal stem cells than the iliac crest bone graft [16] (Fig. 31.3).

Evidence suggests that RIA is relatively safe, with a fairly low overall complication rate of about 6% [20]. However, there are unique complications associated with the use of RIA, such as femoral neck fracture, anterior femoral cortex perforation, heterotropic ossification, and hypertrophic scar, which can be avoided with meticulous surgical technique [22].

Though autologous bone graft remains the gold standard for small size defects, larger than 5 cm defects require other reconstruction options as the resorption caused by revascularization produces significant mechanical weakening at the construct and failure of osteogenesis.

### 31.3.3 Distraction Osteogenesis (Ilizarov Technique)

Large bone defects can be managed with this technique which involves transporting a free bone segment with either an external fixator or an intramedullary device. Distraction osteogenesis was pioneered by Ilizarov in 1950 [23], and since then, it has been successfully used to treat long bone fractures, non-unions, bone defects, and deformities. This technique has the advantage of not only addressing the bone defect issue but also correcting any shortening, malalignment, joint contractures, or soft tissue loss at the same time. It is mainly based on the use of a circular fixator and on the principle that tissue can be generated under controlled applied tension between corticotomy surfaces. Histologically, this process strongly resembles intramembranous ossification, as seen in the periosteum [24]. In traumatic segmental bone defects, this method can be applied in two ways, acute shortening followed by lengthening to restore the original length or by bone transportation.

Acute limb shortening is a fast and straightforward way of management bone defects. It consists of closing and compressing the bony defect, followed by distraction. It offers the advantage of early soft tissue management and tension-free wound closure. Soft tissues and neurovascular status will dictate the amount of shortening as loss of perfusion caused by artery kinking is one of the complications. A safe limit for acute shortening before neurovascular compromise is about 3–5 cm in the femur and 2–3 cm in the tibia [25]. Greater shortening can be achieved if this is performed gradually instead of acutely.

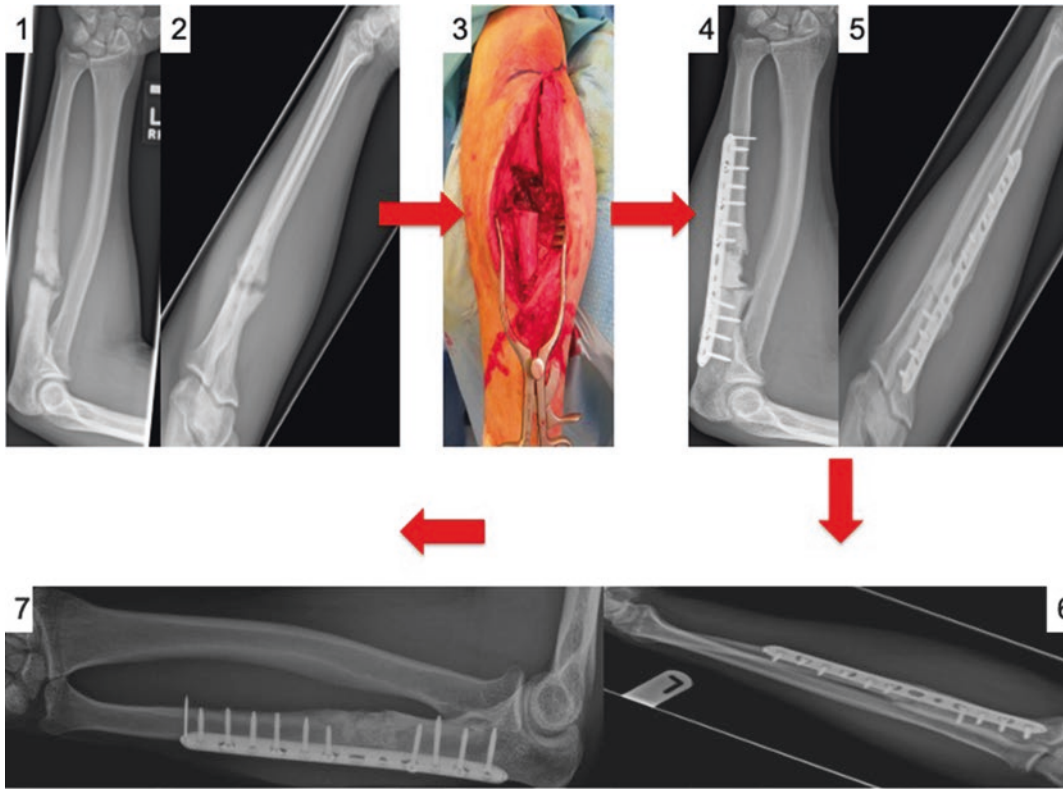


**Fig. 31.3** A 40-year-old male presented with a left proximal ulna non-union which was originally plated, but the patient developed an infection and the plate was removed. 1: AP view left forearm; 2: Lateral view left forearm demonstrating a proximal ulna infected non-union. 3: Intraoperative picture showing the bone defect created following debridement of the infected bone. 4: AP radiograph; 5:Lateral radiograph of the left forearm showing that the fracture has been stabilized with a plate, and a cement spacer has been inserted in the bone defect area for the induction of the induced membrane. 6: Lateral radiograph; 7: AP radiograph of left forearm, 4 months after the second stage of the induced membrane technique demonstrating osseous bone healing of the previous bone defect

Bone transportation consists of gradually moving a free segment of viable bone together with the soft tissue envelope from an adjacent area into the defect. A corticotomy is performed away from the injury, and an external fixator is usually used to transport the bone segment in a mechanically stable and controlled manner. The procedure is divided into three phases, latency, distraction, and consolidation. Following the latency period which is usually 7 days from the osteotomy, distraction is being applied at a rate of 1 mm/day (0.25 mm four times a day). During this phase, a gradually elongated bone gap is produced, and as the apparatus creates tension, bone formation occurs within the callus. The soft tissue envelope is also increasing (distraction histogenesis). When the transported segment reaches the end of the defect, it is compressed for several weeks, and the distraction gap is allowed to bridge and corticalize. For large defects bifocal (corticotomy at either side of the defect), distraction osteogenesis can be performed.

A major drawback of this method is the length of the time required for the reconstruction to be completed, leading to prolonged use of an external fixator. The most common complication is pin tract infection which carries the risk of septic arthritis for pins inserted closed to a joint. Other complications are joint stiffness, refractures, malunions, neurovascular complications, and amputation.

In a systematic review by Papakostidis et al., union rates to about 94% were reported. It was though highlighted that a significant risk of refractures exists for defects >8 cm long. The risk of neurovascular complications was 2.2% and amputations 2.9%, with half of them being voluntary. This finding highlighted the tolerance that patients can demonstrate related to this method, and the authors suggested that careful patient selection is essential to avoid such a complication [26].

### 31.3.4 Vascularized Bone Grafts (VBG)

Vascularized bone grafts can be obtained from several donor areas (fibula, iliac crest, ribs) [17, 27]. They have the advantage due to the preserved circulation (vascular pedicle) to maintain cell viability (osteocytes) compared to non-vascularized grafts. VBGs do not undergo creeping substitution during incorporation, so potentially they preserve their biomechanical properties, and they display better healing properties and reaction to stress [28]. VBGs can also contribute to the revascularization of necrotic bone [29]. They are also useful in combined soft-tissue/bone reconstruction as skin paddles, muscles, tendon, nerves, and other tissues can be harvested at the same time. VBGs are useful in unfavourable healing environments and/or impaired absent blood flow (scarred soft tissue envelop, irradiated or avascular bone bed) and in the cases of concomitant infection [30, 31]. The disadvantages of vascularized grafts are donor site morbidity, prolonged operating times, and the fact that they represent technically challenging procedures requiring microvascular expertise.

Historically, the fibula is the most commonly used vascularized bone graft. It can provide up to 25 cm of bone with minimal donor site morbidity [17]. It can be harvested 4 cm from the fibular head and 6 cm from the ankle without compromising either the proximal tibiofibular joint or the ankle stability [13, 32].

Vascularized grafts are generally used for the management of bone defects greater than 6 cm. However, in a recent review article, it was concluded that it is uncertain if there is enough evidence to support this 6 cm rule and that further research is required to avoid patients undergoing more complex procedures [33]. VBGs can also be used in smaller defects where poor biology is present (atrophic non-unions, infections, scarred soft tissue envelop, irradiated bone, avascular bone).

Union rates of >95% have been reported with a vascularized fibular graft [34, 35].

### 31.3.5 Induced Membrane Technique (IMT)

Masquelet et al. developed a two-stage technique using induced biologic membranes in combination with cancellous autograft for the treatment of large segmental defects. They reported 100% union rates in 35 patients with defects up to 25 cm [36].

The first stage consists of aggressive bone/soft tissue debridement to remove all areas of necrosis and reduce the risk of subsequent infection. It is vital at that stage that multiple tissue samples are sent for microbiology analysis. A methylmethacrylate (PMMA) cement spacer is then inserted into the defect, overlying the periosteum at both ends. Antibiotics can be added to the cement, either targeted or empirical. Stabilization can take place with various methods (IM nail, plate, external fixator) and will remain in place for 4–8 weeks. Soft tissue reconstruction takes place in the first stage, and inflammatory markers are carefully monitored to exclude infection.

At the second stage, the pseudomembrane is carefully incised (maintaining integrity and vascularity), and the cavity is filled with cancellous bone autograft. The graft can be taken from the iliac crest, or the Reamer-Irrigator-Aspirator (RIA) can be used. Graft expanders (cancellous allografts, demineralized bone matrix (DBM), bone morphogenetic proteins (BMPs)) may be used if a greater volume is needed. The bone edges will require further debridement to permit graft incorporation, and the medullary canal should be opened when possible, allowing endosteal communication. It is important to avoid

dense graft impaction, and the membrane is finally sutured. Stable fixation at the end of the second stage, either with internal or external (circular frame), is important [37].

Complications of the IMT are infection (either from inadequate initial debridement or de novo), hardware failures, malalignment, soft tissue healing problems, and delayed stress fractures [38, 39].

Since the first study published by Masquelet et al., several case reports and retrospective case series reported an overall success rate of 86% [37]. In the largest published series of 84 post-traumatic diaphyseal long bone reconstructions, Karger et al. reported union rates in 90% of cases, at a mean of 14.4 months. The size of the treated defects ranged from 2 to 23 cm, with 57% being larger than 5 cm [40].

### 31.3.6 Titanium Mesh Cages

The cylindrical mesh cage technique was first described by Cobos et al. in 2000 [41]. It utilizes the use of cylindrical titanium cages typically used in spinal surgery to bridge the defect by surrounding it. This technique is a one-stage procedure and can be adapted in diaphyseal as well as meta-diaphyseal defects. Following debridement, an appropriately sized cage is selected and packed with graft (cancellous allograft). The construct is reinforced by internal rings placed at both ends and then stabilized for protection [42]. Initially, intramedullary nails were used in combination with titanium mesh-allograft reconstruction though this can also be achieved with plates or external fixators [43].

This technique is characterized by some advantageous biological properties which promote defect reconstitution. The principal among these biological advantages is the actual cage with its biocompatible (titanium) material and its hollow fenestrated design. The fenestrations limit the amount of metal and also permit diffusion of host nutrients and enhance the vascular ingrowth into the defect [42].

The titanium mesh cage technique can be used as an alternative or as salvage to the other described techniques for the treatment of large bone defects. It offers the advantage of an easy single-stage procedure achieving immediate limp stability with no donor site morbidity. It has the disadvantage of metalwork placement in an open fracture which might carry a greater risk of infection. Moreover, the results of treatment are not uniform.

### 31.3.7 Arthroplasty—Megaprosthesis

Arthroplasty can also provide surgical solutions especially in the presence of large traumatic metaphyseal and periarticular defects. The prosthesis design and technology has evolved, and several options currently exist to manage the underlying bone loss. The vast majority of the existing research, data, and outcomes come from the arthroplasty field, but the same principles can be applied to trauma patients.

Mild metaphyseal bone loss can be managed via arthroplasty with cement (with or without screws supplementation), impaction grafting or metal augmentation. Larger defects will require sleeves, trabecular metal cones, or bulk structural allografts. For the massive bone loss, a megaprosthesis has made it possible for orthopaedic surgeons to replace entire limps [44–46]. In the young and lower risks patients, an Allograft Prosthesis Composite (APC) can also be considered which is a revision type of prosthesis combined with an allograft [47].

Megaprostheses were initially designed for the management of oncologic bone loss; however, their indications have expanded to include also non-neoplastic situations such as trauma (with severe bone loss or poor bone quality), complex non-unions (septic and aseptic), bone loss in revision arthroplasty surgery and periprosthetic fractures around unstable implants with inadequate bone stock. These implants offer the advantage of replacing large skeletal segments, providing immediate mechanical stability that allows early weight bear, good functional recovery, improved compliance, and lower cost of surgery [48–50], so they can be considered as a limb salvage option in the absence of other surgical solutions. In 2008, a classification system was developed to guide treatment for patients with

post-traumatic non-union and bone defects (Non-Union Scoring System—NUSS), taking into account not only the radiological features of the injury and the bone quality but also general risk factors as long as the soft tissue status. A patient's score over 75 points indicates that a more definitive treatment, such as amputation, arthrodesis, or replacement with megaprosthesis might be beneficial [51, 52]. It is essential, though, to understand that these patient groups (post-trauma, infective, failed arthroplasty) have different characteristics than oncologic patients and also life expectancy differs [48, 53]. The patient's age, overall condition, other comorbidities, soft tissue status, previous procedures, or previous infection must be carefully evaluated when considering megaprosthesis replacement. Ideally, these procedures should be performed in specialized centres, and the surgical technique and implantation should be meticulous to ensure the longevity of the prosthesis [53].

De Gori et al. in their study over the use of megaprosthesis in non-neoplastic patients (87 patients) found an overall survival rate of 69.1% at 10 years [48]. In two recent systematic reviews regarding the use of megaprosthesis for non-oncological patients, an overall midterm survival rate of 76% for proximal femoral prostheses and 83% for distal femoral prostheses were reported, respectively. The most common complication was dislocation for the proximal femoral replacements and infection for the distal [54–56]. The overall complications and survival rates of megaprosthesis implantation for non-neoplastic conditions are inferior when compared to primary arthroplasty of the hip and knee, but comparable or even better than those in the neoplastic patients [56].

## 31.4 Conclusion

Traumatic bone defects remain a challenging problem for the orthopaedic surgeon and the patient. These complex injuries carry a substantial burden of disease; they lead to prolonged rehabilitation times and are associated with a high complication rate. A multidisciplinary approach to optimize the outcomes is of significant value.

Numerous techniques are presently available to offer solutions. Further research is required to improve our understanding of these injuries, to define what constitutes a critical-sized bone defect and the extent of bone loss that prevents limb salvage and finally to rate each technique and guide treatment accordingly.

**Key Concepts**

- Life-saving procedures, resuscitation, and restoration of physiology remain the priority of early management in patients with polytrauma and injuries associated with open fractures and bone loss.
- Debridement, soft tissue coverage, fixation, and bone reconstruction must all be planned in conjunction, within a multidisciplinary approach, to optimize the outcome.
- Bone defects of more than >1–2 cm, greater than twice the diameter of the diaphysis or > 50% loss of the circumference, are considered "critical".
- For small defects <5 cm, with adequate soft tissue coverage, autologous bone grafting (ABG) remains a good solution for bone healing.
- Ilizarov bone transfer technique, vascularized fibular grafts, and the induced membrane technique are currently the most commonly used techniques for bone defect reconstruction.
- Arthroplasty can provide solutions in selected cases, especially around the metaphysis.

**Take Home Message**

Autologous bone graft remains the gold standard for small defects. For larger defects, several techniques have been described. Historically, the vascularized fibular graft and the Ilizarov technique have been the mainstays of treatment. Although good clinical results have been reported for both methods, they are also associated with complications and significant drawbacks. Distraction osteogenesis is a lengthy procedure with a risk of infection especially when pins are used close to a joint (septic arthritis), whereas vascularized fibula allograft is a technically demanding procedure requiring prolonged operating times and has donor site morbidity. The Masquelet technique is an increasingly utilized method with satisfactory results; it requires though a two-stage approach. The use of titanium mesh cages can potentially provide an alternative; nonetheless, the results of treatment are not consistent. Arthroplasty and megaprosthesis replacement can also be an option in selected cases, especially in the metaphyseal/periarticular area. The treatment method should be carefully chosen for the correct indication and the right patient in order to optimize the results of treatment.

**Conflict of Interest** There are no conflicts of interest.

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# 32 Surgical Management: Acute Soft Tissue and Bone Infections

Lena M. Napolitano

**Core Message**

**Steps in optimal management of patients with severe SSTIs:**

- Early diagnosis and differentiation of necrotizing vs. non-necrotizing SSTI.
- Early initiation of appropriate empiric broad-spectrum antimicrobial therapy with anti-MRSA coverage and consideration of risk factors for specific pathogens.
- "Source control" of SSTI, i.e., early aggressive surgical intervention for drainage of abscesses and debridement of necrotizing soft tissue infection
- Pathogen identification and appropriate escalation or de-escalation of antimicrobial therapy.

## 32.1 Introduction

Skin and soft tissue infections (SSTIs) span a broad spectrum of clinical entities from limited cellulitis or small abscess to rapidly progressive necrotizing fasciitis, which may be associated with septic shock or toxic shock syndrome [1–5]. Severe and complicated SSTIs may result in critical illness and require management in the intensive care unit [6]. The complex interplay of environment, host, and pathogen are important to consider when evaluating SSTIs and planning therapy. The key to a successful outcome in caring for patients with severe SSTIs is (1) early diagnosis and differentiation of necrotizing vs. non-necrotizing SSTI, (2) early initiation of appropriate empiric broad-spectrum antimicrobial therapy with consideration of risk factors for specific pathogens, (3) "source control," i.e., early aggressive surgical intervention for drainage of abscesses and debridement of necrotizing soft tissue infections, and (4) pathogen identification and appropriate de-escalation of antimicrobial therapy (Table 32.1).

## 32.2 Classification of SSTIs

The U.S. Food and Drug Administration (FDA) previously classified SSTIs into two broad categories for the purpose of clinical trials evaluating new antimicrobials for the treatment of SSTIs: Uncomplicated and Complicated (Table 32.2). Uncomplicated SSTIs include superficial infections such as cellulitis, simple abscesses, impetigo, and furuncles. These infections can be treated by antibiotics and/or surgical incision for drainage of abscess alone. In contrast, compli-

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**Table 32.1** Steps in optimal management of patients with severe SSTIs

| |
|---|
| 1. Early diagnosis and differentiation of necrotizing vs. non-necrotizing SSTI |
| 2. Early initiation of appropriate empiric broad-spectrum antimicrobial therapy with anti-MRSA coverage and consideration of risk factors for specific pathogens |
| 3. "Source control" of SSTI (i.e., early aggressive surgical intervention for drainage of abscesses and debridement of necrotizing soft tissue infections) |
| 4. Pathogen identification and appropriate escalation or de-escalation of antimicrobial therapy |

**Table 32.2** Comparison of Old and New Classification of SSTIs by FDA. From: https://www.fda.gov/media/71052/download

| • ***Uncomplicated*** | • ***Complicated*** |
|---|---|
| • Superficial infections, such as:<br>• Simple abscesses<br>• Impetiginous lesions<br>• Furuncles<br>• Cellulitis<br>Can be treated by antibiotics or surgical incision alone | • Deep soft tissue, such as:<br>• Infected ulcers<br>• Infected burns<br>• major abscesses<br>• Significant underlying disease state which complicates response to treatment<br>• Requires significant surgical intervention and antimicrobials |
| ***New FDA Definition (October 2013):***<br>Acute bacterial skin and skin structure infections (ABSSSI) defined as bacterial infection of the skin with a lesion size area of at least 75 $cm^2$ (lesion size measured by the area of redness, edema, or induration), including the following:<br>• ***Cellulitis/erysipelas:*** A diffuse skin infection characterized by spreading areas of redness, edema, and/or induration<br>• ***Wound infection:*** An infection characterized by purulent drainage from a wound with surrounding redness, edema, and/or induration<br>• ***Major cutaneous abscess:*** An infection characterized by a collection of pus within the dermis or deeper that is accompanied by redness, edema, and/or induration | |

cated SSTIs include deep soft tissue infections that require significant surgical intervention, such as infected ulcers, infected burns, and major abscesses, and these patients also have significant underlying comorbidities, i.e., disease states which complicate (and usually delay) response to treatment. Complicated SSTIs are a significant clinical problem, in part related to the increasing resistance of infecting bacteria to our current antibiotic therapies.

***Uncomplicated SSTIs*** are associated with ***low*** risk for life- or limb-threatening infection. These patients can be treated with empiric antibiotic therapy according to likely pathogen and local resistance patterns.

***Complicated SSTIs*** are associated with ***high*** risk for life- or limb-threatening infection. In these patients, it is of paramount importance to initiate appropriate and adequate broad-spectrum initial empiric antimicrobial therapy with coverage for MRSA and to consider the need for surgical intervention for abscess drainage or debridement.

Patients with complicated SSTIs require hospitalization for treatment. Specific circumstances that warrant hospitalization include the presence of tissue necrosis, sepsis, severe pain, altered mental status, immunocompromised state, and organ failure (respiratory, renal, hepatic). SSTIs can lead to serious potentially life-threatening local and systemic complications. The infections can progress rapidly and early recognition and proper medical and surgical management is the cornerstone of therapy. A recent prospective observational US study of complicated SSTI patients ($n$ = 1033) determined that the mean length of hospital stay was 7.1 days, 41.2% underwent surgical procedures related to the study infection, the most common class of initial intravenous antibiotic prescribed was vancomycin, and the hospital mortality rate was 0.4% [7]. In contrast, a similar study in Europe reported mean hospital length of stay of 18.5 days with a mortality rate of 3.4% [8].

In October 2013, FDA changed the SSTI terminology and issued final guidance for the treatment of acute bacterial skin and skin structure infections (ABSSSI) [9]. This guidance defined ABSSSI as cellulitis, erysipelas, wound infection, and major cutaneous abscess. An ABSSSI is defined as a bacterial infection of the skin with a lesion size area of at least 75 $cm^2$ (lesion size measured by the area of redness, edema, or induration). The minimum area of involvement of

75 $cm^2$ is chosen to select patients with acute bacterial skin infections for which a reliable control drug treatment effect can be estimated for the conduct of new antimicrobial treatment trials. While the FDA generally requires two Phase III trials to support approval of drugs to treat acute bacterial skin and skin structure infections (ABSSSI), this guidance stated that a single Phase III study that is supported by additional independent evidence may suffice.

Patients with the following infection types can be enrolled in ABSSSI clinical trials:

- ***Cellulitis/erysipelas:*** A diffuse skin infection characterized by spreading areas of redness, edema, and/or induration.
- ***Wound infection:*** An infection characterized by purulent drainage from a wound with surrounding redness, edema, and/or induration.
- ***Major cutaneous abscess:*** An infection characterized by a collection of pus within the dermis or deeper that is accompanied by redness, edema, and/or induration.

Unfortunately, this guidance does not address less serious skin infections, such as impetigo and minor cutaneous abscess, or more serious infections needing more complex treatment regimens, such as fracture-related infections (FRI), infections resulting from animal or human bites, necrotizing soft tissue infections (NSTI), diabetic foot infection, decubitus ulcer infection, myonecrosis, osteomyelitis, and ecthyma gangrenosum.

## 32.3 Specific Types of SSTIs

### 32.3.1 Traumatic Wound Infections

A report from the Lower Extremity Assessment Project (LEAP), a multi-institutional prospective observational study of 545 patients with limb-threatening lower extremity trauma with 2-year follow-up at 8 Level-1 trauma centers, documented that wound infection (34%) was the most common complication in the primary amputation group, and that nonunion (31.5%) and wound infection (23.2%) were the most common complications in the limb salvage group. Furthermore, the late amputation group had the highest complication rate (68%), mostly due to wound infection [10].

The Bioburden Study is the first large multi-institutional study to characterize the contemporary extremity wound "bioburden" of severe open tibia fractures at the time of definitive wound coverage/closure in both the military and civilian patient populations, using microbiology and PCR techniques [11]. This study has just completed (March 2021) by the Major Extremity Trauma Research Consortium (METRC) and will provide information about whether the "bioburden" can predict whether SSI will occur and also predict the causative SSI pathogens (https://clinicaltrials.gov/ct2/show/NCT01496014).

When traumatic wound infections occur, it is recommended to initiate early empiric broad-spectrum antibiotic therapy to cover methicillin-resistant *S. aureus* (MRSA) and all other potential pathogens, obtain wound cultures, and then tailor definitive antimicrobial therapy once the culture results return. In addition, the wound may require surgical debridement to provide adequate source control.

### 32.3.2 Surgical Site Infections (SSIs)

SSIs are one of the most common SSTIs that occur in orthopedic and trauma care, and are associated with doubling of the cost of treatment for orthopedic trauma patients [12]. SSIs are defined as "superficial incisional" or "deep incisional" SSI based on the depth of the infection as defined by the Centers for Disease Control (CDC) and the National Healthcare Safety Network (NHSN) (Table 32.3).

It has been determined that scores commonly used to predict SSI in other types of surgery [National Nosocomial Infection Surveillance System (NNIS) and Study on the Efficacy of Nosocomial Infection Control (SENIC) scores] are not predictive of SSI after orthopedic fracture surgery [13]. A new score [RIOTS Composite Score includes Fractures classification AO type

**Table 32.3** CDC/NHSN classification of surgical site infections (SSIs) *(from Horan TC* et al. *CDC/NHSN surveillance definition of healthcare-associated infection and criteria for specific types of infections in the acute care setting. Am J Infect Control 2008;36:309–32)*

| Type of SSI | Definition |
|---|---|
| Superficial incisional | Infection occurs within 30 days after the operative procedure<br>And involves only skin and subcutaneous tissue of the<br>Incision and patient has at least 1 of the following:<br>(a) Purulent drainage from the superficial incision<br>(b) Organisms isolated from an aseptically obtained culture of fluid or tissue from the superficial incision<br>(c) At least 1 of the following signs or symptoms of infection: Pain or tenderness, localized swelling, redness, or heat, and superficial incision is deliberately opened by surgeon and is culture-positive or not cultured. A culture-negative finding does not meet this criterion.<br>(d) Diagnosis of superficial incisional SSI by the surgeon or attending physician. |
| Deep incisional | Infection occurs within 30 days after the operative procedure if no implant[a] is left in place or within 1 year if implant is in place and the infection appears to be related to the operative procedure<br>And involves deep soft tissues (e.g., fascial and muscle layers)<br>Of the incision and patient has at least 1 of the following:<br>(a) Purulent drainage from the deep incision but not from the organ/space component of the surgical site<br>(b) a deep incision spontaneously dehisces or is deliberately opened by a surgeon and is culture-positive or not cultured when the patient has at least 1 of the following signs or symptoms: Fever (.388C), or localized pain or tenderness. A culture-negative finding does not meet this criterion<br>(c) an abscess or other evidence of infection involving the deep incision is found on direct examination, during reoperation, or by histopathologic or radiologic examination<br>(d) Diagnosis of a deep incisional SSI by a surgeon or attending physician |

[a]Implant: A nonhuman-derived object, material, or tissue (e.g., prosthetic heart valve, nonhuman vascular graft, mechanical heart, or hip prosthesis) that is permanently placed in a patient during an operative procedure and is not routinely manipulated for diagnostic or therapeutic purposes

C3 or Sanders type 4, 2 points; BMI < 30 kg/m$^2$, 1 point; ASA class ≥3, 1 point] was proposed for SSI prediction in orthopedic fracture surgery that incorporates fracture classification, American Society of Anesthesiologists classification, and body mass index with area under the ROC curve of 0.75, significantly higher than NNIS and SENIC scores.

#### 32.3.2.1 SSI Prevention

A number of SSI prevention strategies have significantly decreased the rate of SSIs following orthopedic surgery and fracture repair in the past decade [14]. The Surgical Care Improvement Project (SCIP) has implemented three measures for antibiotic prophylaxis for SSI prevention: (1) antibiotic received within 1 h prior to surgical incision, (2) appropriate antibiotic selection based on surgical procedure performed, and (3) antibiotic discontinued within 24 h after surgery completed (Table 32.4). Additional evidence-based strategies for SSI prevention include the following: (1) appropriate hair removal (clipping, no shaving); (2) maintenance of normothermia intraoperatively and perioperatively; (3) glycemic control; (4) appropriate skin preparation; (5) supplemental oxygen administration.

#### 32.3.2.2 Microbiology of SSIs

Staphylococcus aureus (*S. aureus*) is the most common causative pathogen for all SSIs in the US data reported by the NHSN (Table 32.5), and an increasing percentage of these *S. aureus* isolates are methicillin-resistant (MRSA). Comparison of the causative pathogens for SSI in US hospitals documents that *S. aureus* increased from 22.5% (1986–2003) to 30% (2006–2007), with MRSA now the leading causative pathogen [15, 16]. More recent data (Table 32.5) confirm similar findings.

**Table 32.4** Antibiotics for SSI Prevention in Orthopedic Surgery

| |
|---|
| ***Choice of antimicrobial agent*** |
| • Cefazolin |
| • If ß-lactam allergy, use clindamycin or vancomycin |
| • Consider preoperative screening for MRSA colonization |
| • If infected or colonized with MRSA, use vancomycin |
| ***Timing of administration*** |
| • Start up to 60 min before incision: Cefazolin, clindamycin |
| • Start up to 120 min before incision: Vancomycin |
| • Infusion completed 10 min before tourniquet inflation |
| ***Dosing*** |
| • Cefazolin, 1–2 g (2 g for patient weighing >80 kg) |
| • Vancomycin (15 mg/kg) and clindamycin (600–900 mg) dosing based on patient mass |
| • Pediatric dosing based on patient mass |
| ***Duration of antimicrobial use*** |
| • Single preoperative dose |
| • Redose antimicrobial intraoperatively for prolonged procedure or significant blood loss |
| • Mupirocin should be given intranasally to all patients with documented colonization with S. aureus. |

*Adapted from:* Bratzler DW, Dellinger EP, Olsen KM, Perl TM, Auwaerter PG, Bolon MK, Fish DN, Napolitano LM, Sawyer RG, Slain D, Steinberg JP, Weinstein RA; American Society of Health-System Pharmacists (ASHP); Infectious Diseases Society of America (IDSA); Surgical Infection Society (SIS); Society for Healthcare Epidemiology of America (SHEA). Clinical practice guidelines for antimicrobial prophylaxis in surgery. Surg Infect (Larchmt). 2013 Feb;14(1):73–156. doi: 10.1089/sur.2013.9999

The advent of community-associated MRSA (CA-MRSA) has impacted SSI significantly. Recent studies document that CA-MRSA is replacing traditional healthcare-associated or nosocomial MRSA strains in SSI among inpatients [17]. CA-MRSA has emerged as a leading cause of healthcare-associated infections among patients with prosthetic joint SSIs [18].

In a study of 8302 patients readmitted to US hospitals with culture-confirmed SSI, the proportion of infections caused by MRSA increased significantly, from 16.1% to 20.6%, and these infections were associated with higher mortality rates, longer stays, and higher hospital costs [19]. In view of this important finding, some surgeons have advocated strongly that patients be screened for nasal carriage of MRSA prior to elective surgery, with consideration of decolonization prior to surgery, and modification of antimicrobial agents for SSI prevention on the basis of the results.

Interestingly, when evaluating the microbiology of SSIs related to orthopedic surgical cases, S. aureus comprised an even greater percentage of isolates when compared to isolates reported for SSIs from all surgical cases (Table 32.5). Specific SSI causative for open reduction of fracture from the National Healthcare Safety Network confirms that Staph aureus is the leading pathogen (Table 32.6) at 27.9% of all SSI pathogens.

Although knowledge of national microbiology of SSIs related to specific surgical procedures is important, it is of even greater importance to know the microbiology of SSIs within your own institution, and this should help to guide empiric antimicrobial management for treatment of SSIs in your local setting. Reports of resistant Gram-negative isolates, particularly multi-drug-resistant Enterobacter isolates producing extended spectrum beta-lactamases (ESBLs), as the etiology of SSIs in orthopedic and trauma surgery is worrisome [20, 21]. This highlights the importance of pathogen identification, i.e., obtaining material for Gram stain and culture, in the management of all SSIs.

#### 32.3.2.3 Closed Long Bone Fractures

A Cochrane Database systematic review of patients undergoing surgery for proximal femoral and other closed long bone fractures (data from 8447 participants in 23 studies) documented that single-dose antibiotic prophylaxis significantly reduced deep incisional SSI (risk ratio 0.40, 95% CI 0.24–0.67), superficial incisional SSI, urinary infections, and respiratory tract infections. Multiple dose antibiotic prophylaxis had an effect of similar size on deep incisional SSI. Therefore, appropriate antibiotic prophylaxis should be used in all patients undergoing surgical management of hip or other closed long bone fractures [22].

The "Clinical practice guidelines for antimicrobial prophylaxis in surgery" by the American Society of Health-System Pharmacists (ASHP), Infectious

**Table 32.5** Causative pathogens for surgical site infections (SSI) in US hospitals 2006–2007 vs. 2011–2014, National Healthcare Safety Network

| Organism | SSIs from all types of surgeries No. (%) of SSIs Total *n* = 7025 (2006–2007) | SSIs from all types of surgeries No. (%) of SSIs Total *n* = 149,009 (2011–2014) | SSIs from orthopedic surgeries **No. (%) of SSIs** Total *n* = 963 (2006–2007) | SSIs from orthopedic surgeries No. (%) of SSIs Total *n* = 31,539 (2011–2014) |
|---|---|---|---|---|
| Staphylococcus aureus | 2108 (30.0%) *MRSA 1006 (49.2%)* | 30,092 (20.7%) MRSA 13,120 (43.6%) | 548 (48.6%) | 15,163 (44.2%) |
| Coagulase-negative staphylococci | 965 (13.7%) | 11,799 (7.9%) | 173 (15.3%) | 4461 (13.0%) |
| Enterococcus spp. | 788 (11.2%) | 11,156 (7.5%) | 104 (10.8%) | 1620 (4.7%) |
| Escherichia coli | 671 (9.6%) | 20,429 (13.7%) | 34 (3.0%) | 1625 (4.7%) |
| Pseudomonas aeruginosa | 390 (5.6%) | 8458 (5.7%) | 38 (3.4%) | 1672 (4.9%) |
| Enterobacter spp. | 293 (4.2%) | 6615 (4.4%) | 37 (3.3%) | 1401 (4.1%) |
| Klebsiella spp. | 213 (3.0%) | 7067 (4.7%) | 19 (2.0%) | 943 (2.7%) |

Adapted from: Hidron AI, Edwards JR, Patel J, et al.; National Healthcare Safety Network Team; Participating National Healthcare Safety Network Facilities. NHSN National Update: Antimicrobial-resistant pathogens associated with healthcare-associated infections: Annual summary of data reported to the NHSN at the DCD, 2006–2007. Infect Control Hosp Epidemiol 2008;29:996–1011

Weiner LM, Webb AK, Limbago B, et al. Antimicrobial-resistant pathogens associated with healthcare-associated infections: Summary of data reported to the National Healthcare Safety Network at the Centers for Disease Control and Prevention, 2011–2014. Infect Control Hosp Epidemiol 2016;1–14

*MRSA* methicillin-resistant Staphylococcus aureus

Orthopedic surgery procedures included: Open reduction of fracture, hip prosthesis, knee prosthesis, limb amputation, spinal fusion, refusion of spine, and laminectomy

**Table 32.6** Causative pathogens for surgical site infections (SSI) in US hospitals 2015–2017, National Healthcare Safety Network for Open Reduction of Fracture

| SSI pathogen distribution among adult patients, 2015–2017, Open reduction of fracture | | | |
|---|---|---|---|
| Procedure | Pathogen | No. of pathogens | % of pathogens |
| FX | Staphylococcus aureus | 855 | 37.9% |
| FX | Enterobacter | 272 | 12.1% |
| FX | Coagulase-negative staphylococci | 234 | 10.4% |
| FX | Pseudomonas aeruginosa | 140 | 6.2% |
| FX | Enterococcus faecalis | 106 | 4.7% |
| FX | Escherichia coli | 79 | 3.5% |
| FX | Klebsiella (pneumoniae/oxytoca) | 69 | 3.1% |
| FX | Proteus | 60 | 2.7% |
| FX | Serratia | 42 | 1.9% |
| FX | Other enterococcus spp. | 37 | 1.6% |

Diseases Society of America (IDSA), Surgical Infection Society (SIS), and Society for Healthcare Epidemiology of America (SHEA) provide evidence-based national recommendations [23].

The recommended regimen in hip fracture repair or other orthopedic procedures involving internal fixation is cefazolin. Clindamycin and vancomycin should be reserved as alternative agents. If there are surveillance data showing that Gram-negative organisms are a cause of SSIs for the procedure, practitioners may consider combining clindamycin or vancomycin with another agent (cefazolin if the patient is not β-lactam-allergic; aztreonam, gentamicin, or single-dose fluoroquinolone if the patient is β-lactam-allergic). Mupirocin should be given intranasally to all patients with documented colonization with S. aureus (Strength of evidence for prophylaxis = A.).

#### 32.3.2.4 Open Fractures

Antibiotics reduce the incidence of early infections in open fractures of the limbs, confirmed by a Cochrane Database systematic review of 913 participants in seven studies. The use of antibiotics had a protective effect against early infection compared with no antibiotics or placebo (relative risk 0.41 [95% confidence interval (CI) 0.27–0.63]; absolute risk reduction 0.08 (95% CI 0.04 to 0.12); number needed to treat (NNT) 13 (95% CI 8–25). There were insufficient data in the included studies to evaluate other outcomes [24].

The Surgical Infection Society evidence-based guidelines for prophylactic antibiotic use in open fractures recommends the use of a short course of first-generation cephalosporins, begun as soon as possible after injury, in addition to modern orthopedic fracture wound management (Table 32.7) [25]. Open fracture grade (Gustilo) and the degree of associated soft tissue injury are independent determinants of infection risk. A single-institution review of patients with Gustilo IIIB tibial fractures ($n = 52$) determined that nosocomial bacterial pathogens (Enterococci, Pseudomonas, Enterobacter, and MRSA) were responsible for deep tissue infections, and advocated for tailoring antimicrobial prophylaxis against nosocomial organisms at the time of definitive wound closure [26].

### 32.3.3 Necrotizing Soft Tissue Infections (NSTIs)

NSTIs are aggressive soft tissue infections that cause widespread necrosis and can include nec-

**Table 32.7** Risk of SSTI in adult trauma patients with open extremity fractures and antimicrobial prophylaxis recommendations

| Grade of open fracture | Characteristics of Gustilo grade open fracture | Infection rate | Amputation rate |
|---|---|---|---|
| Grade I | Clean wound smaller than 1 cm in diameter, simple fracture pattern, no skin crushing. | 0–2% | 0% |
| Grade II | A laceration larger than 1 cm but without significant soft tissue crushing, including no flaps, degloving, or contusion. Fracture pattern may be more complex. | 2–7% | 0% |
| Grade III | An open segmental fracture or a single fracture with extensive soft tissue injury. Also included are injuries older than 8 h. type III injuries are subdivided into three types: | | |
| Grade III A | Adequate soft tissue coverage of the fracture despite high-energy trauma or extensive laceration or skin flaps. | 5–10% | 2.5% |
| Grade III B | Inadequate soft tissue coverage with periosteal stripping. Soft tissue reconstruction is necessary. | 10–50% | 5.6% |
| Grade III C | Any open fracture that is associated with an arterial injury that requires repair. | 25–50% | 25% |
| **Grade of open fracture** | **Recommended antibiotic** | **Alternate if PCN allergy** | |
| Grade I or II | Kefzol 1–2 g load then 1 g IV q8h for 48 h | Clindamycin 900 mg IV q8h for 48 h | |
| Grade III | Ceftriaxone 1 g IV q24h for 48 h | Clindamycin 900 mg IV q8h and Aztreonam 1 g IV q8h for 48 h | |

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**Table 32.8** Clinical Clues to the Diagnosis of Necrotizing Soft Tissue Infections

| | |
|---|---|
| **Skin findings** | Erythema |
| | Tense edema |
| | Gray or discolored wound drainage |
| | Vesicles or bullae |
| | Skin necrosis |
| | Ulcers |
| | Crepitus |
| **Systemic features** | Severe pain out of proportion to physical findings |
| | Pain that extends past margin of apparent skin infection |
| | Fever |
| | Tachycardia, tachypnea |
| | Diaphoresis |
| | Delirium |

rotizing cellulitis, fasciitis, and myositis/myonecrosis [27, 28]. Establishing the diagnosis of NSTI can be the main challenge in treating patients with NSTI, and knowledge of all available tools is key for early and accurate diagnosis (Table 32.8) [29]. There have been a number of recent advances in the definition, pathogenesis, diagnostic criteria, and treatment of necrotizing soft tissue infections [30, 31].

Patients with NSTIs require prompt aggressive surgical debridement, appropriate intravenous antibiotics, and intensive support. Despite aggressive treatment, their mortality and morbidity rates remain high, with some series reporting mortality rates of 25–35% [32]. A high index of suspicion should be used in conjunction with laboratory and imaging studies to establish the diagnosis as rapidly as possible. Successful treatment requires early, aggressive surgical debridement of all necrotic tissue, appropriate broad-spectrum systemic antibiotic therapy, and supportive care (fluid resuscitation, organ, and critical care support) to maintain oxygenation and tissue perfusion. Delayed definitive debridement remains the single most important risk factor for death.

A recent single-institution series of 166 patients documented that the overall mortality rate was 16.9% and limb loss occurred in 26% of patients with extremity involvement [33]. Independent predictors of mortality included white blood cell count greater than $30,000 \times 10^3/\mu L$, creatinine level greater than 2 mg/dL (176.8 μmol/L), and heart disease at hospital admission. Independent predictors of limb loss included heart disease and shock (systolic blood pressure < 90 mm Hg) at hospital admission. Clostridial infection was an independent predictor for both limb loss (odds ratio, 3.9 [95% confidence interval, 1.1–12.8]) and mortality (odds ratio, 4.1 [95% confidence interval, 1.3–12.3]) and was highly associated with intravenous drug use and a high rate of leukocytosis on hospital admission.

A 30-day postoperative mortality risk calculator for NSTI was recently developed using the National Surgery Quality Improvement Project (NSQIP) which identified 7 independent variables that correlated with mortality: age older than 60 years (odds ratio [OR] = 2.5; 95% CI 1.7–3.6), functional status (partially dependent: OR = 1.6; 95% CI 1.0–2.7; totally dependent: OR = 2.3; 95% CI 1.4–3.8), requiring dialysis (OR = 1.9; 95% CI 1.2–3.1), American Society of Anesthesiologists class 4 or higher (OR = 3.6; 95% CI 2.3–5.6), emergent surgery (OR = 1.6; 95% CI 1.0–2.3), septic shock (OR = 2.4; 95% CI 1.6–3.6), and low platelet count (<50 K/μL: OR = 3.5; 95% CI 1.6–7.4; <150 K/μL but >50 K/μL: OR = 1.9; 95% CI 1.2–2.9). The receiver operating characteristic area was 0.85 (95% CI 0.82–0.87), which indicated a strong predictive model that can aid physicians in the decision-making process [34].

#### 32.3.3.1 Aids to Diagnosis of NSTIs

Early operative debridement is a major determinant of outcome in NSTIs. However, early recognition of NSTIs is difficult clinically. A novel diagnostic scoring system for distinguishing NSTIs from other severe soft tissue infections based on laboratory tests routinely performed for the evaluation of severe SSTIs is called the Laboratory Risk Indicator for Necrotizing Fasciitis (LRINEC) score (Table 32.9) [35].

The LRINEC score was initially developed in a retrospective observational study including 145 patients with necrotizing fasciitis and 309 patients with severe cellulitis or abscesses admitted to the

**Table 32.9** The laboratory risk indicator for necrotizing fasciitis (LRINEC) score

| Variable, units | Score |
|---|---|
| *C-reactive protein (mg/L)* | |
| <150 | 0 |
| ≥150 | 4 |
| *Total white cell count (per mm³)* | |
| <15 | 0 |
| 15–25 | 1 |
| >25 | 2 |
| *Haemoglobin (g/dL)* | |
| >13.5 | 0 |
| 11–13.5 | 1 |
| <11 | 2 |
| *Sodium (mmol/L)* | |
| ≥135 | 0 |
| <135 | 2 |
| *Creatinine (μmol/L)* | |
| ≤141 | 0 |
| >141 | 2 |
| *Glucose (mmol/L)* | |
| ≤10 | 0 |
| >10 | 1 |

The maximum score is 13; a score ≥ 6 should raise the suspicion of necrotizing fasciitis and a score of ≥8 is strongly predictive of this disease

two tertiary care hospitals. The cutoff value for the LRINEC score was 6 points with a positive predictive value of 92.0% and negative predictive value of 96.0%. The LRINEC score is a robust score capable of detecting even clinically early cases of necrotizing fasciitis. The variables used are routinely measured to assess severe soft tissue infections. Patients with a LRINEC score of ≥6 should be carefully evaluated for the presence of necrotizing fasciitis.

Since the initial development of the LRINEC score, a number of other cohort studies have validated its utility in the diagnosis of NSTIs [36]. A multicenter study in 229 patients with NSTIs from 2002 to 2005 reported an overall mortality rate of 15.8% and amputation rate of 26.3%. This study also documented that a LRINEC score ≥ 6 was associated with a higher rate of both mortality and amputation [37].

#### 32.3.3.2 Diagnostic Imaging in NSTIs

A high clinical index of suspicion is required if the diagnosis is to be made sufficiently early for successful treatment. NSTIs necessitate prompt aggressive surgical debridement for satisfactory treatment in addition to antimicrobial therapy. It is critical to remember that because of the rapidly progressive and potentially fatal outcome of this condition, if imaging cannot be performed expeditiously, delaying treatment is not justified. Plain film findings may reveal extensive soft tissue gas. CT examination can reveal asymmetric thickening of deep fascia in association with gas, and associated abscesses may also be present. MR imaging can also assist in the diagnosis of NSTIs [38]. MR imaging has been documented to effectively differentiate between necrotizing and non-necrotizing infection of the lower extremity and other areas of the body, but should not delay prompt surgical intervention in NSTIs management [39–41].

#### 32.3.3.3 Microbiology of NSTIs

Necrotizing fasciitis and myonecrosis are typically caused by infection with Group A streptococcus, Clostridium perfringens, or, most commonly, aerobic and anaerobic organisms as part of a polymicrobial infection that may include S. aureus. In case series, CA-MRSA has recently been described as a predominantly monomicrobial cause of necrotizing fasciitis [42, 43]. A retrospective review of patients presenting with necrotizing fasciitis indicated that MRSA was the most common pathogen, accounting for one-third of the organisms isolated [44].

NSTIs have been classified into two types, either polymicrobial (Type I) or monomicrobial (Type II). Polymicrobial infections are more common, due to both aerobic and anaerobic organisms, and commonly occur in the trunk and perineum. NSTIs that are monomicrobial in origin commonly occur in the limbs and are typically caused by infection with Group A streptococcus, *Clostridium perfringens*, or *S. aureus*. NSTIs are categorized into these two specific types based on the microbiologic etiology of the infection, and this classification does impact on the specific antimicrobial agents required for treatment of these NSTIs.

- **Type 1, or polymicrobial**
- **Type 2, or monomicrobial**

Increasingly, MRSA has been identified as the causative microbe in NSTIs, but a separate category for this NSTI does not currently exist [45–49]. Given this finding, anti-MRSA empiric antimicrobial therapy should be initiated in all patients with NSTIs and pathogen-directed antimicrobial therapy considered once tissue culture results are available.

Uncommon microbiologic causes of NSTIs and primary sepsis include Vibrio and Aeromonas species, virulent Gram-negative bacteria and members of the Vibrionaceae family that thrive in aquatic environments [50]. These NSTIs are likely to occur in patients with hepatic disease, diabetes, and immunocompromised conditions [51]. These organisms are found in warm sea waters and are often present in raw oysters, shellfish, and other seafood. The diagnosis of vibrio NSTIs should be suspected when a patient has the appropriate clinical findings and a history of contact with seawater or raw seafood [52]. Early fasciotomy and culture-directed antimicrobial therapy should be aggressively performed in those patients with hypotensive shock, leukopenia, severe hypoalbuminemia, and underlying chronic illness, especially a combination of hepatic dysfunction and diabetes mellitus. The rate of amputation and mortality is very high in these patients, and early definitive management is of paramount importance [53–55].

A recent study of 125 patients identified that a LRINEC score of 2 or greater and the presence of hemorrhagic bullous/blistering lesions in patients with Vibrio vulnificus SSTI are associated with an 11.9-fold increased risk for the presence of NSTI and necrotizing fasciitis [56].

### 32.3.4 Pyomyositis

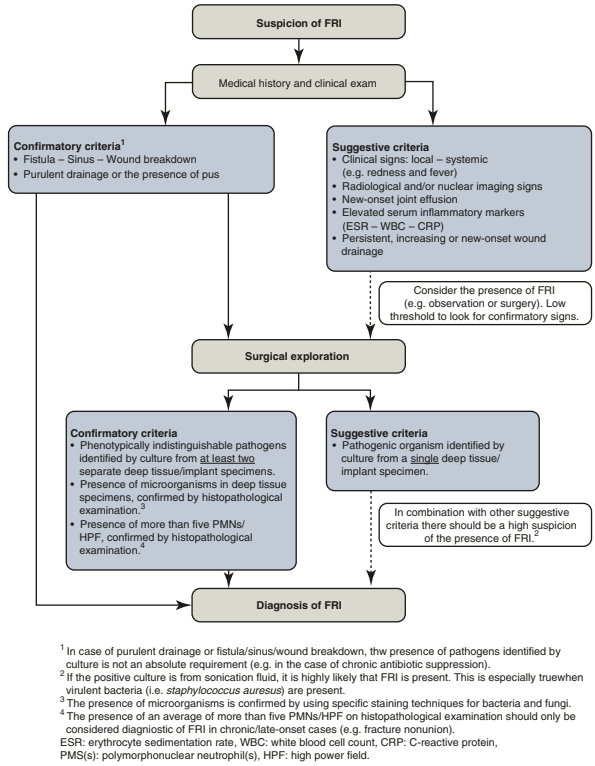
Myositis is a rare infection that may lead to serious and potentially life-threatening local and systemic complications [57]. The infection can progress rapidly, and early recognition and proper medical and surgical management is therefore the cornerstone of therapy. With the increasing prevalence of community-associated MRSA as a pathogen in severe SSTIs, pyomyositis is more common than in past years. Myositis often occurs in muscle sites that have been compromised by injury, ischemia, malignancy, or surgery. The predominant pathogens are S. aureus, Group A streptococci (GAS), Gram-negative aerobic and facultative bacilli, and the indigenous aerobic and anaerobic cutaneous and mucous membranes local microflora.

CT scan imaging is a rapid and sensitive diagnostic test and commonly demonstrates diffuse enlargement of the involved muscle and may demonstrate the presence of fluid or gas collections within the muscle suggesting the presence of abscesses. MRI is more sensitive in showing early inflammatory changes prior to development of abscesses in myositis [58]. Emergency surgical exploration is warranted in order to define the nature of the infective process which is accomplished by direct examination of the involved muscles. Surgical intervention is required to perform appropriate abscess drainage and debridement and to also evaluate for necrotizing myositis. Fasciotomies and extremity amputation are sometimes necessary.

#### 32.3.4.1 Fracture-Related Infection (FRI)

A recent consensus definition was developed for fracture-related infection (FRI), which is a severe complication after bony trauma (Figs. 32.1 and 32.2), based on two systematic reviews to standardize diagnostic criteria and promote optimal patient care for these patients [59–61]. Along with the new consensus definition of FRI were published consensus recommendations for systemic antimicrobial therapy for FRI from an international expert group [62], including the following principles:

- For the antimicrobial treatment of FRI, the presence of a biofilm, fracture stability, and fracture consolidation are important determinants that should be key determinants in the decision-making process.
- If there are confirmatory or suggestive signs of FRI, empiric intravenous antimicrobial ther-



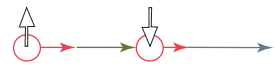

[1] In case of purulent drainage or fistula/sinus/wound breakdown, thw presence of pathogens identified by culture is not an absolute requirement (e.g. in the case of chronic antibiotic suppression).
[2] If the positive culture is from sonication fluid, it is highly likely that FRI is present. This is especially truewhen virulent bacteria (i.e. *staphylococcus auresus*) are present.
[3] The presence of microorganisms is confirmed by using specific staining techniques for bacteria and fungi.
[4] The presence of an average of more than five PMNs/HPF on histopathological examination should only be considered diagniostic of FRI in chronic/late-onset cases (e.g. fracture nonunion).
ESR: erythrocyte sedimentation rate, WBC: white blood cell count, CRP: C-reactive protein, PMS(s): polymorphonuclear neutrophil(s), HPF: high power field.

| |
|---|
| The diagnosis of FRI should always be considered is case of impaired fracture healing. |
| The presence of confirmatory signs of FRI should prompt the treating, multidisciplinary, medical team to proceed with developing a treatment strategy. |
| The presence of suggestive signs of FRI should prompt the treating, multidisciplinary, medical team to further investigate the probability of an FRI. |
| The only confirmatory clinical signs of FRI are the presence of a fistula, sinus, or wound breakdown and/or purulent drainage fromo the wound or presence of pus during surgery. |
| Caution when interpreting the results of derum inflammatory markers in FRI is warrented, as their predictive value is low. |
| The imaging modality of choice depends on the local availability of the technique and the questions to be answered. |
| Nuclear imaging (FDG-PET/CT or WBC scintigraphy + SPECT/CT) is more accurate than MRI for detecting FRI, but MRI is better in visualzing surgical relevant details. Therefore, apart from radiological signs, nuclear medicine signs should be included in the diagnostic pathway (definition) of FRI. |
| As edivance on histopathology is accumulating, it seems appropriate to include it in the diagnostic pathway (definition) of FRI for chronic/late-onset cases (e.g, nonunion). |

**Fig. 32.1** Descriptive flow chart of the diagnostic criteria of fracture-related infection (FRI). *From*: Metsemakers WJ et al., Fracture-related infection: a consensus on definition from an international expert group. 2018 *Injury*:49/ Issue 6, with permission from Elsevier. Govaert GAM, Kuehl R, Atkins BL, et al. Diagnosing Fracture-Related Infection: Current Concepts and Recommendations. Journal of Orthopaedic Trauma 34(1):8–17, January 2020. doi: 10.1097/BOT.0000000000001614

apy should be started immediately after operative tissue sampling.

- Empiric therapy should be broad-spectrum including a lipo/glycopeptide and an agent covering Gram-negative bacilli. Thereafter, it should be narrowed according to culture results as soon as possible.
- IV antibiotics can be switched to appropriate bioavailable organ agents—if applicable—as soon as definite culture and sensitivity results are known.
- Targeted antibiotic therapy should be guided by the retrieved pathogens and the surgical strategy.
- Expert microbiology/ID physician advice should always be sought especially when there is antimicrobial resistance, intolerance, or risk of drug interactions.

| Procedure/strategy | Antimicrobial therapy | Total duration |
|---|---|---|
| Removal & osteomyelitis treatment |  | 6 weeks |
| Retention & eradication |  | 12 weeks |
| One stage exchange & eradication |  | 12 weeks |
| Two stage exchange & eradication (short interval) |  | 12 weeks |
| Two stage exchange & eradication (short interval) without antibiotic free interval |  | 12 weeks |
| Two stage exchange & eradication (long interval) with antibiotic free interval |  | 1 – 2 weeks after implantation* |
| Debridement & suppression until fracture healing |   | 1 – 2 weeks after removal implant |

Debridement, irrigation and acquisition of multiple tissue samples.

IV- antibiotics are contiuned untill culture and sensitivity results are avilable and then, if there are appropriate oral agents avaiable, the patient can be switched to oral antibiotic therapy (in general IV 1 - 2 weeks).

Oral antibiotics without biofilm activity (apporx. 4 weeks, to complete 6 weeks of total antibiotic course).

Oral antibiotics with biofilm activity

Antibiotic free interval (≥ 2 weeks).

Ex-and implantation of fixation device.

One stage exchange of the fixation device.

* When the cultures are negative, the antibiotic therapy can be stopped.
When positive contiune to the guidelines for the one stage exchange (i.e. 12 weeks of antibiotics).

**Fig. 32.2** Recommendations for systemic antimicrobial therapy in fracture-related infection: A consensus from an international expert group. *From:* Recommendations for Systemic Antimicrobial Therapy in Fracture-Related Infection: A Consensus from an International Expert Group. Depypere M, Kuehl R, Metsemakers WJ, et al. Journal of Orthopaedic Trauma 34(1):30–41, January 2020. doi: 10.1097/BOT.0000000000001626

- Antibiotics should be used prudently and in line with the principles of good antimicrobial stewardship.

Clinical studies are now examining specific treatment strategies for FRI, such as the VANCO trial, a large multicenter trial to evaluate the efficacy of vancomycin powder to lower the SSI rate after fracture fixation surgery [63]. A recent single Level I Trauma center retrospective study documented a significantly lower SSI rate [0% (0/35) with vancomycin powder vs. control 10.6% (58/548)] [64].

### 32.3.5 Osteomyelitis

Bone and joint infections after polytrauma are challenging to diagnose and treat [65]. The key to successful management is early diagnosis and early treatment with culture-directed antibiotics and surgical debridement of any nonviable tissue. The recommended algorithm for diagnosis and treatment of acute osteomyelitis is presented in Fig. 32.3. Bone sampling may be required for microbiological and pathological examination to allow targeted appropriate antimicrobial therapy. There are three types of ***acute*** osteomyelitis (in order of decreasing frequency):

1. Osteomyelitis secondary to a contiguous focus of infection (after trauma, surgery, or insertion of a joint prosthesis).
2. Osteomyelitis secondary to vascular insufficiency (in diabetic foot infections or peripheral vascular disease).
3. Osteomyelitis secondary to hematogenous origin.

The rate of osteomyelitis following severe limb-threatening lower extremity trauma reported in the LEAP study was 9.4% in the total study cohort of 330 patients. The rates of osteomyelitis ranged from 3.1% in the primary amputation group to the highest rate of 27.3% in patients with Grade IIIC tibia fracture [66].

***Acute*** osteomyelitis is treated with antibiotics and a very careful assessment of any associated wound to determine if the soft tissue and wound require infection source control by surgical debridement. Importantly, debridement of all necrotic tissue, removal of foreign material, drainage of abscesses and infection at the site are required for optimal treatment of acute osteomyelitis.

In contrast, ***chronic*** osteomyelitis is associated with avascular necrosis of bone and formation of sequestrum (dead bone), and surgical debridement is necessary for cure in addition to antimicrobial therapy, with 6 weeks of parenteral antibiotic therapy recommended. However, oral antibiotics that achieve adequate levels in bone are now available, and similar cure rates have been achieved with oral and parenteral antimicrobial therapies [67].

#### 32.3.5.1 Microbiology of Osteomyelitis

The most common pathogenic microorganism in any type of osteomyelitis is *Staphylococcus aureus*, either susceptible (MSSA) or resistant (MRSA) to methicillin and coagulase-negative staphylococci are common in foreign-body-associated osteomyelitis. The ability of S. aureus to adhere is thought to be crucial for the early colonization of host tissues and implanted biomaterials, causing the development of biofilm formation which is very difficult to eradicate.

But microbiology can differ from other geographic locations. A report of the microbiology of post-traumatic osteomyelitis in Middle-East war-wounded civilians (n = 558) confirmed that *Enterobacteriaceae* (31.5%) were the most common pathogen, followed by *S. aureus* (26.3%), *Pseudomonas aeruginosa* (13.5%), and *Acinetobacter baumannii* (2.8%) [68]. It is therefore imperative to understand the local microbiology of post-traumatic osteomyelitis in order to provide appropriate antimicrobial treatment. It is also mandatory to obtain multiple samples of fluid and tissue for culture at the time of surgical intervention to determine the specific causative pathogens of post-traumatic osteomyelitis.

#### 32.3.5.2 Surgical Treatment of Osteomyelitis

Aggressive debridement of all devitalized and necrotic tissue is necessary to eradicate the infection. Bony debridement is also required, and any non-essential hardware must be removed. This may ultimately require a staged approach with multiple debridements. In these circumstances, negative pressure therapy with a wound VAC may be considered to continue to actively drain infection and promote new granulation tissue at the site. Once the osteomyelitis debridement is completed and the infection is appropriately treated with antibiotics, then skeletal stabilization and soft tissue reconstruction, preferably with vascularized soft tissue flaps, should be considered (Fig. 32.4).

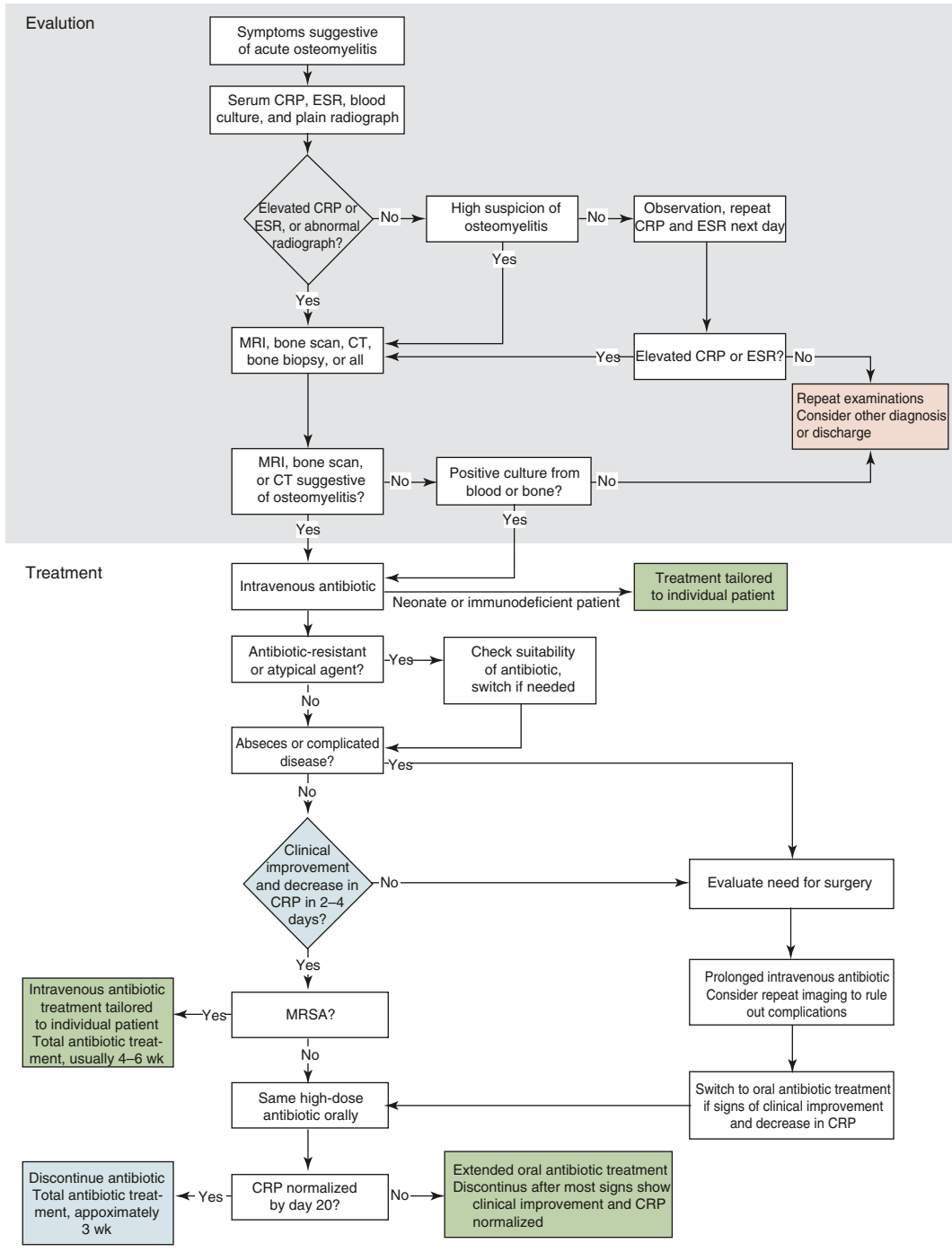



**Fig. 32.3** Diagnosis and treatment of acute osteomyelitis. *From:* Peltola H, Pääkkönen M. Acute osteomyelitis in children. N Engl J Med 2014;370:352–60

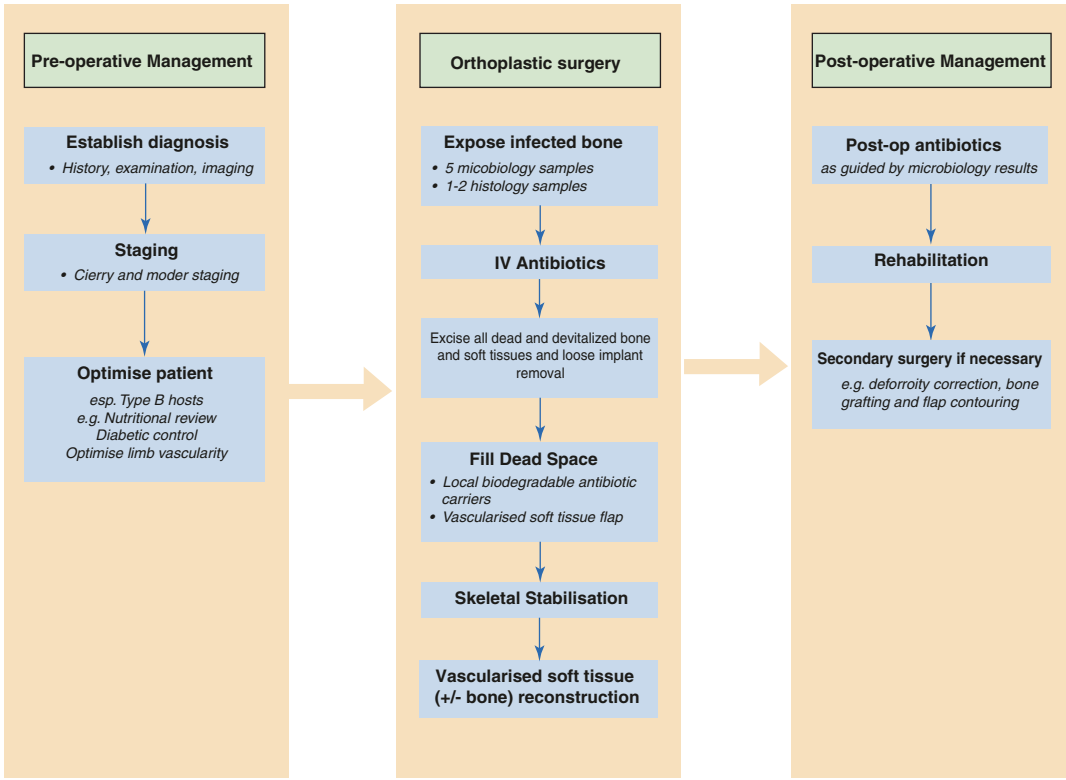



**Fig. 32.4** Acute management of post-traumatic osteomyelitis. *From*: Chan JKK, Ferguson JY, Scarborough M, McNally MA, Ramsden AJ. Management of Post-Traumatic Osteomyelitis in the Lower Limb: Current State of the Art. *Indian J Plast Surg*. 2019;52(1):62–72. doi:10.1055/s-0039-1,687,920

### 32.3.6 Four Important Steps in SSTI Treatment

#### 32.3.6.1 Early Diagnosis and Differentiation of Necrotizing Vs. Non-necrotizing SSTI

A classification for SSTIs that is commonly used is the differentiation of ***necrotizing soft tissue infections (NSTIs)*** from ***non-necrotizing infections***. This differentiation is critical since necrotizing infections warrant prompt aggressive surgical debridement. Clinical clues to the diagnosis of NSTIs are listed in Table 32.8. The differentiation of necrotizing infections from non-necrotizing infections is critical to achieving adequate surgical therapy [69]. A clear approach to these infections must allow rapid identification and treatment of NSTIs because they are limb-threatening and life-threatening.

When clinical "hard clinical signs" (bullae, crepitus, gas on x-ray, hypotension with SBP < 90 mm Hg, or skin necrosis) of NSTI are present, establishing the diagnosis of NSTI is not difficult. However, hard signs of NSTIs are often absent on presentation, thus potentially delaying diagnosis and surgical intervention. Studies have documented that less than 50% of patients with a definitive diagnosis of NSTI presented with "hard clinical signs" of NSTI [70]. Admission white blood cell count >15,400 × $10^9$/L and/or serum sodium <135 mEq/L was documented to help differentiate NSTI from non-NSTI and aided in early diagnosis [71, 72]. The Laboratory Risk Indicator for Necrotizing Fasciitis (LRINEC) score is also helpful as a laboratory aid in distinguishing necrotizing from non-necrotizing SSTIs (see NSTI section above).

If there is any question regarding the possible diagnosis of an NSTI, it is imperative to proceed

with surgical intervention and to be certain that the surgical incision is continued down to the fascial and muscle level to make a definitive diagnosis.

#### 32.3.6.2 Early Initiation of Appropriate Empiric Broad-Spectrum Antimicrobial Therapy with Anti-MRSA Coverage and Consideration of Risk Factors for Specific Pathogens

Antimicrobial therapy is an essential element in the management of severe SSTIs. As in all serious life-threatening infections, it is important to initiate ***early*** and ***appropriate*** empiric antimicrobial therapy. It is well established that prompt appropriate treatment of hospitalized infections reduces mortality [73]. Similar findings were reported in studies of patients with ventilator-associated pneumonia [74] and sepsis [75]. A study of ICU patients found that the higher mortality rate associated with inappropriate initial therapy is still observed when antibiotics are switched from an inappropriate to an appropriate treatment [76].

Furthermore, appropriate and timely antibiotic therapy improves treatment outcomes for SSTIs caused by methicillin-resistant *Staphylococcus aureus* (MRSA) [77]. In a study of 492 patients with community-onset MRSA SSTIs, 95% of episodes treated with an active antibiotic within 48 h were treated successfully, compared with an 87% rate of successful treatment in patients who did not receive an active antibiotic ($P = 0.001$). In logistic regression analysis, failure to initiate active antimicrobial therapy within 48 h of presentation was the only independent predictor of treatment failure (adjusted OR, 2.80; 95% CI, 1.26 to 6.22; $P = 0.011$). Similarly, in a study of patients admitted to the hospital with MRSA sterile-site infection, multivariate analysis found inappropriate antimicrobial treatment to be an independent risk factor for hospital mortality (adjusted OR, 1.92; 95% CI, 1.48 to 2.50; $P = 0.013$) [78].

An empiric treatment algorithm for SSTI directed against CA-MRSA in the emergency department that promotes both the use of antibiotics likely active against CA-MRSA and early incision and drainage of abscesses was examined. Clinical failure occurred in only 3% of cases treated according to the algorithm, compared with 62% of those not treated according to the algorithm ($p < 0.001$). Furthermore, among cases that underwent immediate incision and drainage, initial treatment with antibiotics active in vitro against the MRSA isolate was associated with a decreased clinical failure rate when compared to those treated with inactive antibiotics 0% vs. 67%, $p < 0.001$) [79].

Empiric antibiotic therapy should be initiated in ***all*** patients with cSSTIs. Intravenous broad-spectrum antimicrobial therapy should be initiated when an infection is severe or progresses rapidly, when there are signs of systemic illness, when the patient has comorbidities or is immunosuppressed, for very old or young patients, when an abscess cannot be completely drained, and when the infection does not respond to incision and drainage [80].

***Timely*** initiation of antimicrobial therapy is also important in the treatment of severe SSTIs, particularly if associated with septic shock [81, 82]. In a study of 2731 adult patients with septic shock, a strong relationship between the delay in effective antimicrobial initiation and in-hospital mortality was noted (adjusted odds ratio 1.119 [per hour delay], 95% confidence interval 1.103–1.136, $p < 0.0001$) [83]. Administration of an antimicrobial effective for isolated or suspected pathogens within the first hour of documented hypotension was associated with a survival rate of 79.9%. Each hour of delay in antimicrobial administration over the ensuing 6 h was associated with an average decrease in survival of 7.6%. By the second hour after onset of persistent/recurrent hypotension, in-hospital mortality rate was significantly increased relative to receiving therapy within the first hour (odds ratio 1.67; 95% confidence interval, 1.12–2.48). In multivariate analysis (including Acute Physiology and Chronic Health Evaluation II score and therapeutic variables), time to initiation of effective antimicrobial therapy was the single strongest predictor of outcome. Interestingly, only 50% of

septic shock patients received effective antimicrobial therapy within 6 h of documented hypotension.

### Epidemiology and Microbiology of SSTIs

An understanding of the changing epidemiology and microbiology of all SSTIs is required for diagnosis and selection of appropriate empiric antibiotic therapy. Staphylococci and streptococci have long been the leading microbiologic causes of cSSTIs [84]. In recent years, however, *S. aureus* has emerged as the most common cause of SSTIs. In addition to Group A streptococci and Staphylococcus aureus, the indigenous aerobic and anaerobic cutaneous and mucous membranes local microflora usually is responsible for polymicrobial infections, such as NSTIs and diabetic foot infections. Severe SSTIs can also be due to Clostridium spp., microorganisms associated with water sources (vibrio spp., aeromonas), and polymicrobial/mixed infections.

Community-associated MRSA (CA-MRSA) infections have risen rapidly in the last decade, and SSTIs are the predominant site of infection, accounting for 74% of all CA-MRSA infections in one study [85]. A 15-year study of the changing epidemiology of MRSA infections from military medical facilities in San Diego from 1990 to 2004 documented that 65% of MRSA infections were community-acquired, with SSTIs as the major site of infection in 95% of cases [86].

MRSA was the most common identifiable cause of SSTI presenting to EDs in a prospective multicenter US study. *S. aureus* was isolated from 320 (76%) of 422 patients with SSTI. The prevalence of MRSA was 59% overall and ranged from 15% to 74% by ED. Pulsed-field type USA300 accounted for 97% of MRSA isolates; 72% of these were a single indistinguishable strain (USA300–0114). SCC*mec* type IV and the Panton-Valentine leukocidin toxin gene were each detected in 98% of MRSA isolates. Among methicillin-susceptible *S. aureus* isolates, 31% were USA300 and 42% contained PVL genes [87]. The spectrum of skin infections caused by CA-MRSA is wide and can range from simple cutaneous abscesses to large abscesses, severe pyomyositis, and fulminant necrotizing soft tissue infections [88–92].

Importantly, since its emergence in 2000, epidemic spread of the MRSA clone USA300 has led to a high burden of SSTIs in the USA and is strongly correlated with MRSA bloodstream infection. It has been concluded that USA300 SSTIs serve as a source for bloodstream infection given that isolates from concurrent SSTI were the same genotypically as the USA300 isolates that caused bloodstream infections [93]. Given this important findings, it is imperative to provide prompt and definitive source control and antimicrobial therapy for CA-MRSA SSTIs in all patients.

MRSA has also been identified as the most common cause of severe SSTIs requiring surgical drainage and debridement in a single-center 7-year study from Houston [94]. From 2000 to 2006, 288 patients with SSTIs that required operative debridement were identified. The most common microorganism retrieved from intraoperative cultures was S. aureus, 70% of which were MRSA. Streptococcus species accounted only for 15% of microbes isolated. Monomicrobial etiology was identified in 67% of patients and MRSA was also the predominant microbe isolated from such cultures (68%). The frequency of MRSA isolates increased significantly during the study from 34% in the year 2000 to 77% in the year 2006, $p < 0.001$). Interestingly, the examination of vancomycin MIC demonstrated a shift for MRSA isolates over this time period, with 38% of the isolates having an MIC ≥1 μg/mL, with 31% of isolates with MIC = 2 μg/mL. This is concerning given recent reports documenting high treatment failure rates for MRSA infections with increased MIC [95, 96].

In a study of 12,506 patients with culture-proven skin, soft tissue, bone or joint infection in hospitalized patients, S. aureus caused infection in 54.6% of patients and 28.0% of the S. aureus isolates recovered were methicillin-resistant. Healthcare-associated infections and complicated SSTIs were associated with significantly higher mortality rates, longer and more costly length of hospital stay [97].

Based on this change in microbiologic etiology of SSTIs, all patients who present with or develop severe cSSTIs should be treated with early empiric broad-spectrum antimicrobial therapy, including mandatory coverage for MRSA. Patients who present to the hospital with severe infection or infection progressing despite antibiotic therapy should be treated aggressively. In these cases, if *S aureus* is cultured, the clinician should assume the organism may be resistant and should treat with agents effective against MRSA, such as vancomycin, linezolid, or daptomycin [98]. Although risk factors for MRSA SSTIs have been identified, in patients with severe SSTIs one should not rely solely on the use risk factors for MRSA in the decision-making regarding whether empiric anti-MRSA antimicrobials should be used.

Choice of empiric antimicrobial therapy for SSTIs is guided by a number of factors. For patients with severe SSTIs that are surgical site infections, it is important to choose an empiric antimicrobial agent that is different than the class of antibiotics that was used for surgical site infection prophylaxis as the time of the initial surgery. In the case of surgical site infection (SSI), the type and site of operation dictate which pathogens are suspected. Infections following operations in the gastrointestinal or genitourinary tract may be monomicrobial or mixed and may be caused by Gram-positive or Gram-negative bacteria. In contrast, infections following clean operations in other parts of the body are typically caused by Gram-positive pathogens. Immunocompromised or neutropenic patients are, of course, at increased risk of infection and are less able to control local infection and therefore should be treated with empiric, broad-spectrum antibiotics at the first clinical signs of infection, including fever.

It is important to provide anti-MRSA coverage in the empiric regimen of *all* patients with severe SSTIs. The MRSA carriage status of the patient should not be used as a guide to treatment for SSTIs, as it poorly predicts the need for anti-MRSA coverage in hospitalized orthopedic patients [99].

A number of intravenous anti-MRSA antimicrobials are approved by the FDA (vancomycin, linezolid, daptomycin, tigecycline, telavancin, ceftaroline, dalbavancin, oritavancin, delafloxacin, omadacycline) and a number of new anti-MRSA antimicrobials are in development. Guideline-based recommendations for the treatment of MRSA bone/joint infections vs. SSTIs and ABSSSIs are shown in Table 32.10. Comprehensive reviews of SSTI antimicrobial studies are available [100, 101]. Options for oral treatment of MRSA SSTIs include clindamycin, trimethoprim-sulfamethoxazole, doxycycline, minocycline, linezolid, and tedizolid (a new oral oxazolidinone) [102]. Oral tedizolid at a dose of 200 mg once daily for 6 days was noninferior to 10 days of 600 mg twice daily linezolid for the treatment of ABSSSIs, including those of MRSA etiology [103]. There is currently no evidence to recommend any specific antibiotic in the treatment of MRSA SSIs [104] or MRSA infections in non-surgical wounds [105].

When selecting empiric antimicrobials for treatment of severe cSSTIs, selection of specific antimicrobials that inhibit toxin production may be helpful, particularly in those patients with evidence of toxic shock syndrome. This is commonly present in patients with streptococcal and staphylococcal infections. Protein cytotoxins play an important role in the pathogenesis of a variety of staphylococcal infections, and toxin production should be considered when selecting an antimicrobial agent for Gram-positive pathogens [106]. The recent identification of a class of secreted staphylococcal peptides [phenol-soluble modulin (PSM) peptides] document that they have a remarkable ability to recruit, activate, and lyse human neutrophils, thus eliminating the main cellular defense against MRSA infection [107]. The β-lactams actually enhance toxin production. In contrast, both clindamycin and linezolid have the ability to inhibit toxin production by suppression of translation, but not transcription, of toxin genes for S. aureus and by direct inhibition of synthesis of group A streptococcal toxins. Particularly when patients exhibit signs and symptoms of streptococcal toxic shock syn-

**Table 32.10** Antimicrobial treatment of MRSA bone/joint infections compared with SSTIs or ABSSSIs

| **Antibiotic treatment of MRSA bone and joint infections** | **Dose** |
|---|---|
| Vancomycin | 15–20 mg/kg IV Q8-12h |
| Daptomycin | 6 mg/kg IV QD |
| Linezolid | 600 mg PO/ IV BID |
| TMP-SMX + rifampin | 4 mg/kg/dose (TMP) Q8-12h and 600 mg QD (rifampin) |
| Clindamycin | 600 mg PO/ IV Q8h |
| Surgical debridement is the mainstay of therapy<br>Some experts recommend adding rifampin (300–450 mg BID)<br>Thabit AK, Fatani DF, Bamakhrama MS et al. antibiotic penetration into bone and joints: An updated review. International journal of infectious diseases 2019;81:128–136. | |
| **Antimicrobial treatment of MRSA complicated SSTIs or ABSSSIs** | |
| **Antibiotic treatment of complicated SSTIs or ABSSSIs** | **Dose** |
| Vancomycin | 15–20 mg/kg IV Q8-12h |
| Daptomycin | 4 mg/kg IV QD |
| Linezolid | 600 mg PO/ IV BID |
| Tedizolid | 200 mg PO QD |
| Telavancin | 10 mg/kg/dose IV QD |
| Ceftaroline | 600 mg IV Q12h |
| Clindamycin | 600–900 mg PO/ IV Q8h |
| Doxycyclin or minocycline | 100 mg IV/PO q12h |
| Delafloxacin | 300 mg IV q12h; 450 mg PO q12h (noninferior to IV vancomycin and aztreonam for ABSSSI) |
| Omadacycline | 450 mg PO q24h for 24 h, then 300 mg q24 (noninferior to PO linezolid for ABSSSI) |
| Dalbavancin | 1 gm IV day 1, then 500 mg day 8 (noninferior to IV vancomycin and oral linezolid for ABSSSI) |
| Oritavancin | Single 1200 mg IV dose (noninferior to 7–10 days IV vancomycin for ABSSSI) |

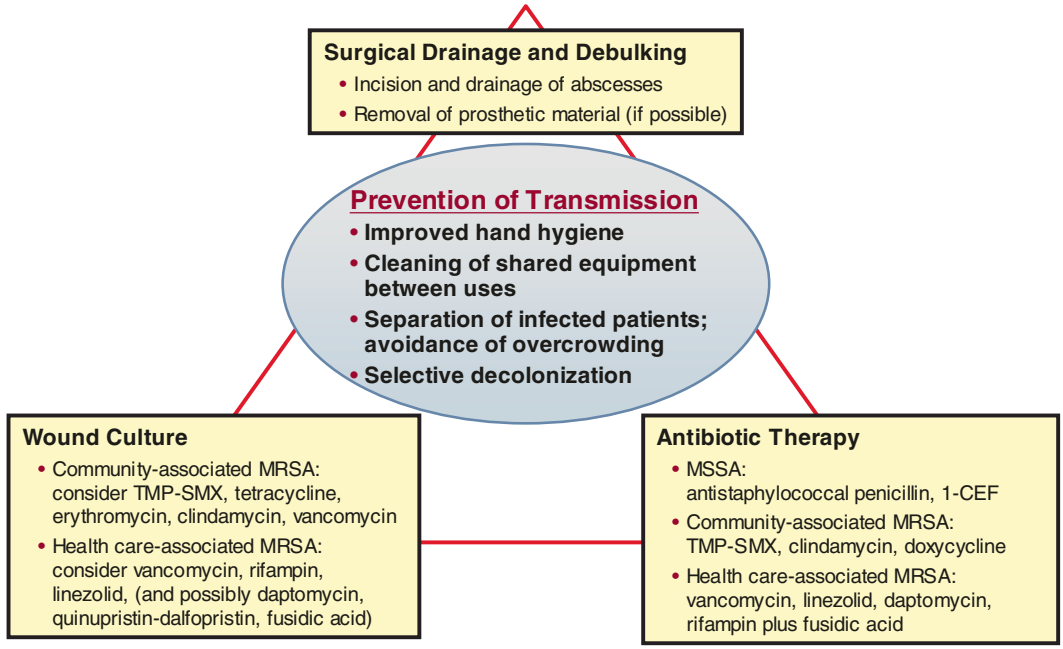
drome (shock, coagulopathy, organ failure, and NSTI), anti-toxin antimicrobials (clindamycin or linezolid) should be promptly initiated [108].

#### 32.3.6.3 "Source Control," I.E., Early Aggressive Surgical Intervention for Drainage of Abscesses and Debridement of Necrotizing Soft Tissue Infections

"Source control" includes drainage of infected fluids, debridement of infected soft tissues, removal of infected devices or foreign bodies, and finally, definite measures to correct anatomic derangement resulting in ongoing microbial contamination and to restore optimal function [109]. Source control represents a key component of success in the therapy of sepsis since it is the best method of prompt reduction of the bacterial inoculum at the site of infection. Source control has been best identified as an important therapeutic strategy in the treatment of complicated abdominal infections [110], but is of paramount importance in the treatment of cSSTIs as well. Appropriate and timely source control is mandatory in the treatment of severe SSTIs, particularly in the case of NSTIs. This is depicted as the main pillar of the "Treatment Triangle" of SSTIs in Fig. 32.5.

#### 32.3.6.4 Pathogen Identification and Appropriate Escalation or de-Escalation of Antimicrobial Therapy

Given the increasing prevalence of multi-drug-resistant pathogens as the etiology of severe SSTIs, pathogen identification is of paramount importance. All patients with severe SSTIs should have blood cultures obtained on admission, prior to initiation of empiric antimicrobial therapy if possible. In addition, cultures should be obtained directly from the SSTI site, either abscess fluid when incision and drainage is performed or tissue sample in the case of NSTIs when surgical debridement is performed.




Grayson ML. *N Engl J Med.*2006;355:724-727.

The three components of the treatment of presumed S. aureus infection include surgical drainage and debridement, obtaining a wound culture, and initiation of appropriate empiric antimicrobial therapy. If MRSA SSTI is confirmed, it is critically important to utilize all methods to prevent microbial transmission, including hand hygiene.

For wound cultures that are positive for community-associated MRSA (usually not a multi-drug-resistant phenotype), in vitro susceptibility to trimethoprim–sulfamethoxazole (TMP-SMX), tetracycline, erythromycin, clindamycin, and vancomycin should be assessed. If the isolate is resistant to erythromycin but susceptible to clindamycin, the clindamycin D-zone test should be performed if clindamycin therapy is being considered.

For wound cultures that are positive for healthcare-associated MRSA (usually a multi-drug-resistant phenotype), in vitro susceptibility to vancomycin, rifampin, and linezolid should be assessed. Assessment of susceptibility to daptomycin and quinupristin–dalfopristin is not necessary unless therapy with these agents is being considered. Susceptibility to fusidic acid may be assessed in countries where this agent is available. Empirical antibiotic therapy should be reviewed once susceptibility data are known. For methicillin-susceptible S. aureus (MSSA), antistaphylococcal penicillin or a first-generation cephalosporin (1-CEF) may be suitable. For community-associated MRSA, TMP-SMX, clindamycin, or tetracycline may be suitable. For healthcare-associated MRSA, vancomycin, linezolid, daptomycin, or rifampin plus fusidic acid may be suitable

**Fig. 32.5** Treatment triangle for S. aureus infection. Adapted From Grayson ML. N Engl J Med 2006;355:724–727

Initial management of cSSTIs should include collection of specimens for culture and antimicrobial susceptibility testing from ***all*** patients with abscesses or purulent lesions. Culture and susceptibility findings are useful both for individual patient management and in monitoring local patterns of antimicrobial resistance. It has been documented that physicians and other healthcare workers cannot accurately predict if an SSTI is due to MRSA. A prospective observational study conducted in an urban tertiary academic center in emergency department patients presenting with purulent wounds and abscesses that received wound

culture ($n$ = 176) documented that physician suspicion of MRSA had a sensitivity of 80% (95% CI 71–87%) and a specificity of 23.6% (95% CI 14–37%) for the presence of MRSA on wound culture with a positive likelihood ratio (LR) of 1.0 (95% CI 0.9–1.3) and a negative LR of 0.8 (95% CI 0.5–1.3). Prevalence was 64%. Emergency physician's suspicion of MRSA infection was a poor predictor of MRSA infection [111].

It is important to de-escalate antimicrobial therapy in the treatment of severe SSTIs once culture results return. Pathogen-directed antimicrobial therapy is then initiated, with de-escalation from the initial broad-spectrum empiric antimicrobial regimen, with an attempt to decrease to monotherapy if at all possible. De-escalation of antimicrobial therapy should occur as early as possible but is only possible if appropriate microbiologic specimens are obtained at the time of SSTI source control. De-escalation is founded on identification of the pathogen and its antibiotic susceptibilities.

## 32.4 Conclusion

SSTIs are associated with significant morbidity and mortality, and it is important to differentiate necrotizing vs. non-necrotizing SSTIs early in the course of treatment. MRSA is the most common cause of purulent cSSTIs. All patients who present with complicated SSTIs should be treated with broad-spectrum antimicrobial therapy, including mandatory coverage for MRSA. Source control, including abscess drainage and surgical debridement, are the mainstay of therapy in severe cSSTIs. It is of paramount importance to obtain specimens for culture and antimicrobial susceptibilities given the high prevalence of MRSA as a causative pathogen in cSSTIs. Empiric broad-spectrum antimicrobial therapy should be de-escalated to narrow-spectrum agents based on culture pathogen identification and the patient's clinical response.

**Key Concepts**

1. **Steps in optimal management of patients with severe SSTIs:**
   - Early diagnosis and differentiation of necrotizing vs. non-necrotizing SSTI.
   - Early initiation of appropriate empiric broad-spectrum antimicrobial therapy with anti-MRSA coverage and consideration of risk factors for specific pathogens.
   - "Source control" of SSTI, i.e., early aggressive surgical intervention for drainage of abscesses and debridement of necrosis and necrotizing soft tissue infection
   - Pathogen identification and appropriate escalation or de-escalation of antimicrobial therapy.
2. **A recent consensus definition was developed for fracture-related infection (FRI), which is a severe complication after bony trauma.**
   - Empiric antibiotic therapy for FRI should be broad-spectrum including a lipo/glycopeptide to cover S. aureus and an agent covering Gram-negative bacilli. Thereafter, it should be narrowed according to culture results as soon as possible.
3. **The key to successful management of both FRI and osteomyelitis is early diagnosis and early treatment with culture-directed antibiotics and surgical debridement of any nonviable tissue.**
4. **Surgical treatment of osteomyelitis requires removal of all infection, necrosis, and non-essential hardware to eradicate the infection, commonly with staged approach with wound VAC therapy. Then skeletal stabilization and soft tissue reconstruction is indicated when infection is eradicated.**

**Take-Home Message**

Acute soft tissue and bone infections may occur in trauma, particularly related to traumatic wounds and fractures, and require a careful and systematic approach to diagnosis and treatment. Early diagnosis allows early treatment with appropriate empiric IV antibiotics to cover MRSA and Gram-negative bacteria which are transitioned to pathogen-directed antimicrobial therapy once the bacterial pathogens are identified. Necrotizing soft tissue infections (NSTI), fracture-related infections (FRI), and osteomyelitis all require aggressive debridement of all infected and necrotic tissues with the goal to create a well-vascularized, granulating wound site prior to consideration of soft tissue and bony reconstruction.

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# Part IV

# Secondary Period (3–8 Days)

# ICU Management: Disseminated Intravascular Coagulation (DIC)

# 33

Satoshi Gando and Takeshi Wada

**Learning Objectives**

In this chapter, the readers will learn the following points concerning DIC in trauma:

- The definition, diagnosis, phenotypes, and time courses of DIC.
- The pathophysiology of cytokines, PARs, DAMPs, and NETs involved in DIC.
- The multiple effects of thrombin on platelets, coagulation, fibrinolysis, and inflammation.
- How DIC-induced MODS and critical bleeding affect a patient's outcome.
- How to manage DIC in order to improve a patient's outcome.

## 33.1 Introduction

Disseminated intravascular coagulation (DIC) is an acquired syndrome characterized by systemic activation of coagulation not restricted to the site of insults and can be caused by non-infectious and infectious insults [1]. The two major insults that evoke DIC are trauma and sepsis, which induce systemic inflammatory response syndrome (SIRS) [1, 2]. In the early 1990s, SIRS was considered the main cause of organ dysfunction affecting a patient's outcome [2]. Based on this concept, many randomized controlled trials targeting the control of SIRS were performed; however, none of these trials managed to achieve their aims, thereby suggesting that a change in the treatment strategies for controlling only SIRS [3]. Concurrently with this paradigm shift, tight molecular links between inflammation and coagulation were detected, in which thrombin plays a central role, resulting in multiple organ dysfunction syndrome (MODS) and eventually death [4]. DIC represents dysregulated inflammatory and coagulofibrinolytic responses to the insults such as trauma and sepsis; therefore, DIC can induce the development of MODS via the bidirectional interplay between inflammation and coagulation [1].

Penner summarized the trauma studies, including head trauma, published during the 1990s [5]. In those studies, DIC patients showed high inflammatory cytokines levels and increased systemic

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thrombin generation as measured by thrombin antithrombin complex (TAT) or prothrombin fragment 1 + 2 (PF1 + 2) immediately after trauma. These changes were associated with MODS and higher mortality rates than in non-DIC patients. In 2001, the International Society on Thrombosis and Haemostasis (ISTH) published a definition and diagnostic criteria for DIC [6]. This official communication positioned trauma (polytrauma, neurotrauma, fat embolism, etc.) as the main cause of DIC and stated that generalized inflammatory responses to insults with the release of cytokines from multiple inflammatory cells lead to extensive damage of the microvascular endothelium, which can result in organ dysfunction. Following this announcement, close relationships among trauma, inflammatory responses, microvascular disturbances, DIC, and MODS have been identified by the mid 2000s [7–9].

The ISTH again confirmed that tissue damage, including major trauma, is a cause of DIC with a high level of evidence about two decades after the first announcement [10]. DIC is an old disease with a history of over half a century; however, it is still a key disease to be recognized and diagnosed in the critical care setting [11]. In this chapter, the management of DIC in the intensive care unit (ICU) will be reviewed and discussed with the goal of improving the prognosis of critically ill trauma patients.

## 33.2 Trauma-Induced Coagulopathy and DIC

Trauma-induced coagulopathy is defined as the pre-stage of full-blown DIC, such as sepsis-induced coagulopathy. Three subcommittees of the ISTH published an official announcement, noting that dysregulated inflammatory and coagulofibrinolytic responses to trauma converge the trauma-induced coagulopathy in the final pathway of DIC [12] (Fig. 33.1). If trauma is sufficiently severe, however, DIC develops immediately after trauma without first proceeding through the stage of trauma-induced coagulopathy [13]. Expanding our understanding of these relationships between trauma-induced coagulopathy and DIC will likely provide therapeutic benefit to severely injured trauma patients.

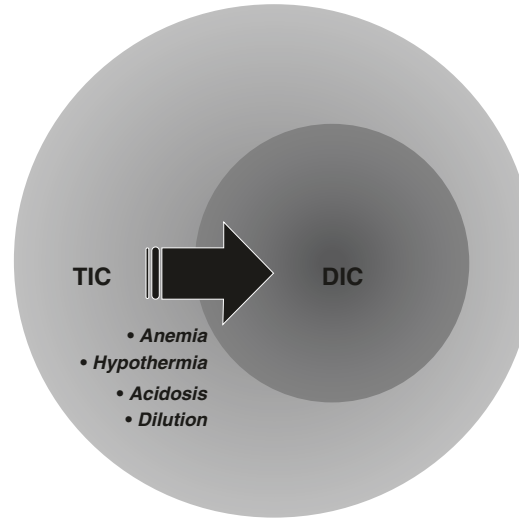



**Fig. 33.1** Relationship between trauma-induced coagulopathy (TIC) and disseminated intravascular coagulation (DIC). TIC is defined as the pre-stage of full-blown DIC. If trauma is sufficiently severe, dysregulated inflammatory and coagulofibrinolytic responses to trauma converge in the final pathway of DIC. Exogenously induced secondary coagulopathies such as anemia-, hypothermia-, acidosis-, and dilution-induced coagulopathies, modify DIC

Another point of note is that trauma-induced coagulopathy comprises primary and secondary coagulopathies [12, 14] (Table 33.1). Trauma-itself-induced primary coagulopathy, namely DIC, is modified by the anemia-, dilution-, hypothermia-, and acidosis-induced secondary coagulopathies.

## 33.3 The Definition and Diagnosis

### 33.3.1 The Definition

The ISTH defined DIC as "DIC is an acquired syndrome characterized by the intravascular activation of coagulation with loss of localization arising from different causes. It can originate from and cause damage to the microvasculature, which if sufficiently severe, can produce organ dysfunction" [6]. The key points of this definition are systemic thrombin generation not restricted to the insult's site and endothelial cell activation followed by subsequent injury.

**Table 33.1** Summary of trauma-induced coagulopathy

| |
|---|
| 1. Physiological changes |
| (a) Hemostasis and wound healing |
| 2. Pathological changes |
| (a) Trauma-itself induced primary coagulopathy |
| • DIC |
| – Activation of coagulation |
| – Insufficient anticoagulant mechanisms |
| – Increased fibrin(ogen)olysis (early phase) |
| – Suppression of fibrinolysis (late phase) |
| – Consumption coagulopathy |
| (b) Exogenously induced secondary coagulopathies that modify DIC |
| • Anemia-induced coagulopathy |
| • Hypothermia-induced coagulopathy |
| • Acidosis-induced coagulopathy |
| • Dilutional coagulopathy |
| • Others |

Modified with permission [14]
*DIC* disseminated intravascular coagulation

The ISTH further states that DIC is accompanied by the loss of tight junctions between endothelial cells which gives rise to capillary leak syndrome [6]. Excessive thrombin generation and endothelial injury with microvascular thrombus formation leads to decreased oxygen delivery to the cells and tissues and subsequent exhaustion of platelets and consumption of coagulation factors, causing MODS and oozing-type bleeding [6]. Therefore, DIC has long been recognized as "thrombohemorrhagic disorder" [15–17]. The definition of DIC established by the ISTH has provided a logical base concerning the pathophysiology of DIC.

### 33.3.2 The Diagnosis

The ISTH proposed overt DIC diagnostic criteria involving two steps; assessing underlying clinical conditions that may be associated with DIC and applying an algorithm for the diagnosis of DIC [6]. Before using the algorithm, a risk assessment to check whether or not a patient has an underlying disorder is mandatory. If a patient has such a disorder, algorithm may be applied. The ISTH overt DIC scoring system was prospectively validated in diverse patients including trauma admitted to the ICU [18]. The results confirmed a sufficient diagnostic accuracy of the ISTH scoring system for diagnosing DIC in ICU patient clinically suspected of having this syndrome.

To diagnose DIC during its latent period before progression to full-blown overt DIC, the ISTH proposed non-overt DIC diagnostic criteria as well [6]. However, the prospective validation of non-overt DIC diagnostic criteria failed to prove the progression of non-overt DIC to overt DIC [19, 20]. To overcome this drawback associated with non-overt DIC diagnostic criteria and the low sensitivity for diagnosing DIC using the overt DIC diagnostic algorithm, the Japanese Association for Acute Medicine (JAAM) established the JAAM DIC diagnostic criteria. The JAAM diagnostic criteria have been prospectively validated in a critical care setting several times [20–22]. These studies showed that the JAAM DIC diagnostic criteria were able to identify DIC patients with high sensitivity and moderate specificity, and that the DIC diagnosed according to the JAAM criteria progresses to the ISTH overt DIC. Of note, the JAAM DIC diagnostic criteria can be applied at an early stage of trauma as well as a late stage with acceptable validity for the DIC diagnosis [23–25]. The ISTH and JAAM DIC diagnostic criteria can be found elsewhere [6, 21].

## 33.4 Phenotypes and Time Courses

### 33.4.1 Phenotypes

DIC comprises fibrinolytic and thrombotic phenotypes [1, 26–28]. DIC essentially is a thrombotic phenotype, and that DIC with a fibrinolytic phenotype is defined as the coexistence of DIC and pathological systemic fibrin(ogen)olysis [26, 28]. A condition wherein one insult simultaneously evokes DIC (with a thrombotic phenotype) and pathological systemic fibrin(ogen)olysis is called DIC with a fibrinolytic phenotype (Fig. 33.2).

Typical conditions that induce DIC with a fibrinolytic phenotype are acute promyelocytic leukemia [29], a long hypoxic state (e.g., asphyxia and drowning) [30], cardiac arrest and resuscitation [31], postpartum hemorrhagic shock [32],

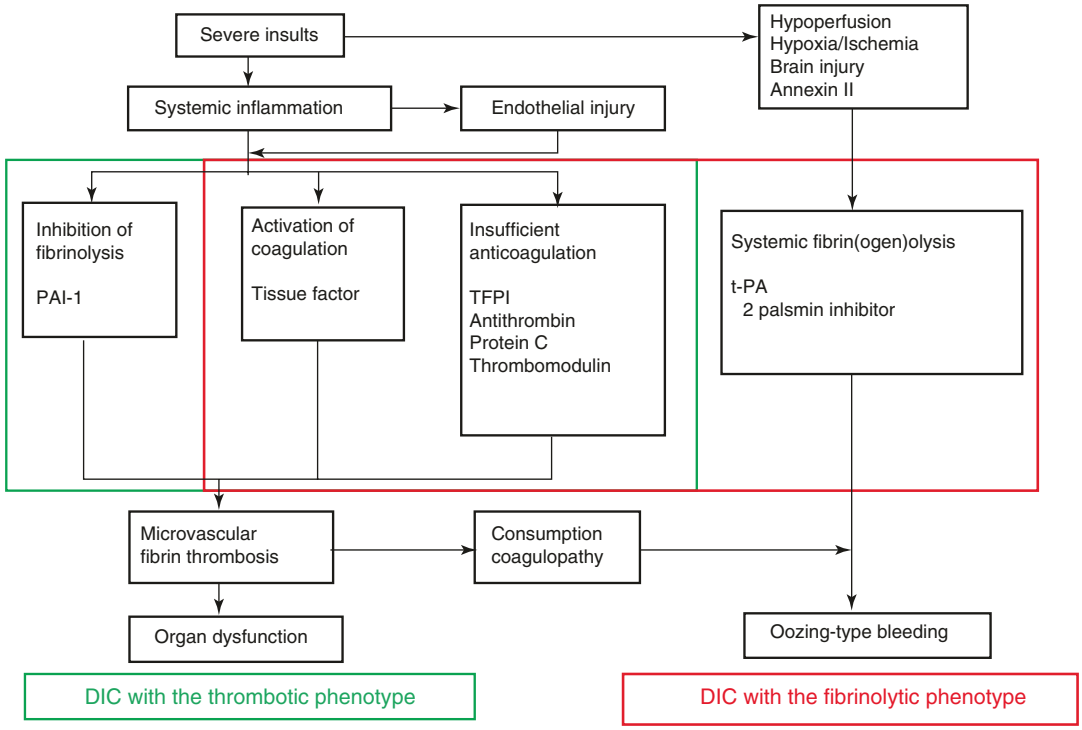



**Fig. 33.2** Two phenotypes of disseminated intravascular coagulation (DIC). DIC essentially is a thrombotic phenotype; DIC with a fibrinolytic phenotype is defined as the coexistence of DIC and pathological systemic fibrin(ogen)olysis due to tissue hypoperfusion, systemic hypoxia/ischemia, etc. A condition wherein one insult simultaneously evokes DIC (with thrombotic phenotype) and pathological systemic fibrin(ogen)olysis is called DIC with a fibrinolytic phenotype. Importantly, massive thrombin generation due to the activation of the tissue factor-dependent coagulation pathway and insufficient anticoagulation controls always underlie both types of DIC. *PAI-1* plasminogen activator ingibitor-1, *TFPI* tissue factor pathway inhibitor, *t-PA* tissue-type plasminogen activator. (Modified with permission (Creative Commons Attribution International License) [28])

isolated traumatic brain injury (iTBI) [33, 34], and severe trauma [35, 36]. The assembly of plasminogen and tissue-type plasminogen activator (t-PA) on promyelocytic leukemia cell surface-expressed annexin II promotes the conversion of plasminogen to plasmin [1, 29]. Common pathomechanisms increasing fibrin(ogen)olysis in asphyxia, drowning, cardiac arrest and resuscitation, postpartum hemorrhagic shock, and severe trauma are prolonged hypoxia- and ischemia-induced massive thrombin generation as well as marked t-PA release from endothelial Waibel-Palade bodies [1, 36–38]. Neurons and other cell types within the central nervous system synthetize and store t-PA in the granules and are rich in tissue factor, both of which are immediately released into the circulation in iTBI, causing DIC and systemic fibrin(ogen)olysis [39, 40]. All conditions, except for acute promyelocytic leukemia, aggravate fibrin(ogen)olysis due to the time delay between the immediate release of t-PA and the delayed expression of plasminogen activator inhibitor-1 (PAI-1) mRNA [1, 7, 13, 35, 36].

### 33.4.2 Time Courses

The time courses in coagulofibrinolytic changes after trauma are shown in Fig. 33.3 [7, 35, 36]. The left side shows the physiologic state of hemostasis and wound healing, while the right side shows the pathological changes observed in DIC. These physiological and pathological states should be and can be distinguished using DIC diagnostic criteria. It is important to recognize, as the ISTH warned, that many published studies have discussed these

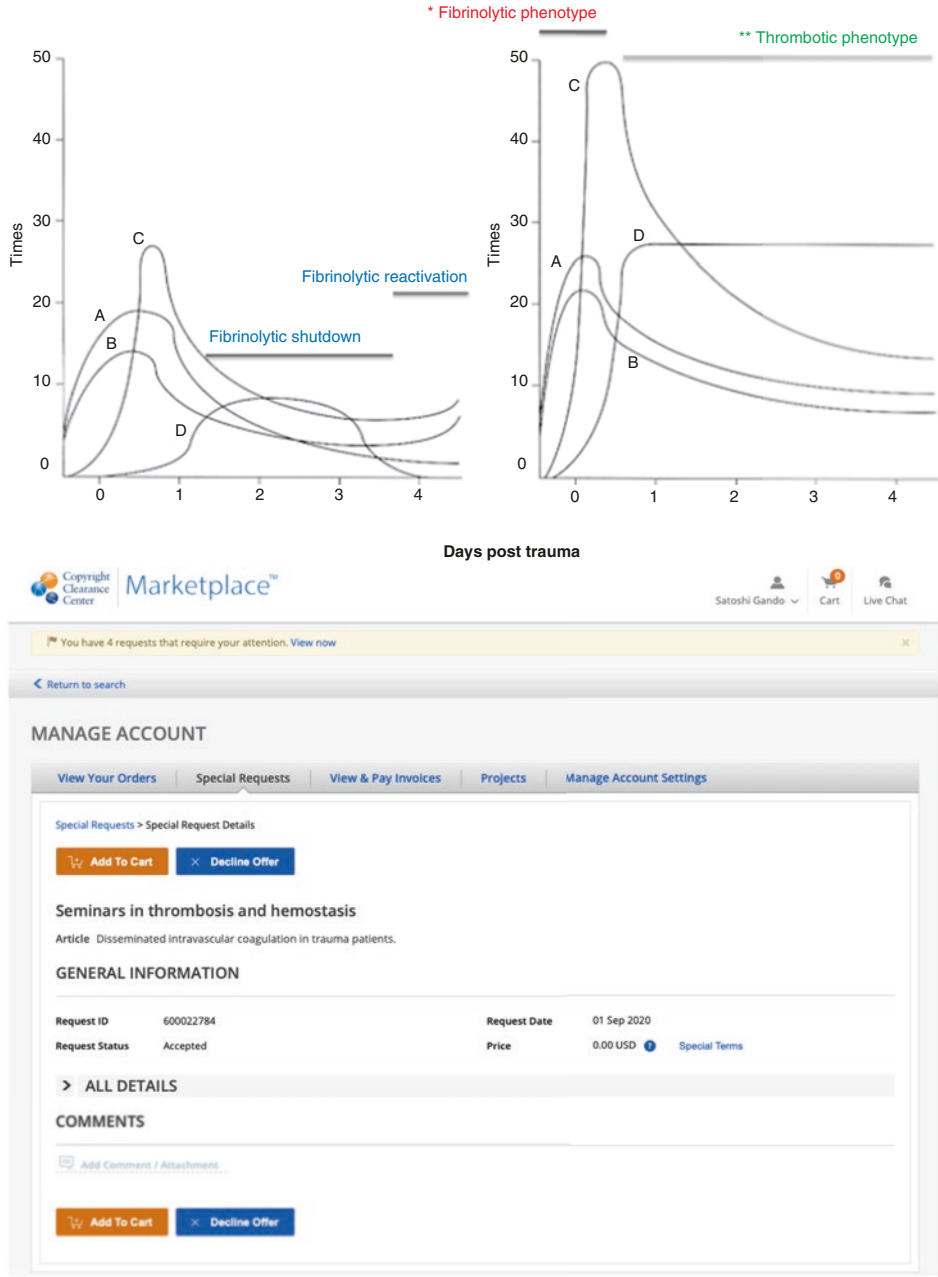



**Fig. 33.3** Schematic diagrams of the variations in thrombin activity (A, measured by fibrinopeptide A, FPA), plasmin activity (B, fibrinopeptide B β15–42, FPBβ15–42), fibrin formation and secondary fibrinolysis (C, D-dimer) from day 0 (in the emergency department) to day 4. Left, normal changes in hemostasis and wound healing. There are three phases of fibrinolysis: early activation, impairment (D, PAI-1: fibrinolytic shutdown), and reactivation. Normally, both the thrombin activity and PAI-1 are completely shut off by days 3–5 after trauma, followed by the reactivation of fibrinolysis. Right, pathological changes in DIC. There is a time delay between immediate t-PA-induced massive plasmin generation and the induction of PAI-1mRNA, which causes systemic hyperfibrin(ogen)olysis (asterisk, DIC with a fibrinolytic phenotype), followed by the impairment of fibrinolysis due to persistent elevation of PAI-1 released from endothelial cells via transcription (double asterisk, DIC with a thrombotic phenotype). Persistent and systemic thrombin generation always underlies these changes in fibrinolysis. *DIC* disseminated intravascular coagulation, *PAI-1* plasminogen activator inhibitor-1, *t-PA* tissue-type plasminogen activator. (Modified with permission [7])

two conditions without clear separation, confusing our understanding of trauma-induced coagulopathy and DIC [36, 41]. The main differences between these two time courses concerning the dynamics of thrombin generation and inhibition of fibrinolysis by PAI-1. Thrombin generation and inhibition of fibrinolysis transiently continues for several days under conditions of the normal hemostasis and wound healing but persist until DIC is improved under DIC conditions.

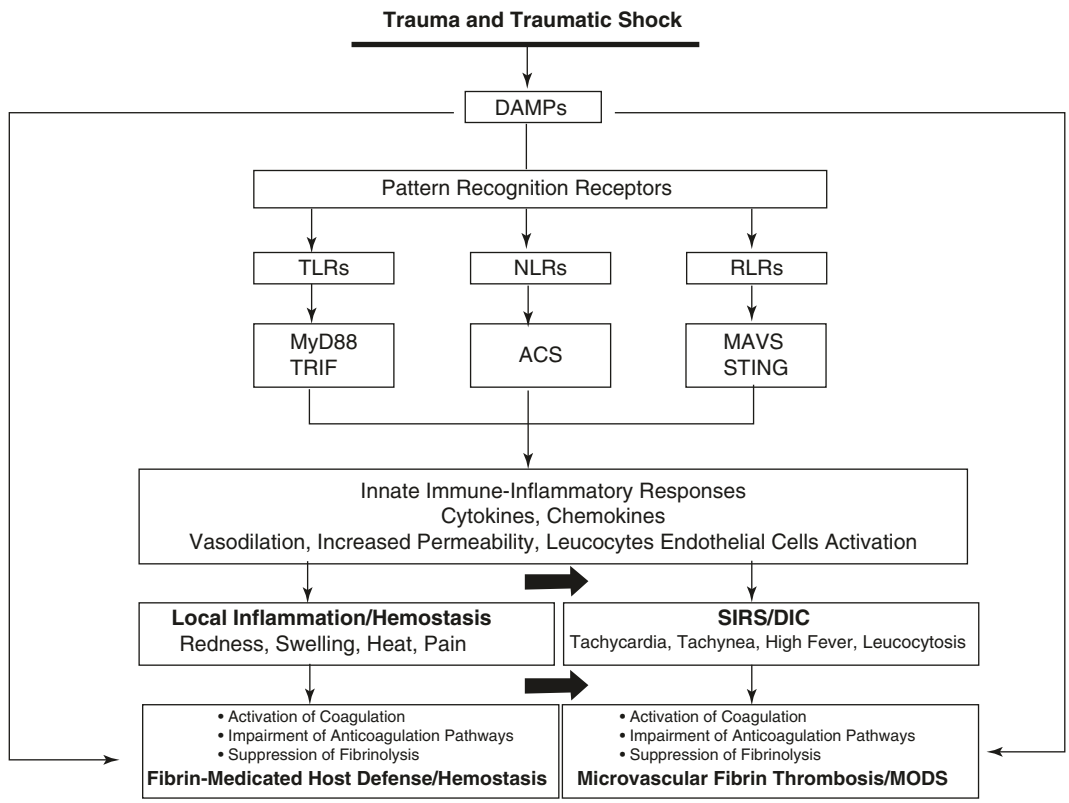
Figure 33.3 (right) further depicts the two phenotypes of DIC. The time delay between the immediate increases in plasmin generation due to t-PA release and delayed elevation of PAI-1 (single asterisk) indicates DIC with a fibrinolytic phenotype, and persistent increases in both thrombin generation and PAI-1 (double asterisk) indicate DIC with a thrombotic phenotype. Furthermore, DIC with a fibrinolytic phenotype exists only for a couple of hours after presentation to the emergency department [13, 31]; however, in cases of severe trauma, the fibrinolytic phenotype progresses to the thrombotic phenotype without complication of sepsis [42].

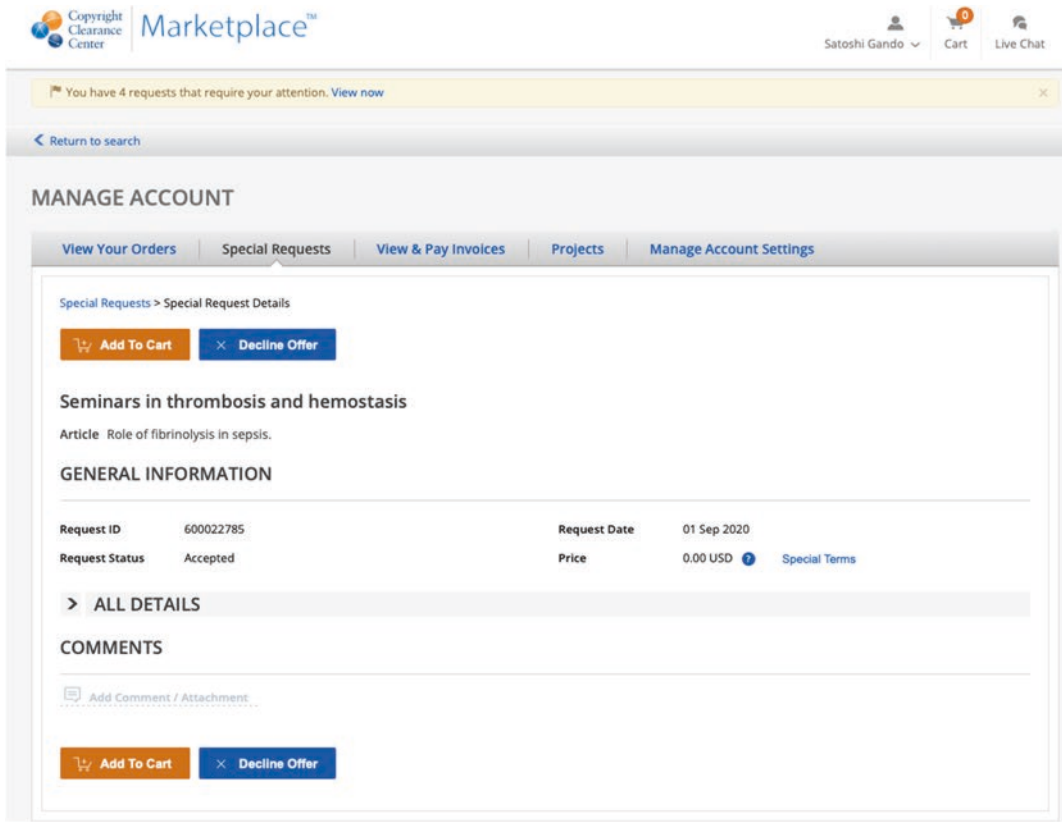
## 33.5 Pathophysiology

Although DIC develops in diverse underlying conditions, once initiated, the pathomechanisms that give rise to DIC are similar, regardless of the setting [1]. The modern pathophysiology of DIC and its characteristics in trauma were established around the 1990s [1, 5, 6, 35]. Recent advances have been described in studies which highlighted bidirectional interplay among innate immunity, inflammation, and coagulofibrinolytic responses, in which histones and neutrophil extracellular traps (NETs) play central roles, constituting the main pathophysiology of DIC [43, 44].

Trauma induces innate immune responses via the altered-self, danger-associated molecular patterns (DAMPs), which are recognized by pattern recognition receptors (PRRs), such as Toll-like receptors (TLRs), NOD-like receptors (NLRs), and RIG-I-like receptors (RLRs). Signal transductions of PRRs leads to the expressions of pro-inflammatory cytokines (TNF-α, IL-1, IL-6) and chemokines (IL-8) as well as anti-inflammatory cytokines (IL-10) [28, 45, 46]. Innate immune responses activate inflammation, coagulation, endothelium, and complement pathways to maintain body homeostasis with the balance of inflammation and anti-inflammation called SIRS and compensatory anti-inflammatory syndrome (CARS), respectively [2, 47]. At the site of insults such as trauma and sepsis, hemostatic thrombosis and immunothrombosis formed by the activation of coagulation cascades and activated neutrophil-released NETs control the insults (hemorrhage and infection), delimits and fixes the insult-induced injuries, and protects the dissemination of DAMPs, pathogen-associated molecular patterns (PAMPs), and microorganisms into the circulation [28, 45, 46, 48]. However, if the insult is sufficiently severe, local physiological thrombosis spreads throughout the whole body and then pathological DIC associated with SIRS ensues [28, 48] (Fig. 33.4).

**Fig. 33.4** Trauma elicits nonspecific innate immune inflammatory responses that limit and repair tissue damage. The figure depicts a simplified schematic representation of the activation of pattern recognition receptors by DAMPs and their signaling through the adaptor proteins. This cascade promotes the transcription of several pro-inflammatory cytokines and chemokines, leading to local and systemic inflammatory responses. Local inflammation begins as an adaptive host response, serving to promote the host defense and physiologic hemostasis and fibrin-mediated host defense called immunothrombosis. Spillover of the DAMPs and inflammatory cytokines into the circulation induces SIRS, which activates systemic coagulation, suppresses fibrinolysis, and overwhelms the anticoagulant control mechanisms that restrict hemostasis locally, giving rise to DIC. Importantly, DAMPs themselves can activate coagulation and impair anticoagulation pathways through endothelial damage. *ACS* apoptosis-associated speck-like protein containing caspase recruit domain, *DAMPs* damage-associated molecular patterns, *DIC* disseminated intravascular coagulation, *MAVS* mitochondrial antiviral signaling, *MODS* multiple organ dysfunction syndrome, *MyD88* myeloid differentiation factor 88, *NLRs* nucleotide-binding oligomerization domain-containing receptors, *RLRs* retinoic acid inducible gene-I-like receptors, *SIRS* systemic inflammatory response syndrome, *STING* stimulator of interferon gene, *TRIF* toll/IL-1 receptor homology domain-containing adaptor inducing interferon β, *TLRs* toll-like receptors. (Modified with permission [45])


Trauma and Traumatic Shock
DAMPs
Pattern Recognition Receptors
TLRs
NLRs
RLRs
MyD88
TRIF
ACS
MAVS
STING
Innate Immune-Inflammatory Responses
Cytokines, Chemokines
Vasodilation, Increased Permeability, Leucocytes Endothelial Cells Activation
Local Inflammation/Hemostasis
Redness, Swelling, Heat, Pain
SIRS/DIC
Tachycardia, Tachynea, High Fever, Leucocytosis
• Activation of Coagulation
• Impairment of Anticoagulation Pathways
• Suppression of Fibrinolysis
Fibrin-Medicated Host Defense/Hemostasis
• Activation of Coagulation
• Impairment of Anticoagulation Pathways
• Suppression of Fibrinolysis
Microvascular Fibrin Thrombosis/MODS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### 33.5.1 Cytokines

Important pro-inflammatory cytokines that induce SIRS following trauma are TNF-α, IL-1, and IL-6. Immediately after trauma, significant increases in these cytokines have been confirmed in DIC and severely injured patients [49, 50]. TNF-α and IL-1 induce tissue factor expression on monocytes and endothelial cells and down-regulate endothelial protein C receptor (EPCR) leading to the suppression of the protein C anti-coagulant pathway [51, 52]. IL-6 is also able to induce the activation of coagulation [53]. These inflammatory cytokines further activate neutrophils and endothelial cells [51], which upregulate or express adhesion molecules such as selectins, integrins, and immunoglobulin superfamily which elicit platelets, neutrophils, and endothelial cells interactions, leading to the release of neutrophil-mediated reactive oxygen species and neutrophil elastase [54–56]. Activated platelets- and endothelial cells-upregulated P-selectin induces the expression of tissue factor on monocytes [1, 57]. Neutrophil-released reactive oxygen species and elastase injure endothelial cells, bringing about the dysfunction of anticoagulation systems comprising tissue factor pathway inhibitor (TFPI), antithrombin/glycosaminoglycan, and protein C/thrombomodulin on the endothelial cells and the glycocalyx [58, 59]. Furthermore, TNF-α induces immediate t-PA release followed by persistent expression of PAI-1, which impairs fibrinolysis [60–62].

Taken together, these findings indicate that inflammatory cytokines are capable of causing all pathomechanisms of DIC. The following pathomechanisms have been confirmed in DIC after trauma: SIRS [49, 63, 64], activation of platelets and systemic thrombin generation [64, 65], insufficient anticoagulant systems such as TFPI [66], antithrombin [36, 63, 65], protein C [36], activation followed by the impairment of fibrinolysis [31, 49, 67, 68] and endothelial cells activation and injury [35, 69, 70].

### 33.5.2 Protease-Activated Receptors (PARs)

Signals of coagulation proteases are transmitted to inflammatory cells via protease-activated receptors (PARs) [71, 72]. The PARs are G-protein coupled receptors with seven transmembrane domains that can sense signals from coagulation proteases with auto-activation mechanisms by the proteases-cleaved and exposed active sequence functioning as tethered ligand. The four known PARs are PAR1, PAR2, PAR3, and PAR4. Tissue factor/FVIIa complex activates PAR2, tissue factor/FVIIa/FXa ternary complex activates PAR1 and PAR2, and FIIa (thrombin) activates PAR1, PAR3, and PAR4, resulting in the inductions of varied effects on platelets, leucocytes, and endothelial cells [73, 74] (Table 33.2). Therefore, the PARs play pivotal roles in bidirectional interplays between inflammation and coagulation [43], which forms vicious cycles in DIC, leading to the development of MODS [1, 74].

### 33.5.3 DAMPs and NETs

Two epoch-making studies were published in the 2000s [75, 76]. One showed that NETs kill bacteria and another reported that extracellular histones are major mediators of death through endothelial injury and microvascular thrombosis in sepsis. Following these studies, DAMPs including histones and NETs containing neutrophil DAMPs such as DNA and histones became major mediators of many pathologic disorders including DIC [1, 48, 77, 78].

#### 33.5.3.1 Cytokines and SIRS

Circulating mitochondrial DAMPs, mitochondrial DNA and formyl peptides, showed immediate and thousands-fold higher increases in severely injured trauma patients than control subjects, which were followed by the TNF-α and

**Table 33.2** Protease-activated receptors (PARs) and their actions on platelets, leukocytes, and endothelium

| | Induction of expression, release, etc. | Actions |
|---|---|---|
| Platelets | 5-HT, ADP, TXA2, P-selectin GPαIIb/β3 | Platelet activation, adhesion, aggregation |
| Leukocytes | TNF-α, IL-6, IL-8, CD11b | Proinflammatory |
| | Tissue factor | Activation of coagulation |
| | Oxygen radicals | Endothelial cells injury |
| Endothelial cells | | |
| | VWF, PAF | Platelet activation and consumption |
| | IL-1, IL-6, IL-1 | Proinflammatory |
| | P-selectin, E-selectin, ICAM-1, VCAM-1, MCP-1 | Endothelial cells activation |
| | MMP7, MMP9, Apoptosis | Apoptosis |
| | Tissue factor, PAI-1, TM down regulation | Activation of coagulation, suppression of fibrinolysis, and impairment of anticoagulation |
| | Nitric oxide, EDHF, histamine, gap formation | Vessels dilatation, increased permeability |
| | Endothelin | Vessels constriction |

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*5-HT* 5-hydroxytriptamine, *ADP* adenine di-phosphate, *TXA2* thromboxane A2, *GP* glycoprotein, *TNF* tumor necrosis factor, *IL* interleukin, *VWF* von Willebrand factor, *PAF* platelet-activating factor, *ICAM-1* intracellular adhesion molecule-1, *VCAM-1* vascular cell adhesion molecule-1, *MCP-1* monocytes chemotactic protein-1, *MMP* metalloprotease, *PAI-1* plasminogen activator inhibitor-1, *TM* thrombomodulin, *EDHF* endothelial hyperpolarizing factor

IL-6 expression associated with SIRS and organ dysfunction [79, 80]. Circulating histones rising to toxic levels immediately after trauma led to IL-6 release, systemic thrombin generation, endothelial injury, and NETs formation, which induced microvascular thrombosis and organ dysfunction [50]. These studies demonstrate close relationships among innate immunity, SIRS, DIC, and MODS in trauma.

The bidirectional interplays between cell injury-induced histones triggering NETs formation and NETs as a source for localized and systemic histones are important in the pathomechanisms of DIC [48, 78]. The above-mentioned DAMPs-induced expression of cytokines and chemokines via PRRs is well recognized [28, 45, 48]. Histones and NETs also induce expression of TNF-α, IL-1, and L-6 via the signal transductions of PRRs, leading to development of SIRS [50, 81–83]. Rapid increases in these cytokines may be due in part to their release from presynthesized storage in addition to the induction of their expressions [50, 81].

#### 33.5.3.2 Platelets and Coagulation

Histones directly or via interactions with TLR2 and TLR4 induce platelet activation and subsequent aggregation associated with P-selectin release and phosphatidylserine exposure, leading to thrombocytopenia in vivo and in critical illness [84–88]. Activated platelets and NETs collaborate to promote thrombin generation and intravascular coagulation [89].

Tissue factor expression on monocytes and its exposure on the endothelium due to endothelial injury is the most important trigger of DIC [1, 90]. Indeed, DIC patients after trauma shows high tissue factor levels associated with persistent thrombin generation [64, 91]. Extracellular histones induce tissue factor antigen, activity, and mRNA in endothelial cells via TLR2 and TLR4 [92, 93]. Histones are able to promote prothrombin auto-activation, which is an important finding indicating that thrombin is independently generated without the activation of coagulation cascades [94]. Furthermore, histone-induced phosphatidylserine exposures on red blood cells (RBCs) and endothelial cells enhance coagulation activation [93, 95]. Other DAMPs, including DNA contained in NETs and RNA released from injured cells, promote thrombosis dependent on the FXII/FXI-induced activation of contact pathways of coagulation [96–98], which is related to a poor prognosis of DIC [99].

#### 33.5.3.3 Anticoagulant Systems and Endothelial Cells

The impairment of thrombomodulin-dependent protein C activation by histones increases thrombin generation, which is a main pathomechanisms of DIC [100]. DIC induces capillary leak syndrome [1, 6]. Histone-induced endothelial injury contributes to increases in endothelial permeability [50, 75] and mitochondrial DAMPs also increase endothelial permeability [101], which gives rise to loss of antithrombin into the extravascular spaces [102]. Neutrophil elastase, a constituent of NETs, cleaves or degrades TFPI, protein C, and antithrombin [1]. High levels of neutrophil elastase associated with endothelial injury in DIC after trauma have been repeatedly confirmed [67, 69, 70]. Furthermore, in vitro, in vivo, and clinical studies of trauma and sepsis confirmed histone-induced endothelial injury by elevated levels of soluble thrombomodulin and its association with thrombin generation and microvascular thrombosis [50, 84]. These findings indicate that histones and NETs are deeply involved in the three major pathomechanisms of DIC; thrombin generation due to insufficient anticoagulant systems, endothelial injury, and capillary leak syndrome.

#### 33.5.3.4 Activation and Impairment of Fibrinolysis

Extracellular DNA acts as a template for the activation of fibrinolysis under the conditions of neutralization by endogenous serpins such as PAI-1; however, under conditions of the over expressions of PAI-1, extracellular DNA has antifibrinolytic effects, which suggests the role of DNA in DIC [103]. Cell-free DNA binds to both plasmin and fibrin, forming ternary complex and consequently inhibiting fibrinolysis [104]. DNA, histones, and NETs were shown to delay t-PA-mediated fibrin clot lysis, and the former two further increased the fibrin clot fiber diameter, resulting in the thrombus stability [105, 106]. Although these results seem to be physiological effects of histones and DNA supporting the strength of immunothrombosis at the insult site, under the pathologic condition of DIC with increased levels of PAI-1, these DAMPs may play pathological roles through the inhibition of fibrinolysis.

#### 33.5.3.5 Brief Summary

In vivo experiments clearly showed that histones were able to decrease platelet counts and fibrinogen levels, and prolong the prothrombin time and activated partial thromboplastin time (APTT), which resulted in platelet and fibrin thrombosis associated with organ dysfunction and low survival probability [84]. Similar results were obtained in an experimental trauma model and in trauma patients [50]. As such, DAMPs, especially histones and NETs constitute the main pathophysiology of DIC [78].

### 33.5.4 Multiple Actions of Thrombin

The most important key factor in DIC is thrombin, which controls and influences all other factors associated with DIC [1] (Fig. 33.5). In addition to the fundamental role of thrombin in the formation of fibrin clots, thrombin enhances inflammation and activates platelets through PARs [71, 74]. On the surface of activated platelets, FIXa/FVIIIa (tenase) and FXa/FVa (prothrombinase) complexes induce thrombin burst, which accelerate thrombin generation about hundreds of thousands-folds [107]. The conversion of prothrombotic and inflammatory properties of thrombin into anti-thrombotic and anti-inflammatory actions can be done via complex formation with endothelial thrombomodulin [1, 43]. The thrombin thrombomodulin complex-formed activated protein C suppresses thrombin generation by the proteolytic degradation of FVa and FVIIIa. This complex also enhances the activation of TAFI by thrombin about 1250-fold [108]. The anti-inflammatory properties of thrombin complexed with thrombomodulin are exerted through several pathways, such as the binding of activated protein C and EPCR-induced changes in PAR1 inflammatory properties [1, 43, 109] and cleaving of carboxy-terminal arginine residues of bradykinin, C3a and C5a as well as osteopontin by TAFIa [110–112]. Thrombin-mediated fibrinolysis control also should be acknowledged. Thrombin stimulates fibrinolysis via immediate t-PA release

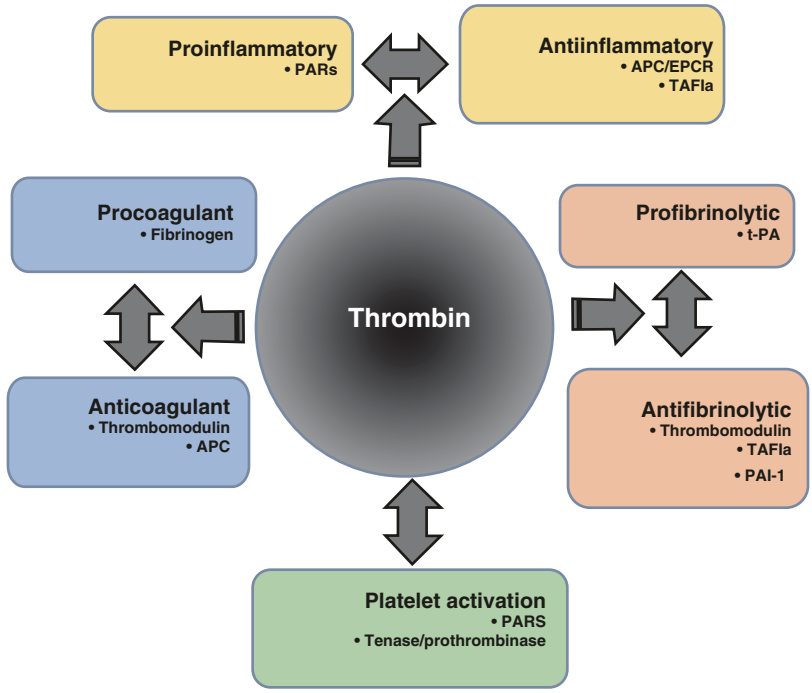



**Fig. 33.5** Multiple actions of thrombin. Multiple actions of thrombin protect the fine balances in the physiological status to maintain homeostasis. Excessive thrombin generation in DIC upsets this balance and induces multifaceted consequences, leading to inflammation, thrombosis, and bleeding. For this reason, DIC has been described as thrombohemorrhagic disorder. Refer to the text for details. *APC* activated protein C, *DIC* disseminated intravascular coagulation, *EPCR* endothelial protein C receptor, *PAI-1* plasminogen activator inhibitor-1, *PARs* protease-activated receptors, *TAFIa* activated thrombin activatable fibrinolysis inhibitor, *t-PA* tissue-type plasminogen activator

from endothelial Waibel-Palade bodies [37, 113]. In addition to the induction of PAI-1 expression in endothelial cells [114], thrombin inhibits fibrinolysis through TAFIa [108, 115, 116]. The thrombin thrombomodulin complex activate TAFI [108], and then TAFIa removes the carboxyl-terminal lysine from fibrin, leading to downregulation of fibrinolysis [115, 116].

Massive thrombin generation from immediately to several days after trauma has been repeatedly confirmed in DIC patients since the early 1990s [7, 9, 64, 65] and recent publications have successfully reproduced these results [13, 117]. Dumber and Chandler elegantly showed that immediate and excessive thrombin generation not restricted to injury sites is due to tissue factor activity in systemic circulation and that reduced antithrombin levels allow systemic thrombin generation to continue once started [118, 119]. Tissue factors in systemic circulation likely cause significant thrombin generation in DIC patients [120]. Substantial evidence of massive thrombin generation in DIC after trauma suggest that the manifestation of bleeding and thrombosis in DIC may be dependent on the fine balance of multiple actions of thrombin [1].

## 33.6 MODS and the Prognosis

Esmon et al. [4] announced that the molecular links between inflammation and coagulation are unquestioned and stated that the inflammation-coagulation autoamplification loop progresses to vascular injury and MODS, leading to death. The ISTH fully accept this concept and published statement that inflammation-induced systemic thrombin generation and endothelial injury give rise to MODS

[6]. DIC is a frequent complication of SIRS [63] and its prevalence increases in parallel with the severity of inflammation associated with stepwise increases in organ dysfunction [121].

DIC patients after trauma consistently showed significantly higher prevalence of MODS and rates of mortality than in non-DIC patients [49, 65, 66, 68–70, 117]. DIC and sustained SIRS for more than 3 days after trauma have shown significant increases in tissue factor levels and thrombin generation for 5 days after trauma associated with high rates of MODS and death [64]. A clinical decision analysis confirmed these results while showing that likelihood ratios of SIRS for more than 3 days and DIC on day 1 for predicting MODS after trauma were 6.25 and 11.6, respectively, and that DIC and sustained SIRS were also significantly associated with high mortality [122]. Stepwise logistic regression analyses and multiple regression analyses with the stepwise method showed that the DIC scores immediately after trauma were independent predictor of massive transfusion and death of trauma patients [24, 25]. A multicenter prospective study confirmed that the area under the receiver operating characteristic curve showed significant performance of DIC score immediately after trauma for predicting MODS, massive transfusion, and patient death [123]. Therefore, irrespective of phenotypes, DIC is a leading cause of MODS and death, and the DIC score has a good performance for predicting poor prognosis in trauma patients. Furthermore, DIC has been recognized as an independent predictor of MODS and death regardless of underlying disorders [1].

### 33.6.1 Microvascular Thrombosis

Microthrombosis after trauma, including iTBI, has been well established [28, 124]. In 1969, McKay reviewed DIC in trauma and reported that a tissue examination of the disease revealed either or both platelet or fibrin thrombi in the arterioles, venules, and capillaries of a variety of organs such as the brain, pituitary gland, lungs, liver, kidneys, adrenal glands, and gastrointestinal tracts [16]. Sevitt et al. [125] showed thrombi formation in the lungs of one patient who died within a few hours after trauma, a stage they called acceleration of fibrinolysis, which equals a period of DIC with a fibrinolytic phenotype [13]. They further confirmed frequent capillary microthrombosis within 3 h (24.4%) and during the next 9 h (37.9%) after injury in trauma patients. Within 48 h of injury, a total of 66.7% autopsied patients revealed thrombi formation [126]. In addition, many studies have produced the evidence supporting microvascular thrombosis in severe trauma [127, 128], in iTBI [129] and in DIC associated with such trauma [40, 130]. A study of iTBI comprising 88% of patients diagnosed as DIC demonstrated that large microthrombi were more commonly observed in autopsy in patients who died immediately after iTBI and that in addition to the brain/spinal cord, remote organ microthrombi formation such as in the liver, lungs, kidneys, pancreas, pituitary gland, thymus, and intestine was frequently observed [130]. The results clearly support the notion that coagulofibrinolytic changes in iTBI are not markedly different from those in trauma patients without head injury [131].

Microvascular thrombosis reduces oxygen delivery to cells and tissues, leading to MODS. Many clinical, experimental, and autopsy studies showing close correlations between microvascular thrombosis and tissue injury in many vital organs, including the brain, lungs, liver, and kidneys, support this theory [74]. However, microvascular thrombosis alone does not explain the pathomechanisms of MODS in DIC [132]; the bidirectional interplay between coagulation and inflammation should also be acknowledged. Pro-inflammatory cytokine-induced neutrophils and endothelial interactions and PAR-mediated amplification of coagulation and inflammation are important for MODS in DIC. TNF-α- and IL-1-induced thrombin formation upregulates P-selectin and induces the expression of E-selectin on the endothelium and L-selectin on the neutrophils, initiating neutrophils and endothelial interactions, and further promoting the expressions of intercellular adhesion molecule-1 (ICAM-1) and vascular cell adhesion molecule-1 (VCAM-1) on the endothelial cells

[54–56, 133]. As a result, activated neutrophils adhering to endothelial cells secrete elastase, myeloperoxidase, and reactive oxygen species, leading to endothelial injury, which promotes thrombin generation and fibrin thrombosis, thus causing MODS [54, 58, 74, 134]. The activation of neutrophils and endothelial injury associated with MODS and the higher mortality rate in post-trauma DIC than in non-DIC patients has been confirmed [69, 70]. Although trauma-related studies are lacking, PARs, especially PAR1, PAR2, and PAR4, contribute to the development of MODS in sepsis through a vicious cycle of inflammation and fibrin thrombosis [73, 74]. Taken together, these findings suggest that microvascular thrombosis associated with endothelial injury is a primary cause of MODS in DIC.

### 33.6.2 Histones and NETs

In addition to microvascular thrombosis associated with neutrophil activation-induced endothelial injury, DAMPs, especially histones, and NETs are now considered a major pathogenesis of MODS both in trauma and sepsis, especially in patients complicated with DIC [76–79, 84, 135]. In clinical settings, histones and NETs are involved in the development of DIC [136–138], MODS [139–141], and high mortality [138, 142] both in trauma and sepsis. Furthermore, experimental studies have shown that histones can cause brain, cardiac, lung, liver, and renal injuries [50, 78, 84].

The pathomechanisms of MODS in DIC caused by histones and NETs can be attributed to their pro-inflammatory, procoagulant, antifibrinolytic effects as well as endothelial injury associated with insufficient anticoagulant systems [78]. In addition to these indirect mechanisms, histone-mediated direct cellular injuries are deeply involved in the development of MODS. Sera from patients with high levels of histones showed a reduced viability of cells derived from the heart, lung, liver, and kidney as well as cultured endothelial cells [141]. A previous study showed the histone-induced promotion of $Ca^{2+}$ influx without intracellular $Ca^{2+}$ mobilization [143]. However, histones bind to endothelial cells and cardiomyocytes, and then induce $Ca^{2+}$ influx and overload with consequent pore formation, leading to endothelial injury and cardiac dysfunction [50, 140]. In cecal ligation and puncture models of sepsis, the accumulations of histones and neutrophils was observed in lungs, liver, kidneys, and spleen suggesting NETs formation [144]. Taken together, these findings indicate that histones and NETs as a source of histones synergistically cause MODS and DIC both in indirect and direct ways and affect the outcomes of the trauma and sepsis patients. These pathomechanisms in DIC are shown in Fig. 33.6 [78].

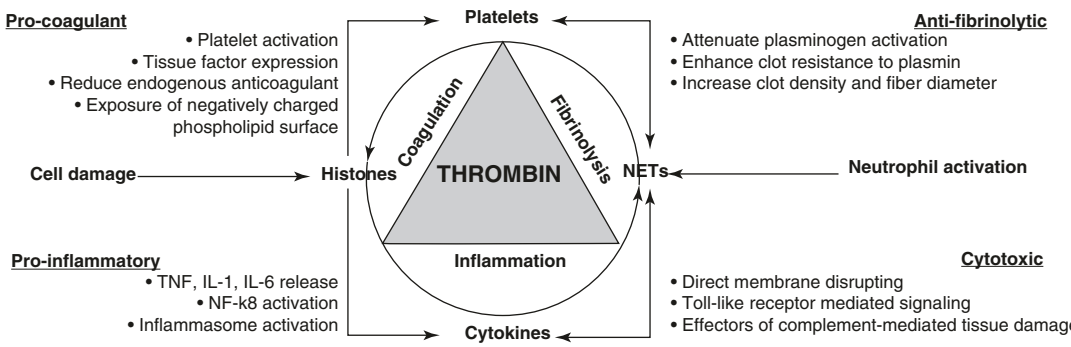



**Fig. 33.6** Bidirectional interplays between histones and NETs in DIC. Histones and NETs as a source of histones synergistically induce inflammation, platelet and coagulation activation, insufficient anticoagulation control, inhibition of fibrinolysis, and cytotoxic effects on cells. Thrombin generation as a result of these processes plays a central role in the cross talk between inflammation and coagulofibrinolytic changes. *DIC* disseminated intravascular coagulation, *NETs* neutrophil extracellular traps. (Modified with permission (Creative Commons Attribution International License) [78])

## 33.7 Management

In the ICU, trauma patients suffer from DIC due to two conditions; trauma itself-induced DIC and complicated sepsis-induced DIC. Because DIC with a fibrinolytic phenotype continues only for a few hours after injury and then progresses to a thrombotic phenotype [13, 42], a majority of DIC diagnosed in the ICU are considered to be the thrombotic phenotype. Whether the etiology involves trauma or sepsis, the same managements approach is applied to thrombotic phenotype DIC [1]. The following descriptions are based on the findings of studies on sepsis; however, findings can also be applied to the management of DIC in severely injured trauma patients in the ICU.

### 33.7.1 Rationale

#### 33.7.1.1 Why

Innate immune, inflammatory, and coagulofibrinolytic responses maintain the body's homeostasis against the insults, such as trauma and sepsis. However, if an insult is sufficiently severe, these physiological responses transform into pathological dysregulated inflammatory and coagulofibrinolytic responses (namely DIC), which affects the patient's outcome due to the disturbance of homeostasis by the development of MODS (Fig. 33.7). The failures of all randomized controlled trials targeting SIRS [3] led to the understanding that bidirectional interplay between innate immunity, inflammation, and coagulation is key to the improvement of the outcome of critical illnesses [4, 43, 44]. In addition, the need to target not only pathological responses but also all components (including the insult itself and MODS) affecting the outcome as a whole is now recognized worldwide. For these reasons, DIC as pathological responses, as well as the insult itself, such as trauma, and MODS need to be treated simultaneously in order to improve a patient's outcome [1].

#### 33.7.1.2 To Whom

Megatrials of anticoagulants, activated protein C and antithrombin, for all populations of sepsis have failed [145, 146]. Following these failures, substantial evidences has been accumulated regarding the actual target patient population. Subgroup analyses of these megatrials have shown that anticoagulants are effective only against sepsis-induced DIC [147–149]. Following these publications, knowledge concerning immunothrombosis progressing to DIC has spread worldwide, promoting the understanding that ambiguous treatment with anticoagulants at the stage of immunothrombosis may deteriorate the body's physiologic responses [48]. Furthermore, a meta-analysis and systematic reviews of randomized controlled trials for anticoagulant therapy in sepsis clearly have shown that the specific target populations are neither whole sepsis patients nor patients diagnosed as "coagulopathy" but patients with a definite diagnosis of DIC [150, 151]. Therefore, the treatment target of anticoagulants therapy is definitively diagnosed DIC [1].

Post hoc analyses of the megatrials showed that anticoagulants have high degree of effectiveness in patients with high risk of death as evaluated by the Acute Physiology and Chronic Health Evaluation II (APACHE II) score, Sequential Organ Failure Assessment (SOFA) score, and Simplified Acute Physiology Score II (SAPS II) [152, 153]. In systematic reviews and meta-analyses for anticoagulants, meta-regression analyses confirmed significant negative correlations between the effect size of anticoagulant therapies and baseline mortality rates in individual studies, suggesting that the beneficial effects of anticoagulants increase with increasing baseline risk [154, 155]. A multicenter cohort study further proved that anticoagulant therapy was associated with a better outcome according to the deterioration of both DIC scores and APACHE II scores [156] (Fig. 33.8). The second key point concerning the target population in addition to a diagnosis of DIC, therefore, is disease severity, and a SOFA score of 13–17 or APACHE II score of 24–29 may be the therapeutic ranges [157].

The third key point concerns heparin administration. Concomitant heparin use with anticoagulants consistently induced the deterioration of the drug effects and was associated with bleeding

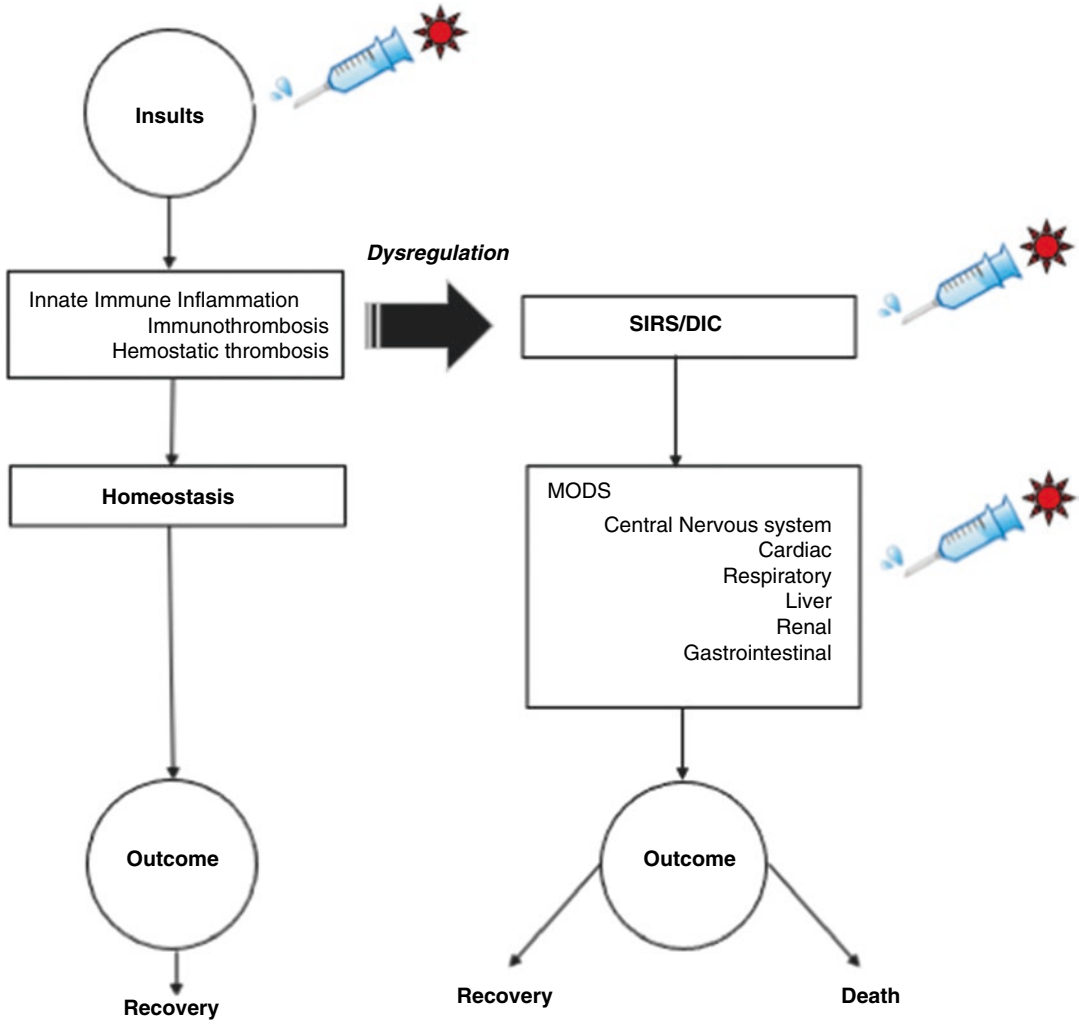


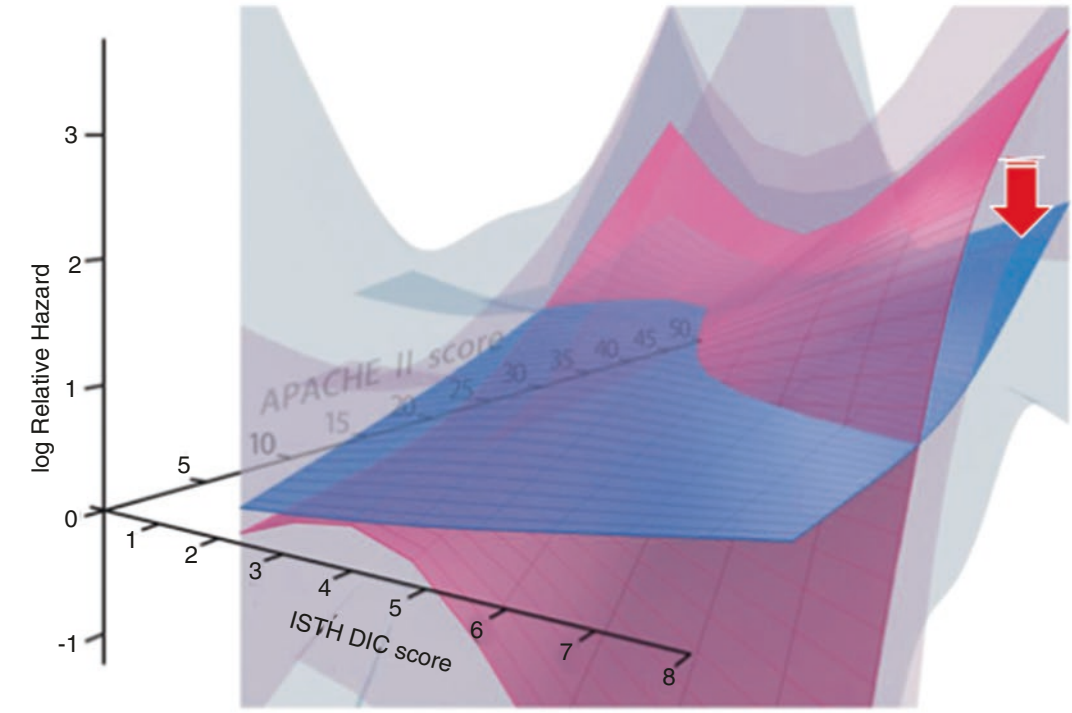

**Fig. 33.7** Innate immune inflammation, and coagulation and fibrinolysis maintain body homeostasis via immunothrombosis and hemostatic thrombosis against the insults. However, if the insult is sufficiently severe, physiological body responses become dysregulated and pathological SIRS and DIC develop, giving rise to MODS, which affects the patient's outcome. To improve the outcome, both the insult and dysregulated inflammatory and coagulofibrinolytic responses, namely SIRS and DIC need to be treated simultaneously. In addition, artificial organ supports, such as a ventilator, renal replacement therapy, etc., are also needed. *DIC* disseminated intravascular coagulation, *MODS* multiple organ dysfunction syndrome, *SIRS* systemic inflammatory response syndrome

complications [158, 159]. The concomitant use of anticoagulants for DIC and a prophylactic dose of heparin for venous thromboembolism should therefore probably be avoided.

Taken together, these findings indicate that the treatment targets are critically ill patients with DIC and a high trauma severity without concomitant heparin use.

#### 33.7.1.3 When

Both the ISTH and JAAM recommend conducting repeated evaluation of DIC scores for the diagnosis and subsequent treatments [6, 22]. Nobody object to the treatment of patients with definitively diagnosed DIC with high DIC scores and high prognostic scores, such as SOFA and APACHE II. However, for patients only sus-



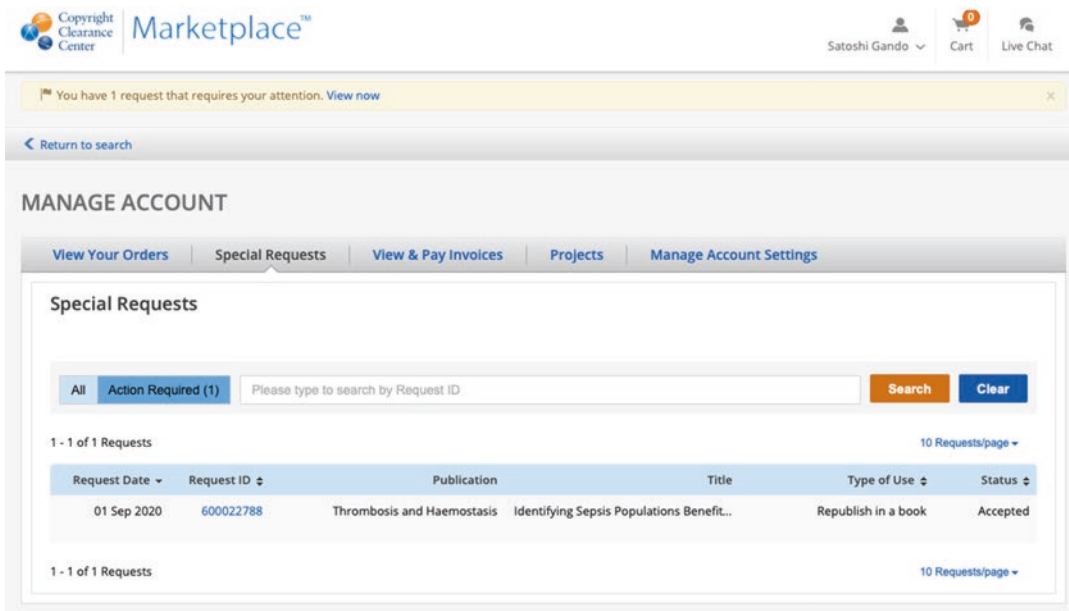




**Fig. 33.8** A three-dimensional chart showing the log-transformed relative hazard ratios with 95% confidence intervals (gray plate) for hospital mortality of the ISTH DIC scores and APACHE II scores with (blue plate) and without (pink plate) anticoagulant therapies. The red arrow indicates the reduction in hazard ratios at the most severe subset in both scores. The result suggests that anticoagulant therapy may be beneficial in patients with DIC and a high disease severity. *APACHE II* Acute Physiology and Chronic Health Evaluation II, *DIC* disseminated intravascular coagulation, *ISTH* International Society on Thrombosis and Haemostasis. (Reprinted with permission [156])

pected of having DIC or with low DIC scores, the repeated calculation of the DIC score is necessary. Continuous or worsening of the coagulation score on the first day of sepsis was associated with an increased risk of MODS and mortality rate [160]. A significantly lower survival probability in patients with newly developed DIC and persistent DIC than in those without DIC or those whose DIC improved from days 0 to 3 after the diagnosis of sepsis was repeatedly confirmed [161, 162]. Odds ratios after adjusting for potential confounders of DIC for the association of DIC with the development of MODS and death were consistently higher on day 3 after the diagnosis of DIC than on day 0 [162]. The results of these studies support the importance of the repeated evaluation of DIC scores for making treatment decisions and predicting the outcome of the patients. Taken together, these findings suggest persistent or worsening DIC score is confirmed, then it is time to start DIC treatment.

## 33.8 Underlying Disorders

The ISTH proposed the concept of controlled and uncontrolled DIC [6]. The endothelial regulatory network is temporarily activated and overridden under condition of controlled DIC, and this event is quickly reversed once the underlying conditions are removed or treated, i.e., transfusion reaction or abruptio placenta. Uncontrolled DIC occurs when the regulatory network becomes insufficient (TFPI, antithrombin, protein C, thrombomodulin) or injured (endothelial cells), i.e., trauma and sepsis. As defined, controlled DIC can be resolved by the resolution of the underlying disorder; however, in uncontrolled DIC, simultaneous treatments of both DIC and the underlying disorders, such as trauma, is always required [1, 6, 163].

## 33.9 Substitution Therapy

Consumption coagulopathy recognized as thrombocytopenia, low fibrinogen levels, and a prolonged prothrombin time and APTT, is more prominent in trauma-induced DIC than in septic DIC due to the synergistic effects of consumption, loss by critical bleeding, and effects of dilution. Hayakawa et al. [164] showed that the platelet counts, prothrombin time, APTT, and fibrinogen reached the critical thresholds for massive bleeding faster in DIC patients than in non-DIC patients during the first 24 h after trauma. Many studies focusing on trauma found that in addition to RBC, DIC patients more frequently needed the transfusion of platelet concentrates, fresh-frozen plasma (FFP), and fibrinogen concentrate than in non-DIC patients [13, 25, 117, 123, 164]. To stop both trauma-induced critical bleeding and DIC-evoked oozing-type bleeding, substitution therapy using platelet concentrate, FFP, or fibrinogen concentrate is required in DIC after trauma. The critical thresholds for initiating each type of substitution therapy are mentioned in the ISTH guidance [163].

Caution should be practiced when the prothrombin complex concentrate (PCC) is applied as substitution therapy [1, 163]. In addition to a lack of essential coagulation factors, such as FV, VIII, and FXIII, PCC does not contain any or contains a very small amount of anticoagulation factors, such as antithrombin, protein C, and protein S [1, 163]. As a result, PCC increases thrombin generation accompanied by thrombocytopenia and a prolonged prothrombin time, potentially inducing or aggravating thromboembolic complications and DIC [165–168]. A careful check of the constituents of PCC at each ICU is required.

### 33.9.1 Anticoagulants

#### 33.9.1.1 Heparin

A recent trend in anticoagulant use for DIC is that anticoagulant factor concentrates is preferred to unfractionated heparin (UFH) and low-molecular-weight heparin (LMWH). Thus far, no robust clinical study on heparin use for DIC showing an improvement of patient's outcome has been published. The ISTH guidance recommends a therapeutic dose of heparin be administered to DIC patients, preferring LMWH to UFH based on the results of a small randomized controlled trial [163, 169].

#### 33.9.1.2 Anticoagulant Factor Concentrates

The ideal anticoagulant factor concentrates to use for the treatment of DIC has been controversial. After the withdrawal of activated protein C from the global market, we now have two anticoagulation factor concentrates available for use; antithrombin and recombinant human soluble thrombomodulin (rhsThrombomodulin) [170]. After the publication of the ISTH guidance recommending the administration of antithrombin or rhsThrombomodulin for DIC (potentially recommended, needs further evidence) [163], many valuable studies on these drugs have been published.

***Antithrombin*** A systematic review and meta-analysis concluding that there was no evidence antithrombin improves the mortality of patients with sepsis or DIC included serious flaws in their analysis of the largest population of the KyberSept trial, due to the fact that in that analysis, they did not select DIC patients [146, 171, 172]. Post hoc analyses of the KyberSept trial showed that antithrombin improved the outcome without increasing bleeding side effects in patients with DIC at high risk of death and without concomitant use of heparin [149, 153, 159]. Although the KyberSept trial used an extremely high dose of antithrombin, evidences supporting a supplementary dose of antithrombin administration for septic DIC has been published. A supplementary dose of antithrombin improved the DIC score and doubled the DIC recovery rate without any risk of bleeding [173]. Using a nationwide database, Tagami et al. showed that antithrombin was associated with a significant reduction in mortality rates among DIC patients [174, 175]. In addition, a meta-analysis concerning antithrombin for sepsis-induced DIC repeatedly confirmed a significant reduction in the mortality rate [176]. Using antithrombin for DIC is promising, so a multinational prospective randomized trial concerning the efficacy of a supplementary dose of antithrombin for DIC needs to be conducted [176, 177].

***rhsThrombomodulin*** A phase III randomized double-blind controlled trial showed the superiority of rhsThrombomodulin to heparin for improving DIC and alleviating bleeding symptoms in patients with infection or hematological malignancies [178]. Following this trial, a phase IIb study restricting participants to those with sepsis and suspected DIC was conducted, which encourage us to conduct further trials on the rhsThrombomodulin in sepsis-associated coagulopathy including DIC [179]. This phase IIb study identified three factors that were associated with a reduced mortality among septic patient; the prothrombin time international normalized ratio (PTINR) >1.4, thrombocytopenia, and dysfunction in at least one organ. However, a phase III trial of rhsThrombomodulin failed to reduce the mortality in patients with sepsis-associated coagulopathy diagnosed with using above-mentioned three factors [180]. Post hoc analyses showed three issues likely associated with the negative results; concomitant heparin use, patients no longer meeting the inclusion criteria for platelet counts and PTINR at the starting point of the drug, and no stratification of the patients by thrombin generation levels [180, 181]. Subgroup analyses of the phase III trial after adjusting for these three factors showed a significant reduction in the mortality rates in rhsThrombomodulin group compared with the control group [180, 182–184]. The new terms "sepsis-associated coagulopathy" and "sepsis-induced coagulopathy" cooperating three items identified in phase IIb trial were established and rhsThrombomodulin therapy for patients who met these criteria showed a reduction in mortality [185]. Further study will need to be performed in order to confirm the positive effect of rhsThrombomodulin on these two coagulopathies and DIC.

### 33.9.2 Antifibrinolytics

Antifibrinolytic agents are contraindicated in DIC with the thrombotic phenotype [1, 163]. However, antifibrinolytics are considered for use in DIC with the fibrinolytic phenotype diagnosed at a very early stage of trauma and in cases with acute promyelocytic leukemia [1, 163]. The CRASH-2 trial showed a reduction in the risk of death in bleeding trauma patients who used

tranexamic acid within 3 h after injury [186, 187]. The coagulofibrinolytic changes in iTBI patients are the same as those in patients without brain injury, so, DIC immediately after iTBI also belongs to fibrinolytic phenotype [33, 131]. The CRASH-3 trial demonstrated significant reductions in head-injury-related death due to the administration of tranexamic acid, especially in patients with mild-to-moderate head injury and those who received early tranexamic acid treatment [188].

The CRASH-2 and CRASH-3 were not intended to include DIC patients; however, the mechanisms underlying the effects of tranexamic acid on the fibrinolytic systems and restricted effective timeframe within a few hours after injury support the notion that tranexamic acid may improve excessive bleeding in DIC patients with a fibrinolytic phenotype at very early stage of trauma and in those with iTBI.

### 33.9.3 Histones and NETs

Histones and NETs are promising targets for improving DIC, organ dysfunction, and the outcome. Some experimental studies have shown that anti-histone antibody ameliorated histone-induced IL-6 release, thrombin generation, endothelial injury, organ dysfunction, and survival probability [50, 76, 140]. rhsThrombomodulin binds to histones and was shown to improve histone-induced platelet aggregation and thrombocytopenia, microvascular thrombosis, organ dysfunction, and the survival probability [84]. Nonanticoagulant heparin prevented the cytotoxic effects of histones and improved the mortality rates in mouse model of sepsis and sterile infection [189]. It further attenuated the histone-induced pro-inflammatory cytokines (IL-6, IL-8) production, tissue factor generation, and C3a formation in a whole blood model [190]. Peptidylarginine deiminase 4 (PAD-4) is a key protein for NETs formation (NETosis) as a citrullinating enzyme of arginine residues of histones that results in chromatin decondensation and the release of neutrophil DNA (NETs) [191]. In addition, PAD4 is now known to regulate pathological thrombosis [191]. Therefore, PAD4 inhibitors prevent the formation of NETs and thrombosis. Already formed NETs DNA could be degraded using DNase. Aside from rhsThrombomodulin, these drugs are still in the experimental phase; however, their potential efficacy is promising for DIC treatment [78, 191].

## 33.10 Conclusions

DIC is defined as dysregulated inflammatory and coagulofibrinolytic responses to the insults and is deeply involved in the outcome of critically ill patients due to the development of bleeding and MODS. DIC involves systemic thrombin generation, insufficient anticoagulation pathways, and increased fibrinolysis (followed by its impairment) in association with endothelial injury. DAMPs, especially histones released from injured cells and activated neutrophil-formed NETs containing neutrophil DNA, histones, and elastase are considered the main pathomechanisms involved in DIC. Histones and NETs synergistically induce systemic inflammation, platelet and coagulation activation, dysfunction of anticoagulant systems, and inhibition of fibrinolysis, leading to microvascular thrombosis. Histone-induced direct cellular injury, including that of endothelial cells, as well as the reduction in oxygen delivery due to microvascular thrombosis give rise to MODS. Platelet dysfunction, consumption coagulopathy, and hyperfibrin(ogen)olysis induce oozing-type of bleeding. DIC can be diagnosed using a diagnostic scoring system. Definitively diagnosed DIC with a high disease severity and persistent or worsening DIC is the true target of the treatment with anticoagulant factor concentrates in trauma patients admitted to the ICU.

Even today, it is important to keep in mind the fact that DIC equals a sign that “Death Is Coming” [192].

**Key Concept**

- DIC, defined as dysregulated inflammatory and coagulofibrinolytic responses to an insult and known as thrombohemorrhagic disorder, markedly affects a patient's outcome due to microvascular thrombosis-induced organ dysfunction and critical bleeding.

**Take Home Messages**

- Trauma is a leading cause of DIC.
- Bidirectional interplays among innate immunity, inflammation, and coagulation play important roles in the pathophysiology of DIC.
- Histones, as well as NETs involved in inflammation, activation of coagulation, impairment of anticoagulation controls, and the inhibition of fibrinolysis, lead to microvascular thrombosis and endothelial cell injury.
- Microvascular thrombosis- and endothelial cell injury-caused MODS and consumption coagulopathy-induced critical bleeding affects a patient's outcome.
- To improve a patient's outcome, the simultaneous treatments of trauma-itself, DIC, and MODS is necessary.

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# 34 Early ICU Management of Polytrauma Patients Who Develop Sepsis

Frederick A. Moore

**Learning Objectives**

- Discuss the evolving definitions of sepsis.
- Provide a historic perspective on evidence-based care of sepsis.
- Discuss the current Surviving Sepsis Campaign evidence-based guidelines as they pertain to the early ICU management of sepsis in polytrauma patients.

## 34.1 Introduction

Polytrauma patients often experience a dysregulated immune response with an injurious systemic inflammatory response syndrome (SIRS) that can cause early multiple organ failure (MOF) independent of infection [1]. This response is also associated with delayed immunosuppression that increases the risk of nosocomial infections. One third of these late infections cause sepsis which can worsen early MOF or trigger late MOF and thus increase hospital mortality, length of hospital stay as well as long-term functional disability [2, 3]. The diagnosis of sepsis is especially challenging in polytrauma patients. The early clinical signs of sepsis are subtle and confounded by the ongoing SIRS and organ dysfunctions induced by the initial traumatic insult. Both trauma and sepsis activate innate immunity through similar mechanisms and result in similar SIRS and organ dysfunctions [1, 4]. Additionally, the recent evolution in the definition of sepsis from the Sepsis-2 to the Sepsis-3 criteria adds to the confusion [5, 6]. Regardless of the definition, over the past 15 years studies have consistently shown that performance improvement (PI) programs that optimally implement the Surviving Sepsis Campaign (SSC) evidence-based guidelines (EBGs) "sepsis bundles" of care substantially reduce hospital mortality [7–9]. Similarly, the author and his colleagues at two US tertiary medical centers (first in Houston, TX; next in Gainesville FL) developed and refined an electronic medical record (EMR)-based sepsis screening process coupled with computerized clinical decision support applications to implement the SCC EBGs in surgical and trauma ICU patients [10–14]. In both experiences, these PI programs reduced in hospital mortality after sepsis/septic shock from over 35% to less than 15%. In the most recent series, in hospital mortality was 10% with a surprisingly low early mortality (<14 days) of <5% [3]. Based on this ongoing experience, this chapter will: (1) discuss the evolving definition of sepsis, (2) provide a historic perspective for evidenced-based sepsis care, and (3) focus on the current SSC EBGs as it per-

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tains to early ICU management of sepsis in polytrauma patients [15].

## 34.2 The Evolving Definition of Sepsis

Roger Bone first defined the "sepsis syndrome" in 1989 [16]. This was followed by an international consensus conference in 1991 that developed the concept and criteria for SIRS to describe how a local infection can lead to injurious systemic inflammation which (if not interrupted) progresses from sepsis to severe sepsis to septic shock leading to refractory shock, MOF, and death [17]. This conceptual framework was widely accepted and served as the foundation for daily clinical practice, ongoing research related to the underlying pathobiology and clinical trials testing novel anti-SIRS interventions. A second international consensus conference was convened in 2001 to revisit this topic based on new advances in knowledge [5]. This group developed the PIRO (predisposition, insult, response, and organ dysfunction) system to better describe sepsis progression and refined the previous definitions sepsis into three categories is (now referred as the Sepsis-2 criteria): (1) sepsis = SIRS plus suspected infection, (2) severe sepsis = sepsis plus organ dysfunction, and (3) septic shock = sepsis plus hypotension despite adequate fluid resuscitation. Although widely accepted, these definitions were problematic. First, the SIRS criteria proved to be too sensitive. This is especially true after polytrauma where ongoing tissue injury can elicit a very similar innate immune response that causes SIRS as is seen with microbial sepsis [1, 4]. A second problem was the variability in how organ dysfunctions and septic shock were defined. A third international consensus conference was convened in 2016 to address these and other issues [6]. This group developed the new Sepsis-3 criteria. Of note, SIRS and the category of severe sepsis were eliminated. As a result, there are now only two categories: (1) sepsis is defined as suspected or documented infection plus an acute increase of two or more Sequential Organ Failure Assessment (SOFA) points as a proxy for organ dysfunction. Septic shock is defined by the clinical criteria of sepsis and vasopressor therapy needed to elevate mean arterial pressure ≥65 mmHg and lactate >2 mmol/L despite adequate fluid resuscitation. There is ongoing debate concerning the pros and cons of these new definitions [18–21]. One notable problem is that the Sepsis-3 definitions eliminate the concept that early sepsis starts without organ dysfunctions. This minimizes the importance of early recognition and treatment of infections before organ dysfunction when certain interventions (i.e., antimicrobial agents and source control) are more effective interrupting the underlying pathobiology. Ideally, patients at risk for sepsis should be identified and treated before SIRS becomes severe enough to cause organ dysfunction.

## 34.3 Historic Perspective of Early Evidence-Based Sepsis Care

In 2001, Rivers et al. published a single center prospective randomized trial (PRT) testing early goal directed therapy (EGDT) for patients presenting in the emergency department with severe sepsis and septic shock [22]. The EGDT protocol involved resuscitation through a series of four "goals" that included (1) mean arterial pressure (MAP ≥65 and ≤90 mmHg), (2) central venous pressure (CVP of 8–10 mmHg), (3) central venous hemoglobin oxygen saturation ($ScvO_2 \geq 70\%$), and (4) hematocrit level (≥30%). EGDT compared to "usual standard care" resulted in a dramatic reduction in hospital mortality from 46% to 30%. Of note, the "usual standard care" was poor compared to today standards. However, this landmark publication persuasively focused international attention on early recognition and rapid delivery of protocolized care for sepsis. This was followed in 2004 publication of the SSC EBG (which was revised in 2008, 2012, and 2016 based on advances in knowledge) [15,

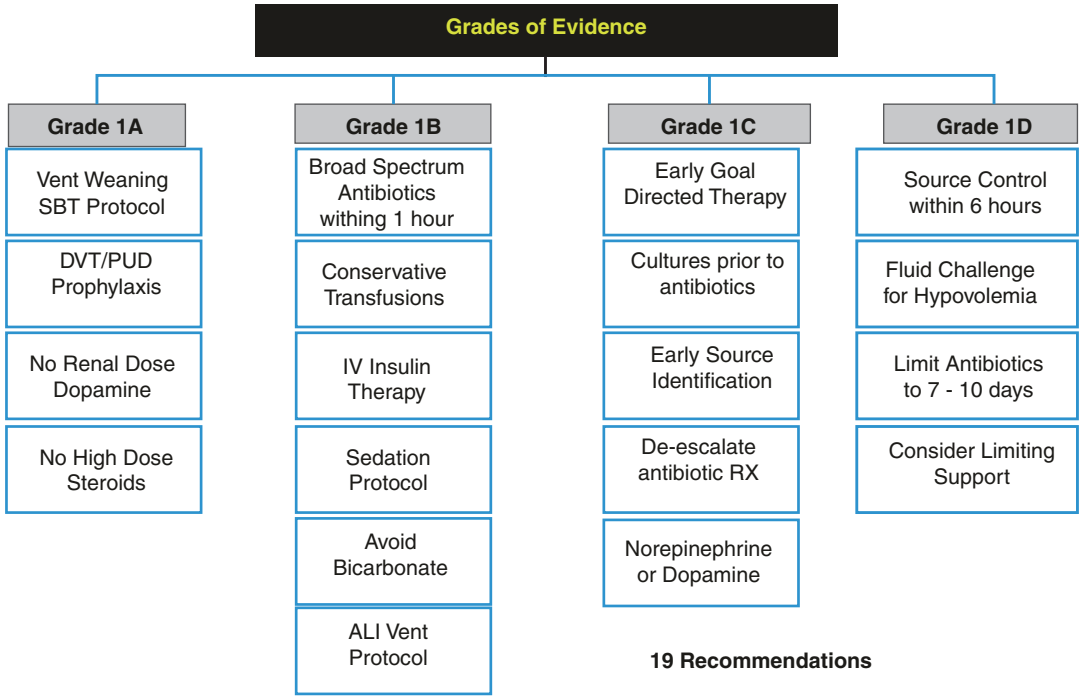


**Fig. 34.1** Surviving Sepsis Campaign guidelines 2004

23–25]. This represented a significant contribution in refining and grading the evidence, but optimal implementation has been challenging for a variety of reasons. The most notably was that it offered 19 recommendations (most based on low grade evidence) that were difficult for bedside clinicians to remember and prioritize (see Fig. 34.1). Additionally, EGDT became an integral component of the early (6 h) SSC "sepsis bundle" of care. However, on further evaluation in three large multicenter PRTs (ProCESS, ARISE, ProMISe), EGDT was shown to offer no survival benefit compared to the much improved "usual standard care," but resulted longer duration of ICU stay and increased use of vasopressors [26–28]. As a result, EGDT has been removed from the 2016 SSC EBG. Regardless of the challenges of implementing SSC EBGs and its evolving recommendations, over the past 15 years numerous studies have consistently shown that PI programs that provide early care consistent with the SCC EBGs substantially reduces early mortality [7–14].

## 34.4 Current SSC EBG Care of Sepsis as It Pertains to Polytrauma Patients

Based on these ongoing PI efforts, the following is a summary of key interventions in early management of sepsis as they pertain to polytrauma patients who develop sepsis.

**Sepsis Screening**: The early identification sepsis remains a significant challenge. However, if patients are allowed to progress from sepsis into septic shock, their mortality becomes prohibitively high (>30%) despite aggressive interventions. The signs and symptoms of sepsis are nonspecific, particularly in the early phases of sepsis. Because healthcare providers focus on multiple priorities and tasks, early signs of sepsis are often missed. In the trauma patient, some of the early signs of sepsis are attributed to other common problems. For example, altered mental status is often associated to the administration of narcotic pain medication or

sundowning, particularly in the elderly patient. Oliguria is often attributed to under resuscitation. Although many nurses notify physicians of hyperthermia, hypothermia, which is also an early sign of sepsis, is often not reported. Likewise, acute hypoxia spurs a workup for pulmonary embolism. However, it is much more likely to herald the onset of sepsis or septic shock. Considering these factors, the benefit of routine, accurate screening of patients for sepsis makes complete sense. Unfortunately, the literature offers confusing data concerning different screening tools [29–31]. Most perform poorly in early identification of sepsis. The most recent method being promoted is quick SOFA (qSOFA) score (range, 0–3 points) with one point each for systolic hypotension (≤100 mmHg), tachypnea (≥22/min), or altered mentation.

As an alternative approach recognizing that trauma and sepsis induce similar SIRS, we developed and refined a two-step process [10–14]. The first step is to frequently monitor (q 4 h) for signs of significant physiologic derangement through the EMR. We initially used a SIRS Severity Score and later we refined the Modified Early Warning Score (MEWS) by include most recent white blood cell count and changes in mental status into what we call the MEWS-Sepsis Recognition Score [(SRS)—see Fig. 34.2] [10, 13]. When a patient develops a MEWS-SRS >5, the bedside nurse confirms the data and notifies a physician extender trained to recognize sepsis to perform the second screening step. The second step involves using a check list approach to assess the patient for possible sites of infection. If a potential site of infection is found, the physician is notified and order sets are implemented to initiate the sepsis protocol. Figure 34.3 depicts a recent 12-month audit of screening experience in a 24-bed trauma/emergency surgery ICU. There were a total 686 MEWS-SRS-positive patients (~57 per month) who are screened to possible site of infection. Of these 209 (31%) patients (~17 cases/month) were thought to have an infection. They were diagnosed as being septic and entered into sepsis protocol. After 24–48 h,

**Modified Early Warning Score (MEWS) – Sepsis Recognition Score (SRS)**

| Score | 3 | 2 | 1 | 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|
| Temperature | < 32 | < 35 | < 36 | 36-38.4 | 38.5-38.9 | 39-40.9 | ≥ 41 |
| Heart Rate | < 40 | 40-44 | 45-50 | 50-100 | 101-110 | 111-129 | ≥ 130 |
| Respiratory Rate | ≤ 7 | 8 | 9 | 10-14 | 15-20 | 21-29 | ≥ 30 |
| Systolic Blood Pressure | ≤ 70 | 71-80 | 81-100 | 101-160 | 161-180 | 181-199 | ≥ 200 |
| Change in Mental Status # | No response Coma | Stupor Responds to noxious stiumuli | Lethargic Responds to voice or tap | Alert Calm Cooperative | Mildly agitated confused anxious | Very agitated Requires restraint | Agtated and Danger to self and others |
| Lastest WBC | <1 * | 1-2.9* | | 3-14.9 | 15-19.9 | 20-39.9 | ≥ 40 |

# Change threshold score when patient is receiving medication to induce sedation or when patient has preexisting neurologic injury (e.g. TBI, stroke)

* Non-oncologic reasons

**Fig. 34.2** Modified early warning score (MEWS)—Sepsis recognition score (SRS)

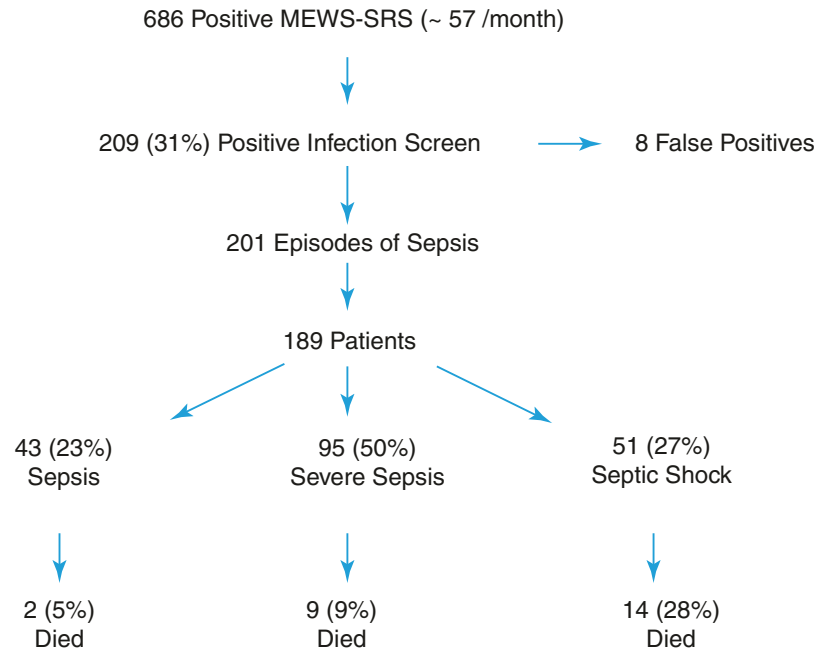


**Fig. 34.3** Sepsis screening in trauma/emergency surgery ICU (12 months)

8 patients (4%) sepsis protocol patients were proven to be false negatives. However, these patients have alternative problems (such occult bleeding, pancreatitis, new onset atrial fibrillation) causing abnormal physiology that warrant attention and the initial sepsis interventions were not harmful. A breakdown of the 189 septic patients (nine had two episodes of sepsis, one had three episodes) by Sepsis-2 criteria revealed that a quarter designated as sepsis (with hospital mortality of 5%), half were designated as severe sepsis (hospital mortality 9%) and remaining quarter were designated as septic shock (hospital mortality 28%).

**Vascular Access and Monitoring**: Establishing a large bore peripheral intravenous (IV) line is a critical first step. In hemodynamically unstable patients, two IVs are optimal to simultaneously administer initial fluid resuscitation and multiple antimicrobial agents [32]. If peripheral IV access is not easily attainable and urgently needed, an interosseous (IO) access should be considered as a bridge to placement a central venous line (CVL) if vasoactive medications are needed or anticipated [33]. The CVL should be placed in the internal jugular (IJ) vein using full sterile precautions under ultrasound guidance to minimize complications. The subclavian (SC) is the next preferred site followed by the femoral vein. An arterial (A) line should be placed in patients with unresponsive hypotension. The use of noninvasive blood pressure monitoring often produces inaccurate measurements in shock and should not be used for titration of vasoactive medications. A Foley catheter is inserted to allow for close monitoring of urine output. Bladder pressures should be monitored in patients have required a large volume resuscitation to recognize intra-abdominal hypertension before the onset of overt abdominal compartment syndrome (ACS). A lines, CVLs, and Foley catheters use should be assessed daily and they should be removed as soon as their use is not required to minimize the risk of complications.

**Administer Broad-spectrum Antimicrobial agent(s)**: These should be administered after appropriate cultures have been collected but within 1 h of sepsis recognition. Studies have convincing shown that the time to administration is a critical factor in survival of patients presenting with sepsis [34]. Maintaining a supply of commonly used "workhorse" anti-

microbial agents on the wards and in the ICU can assist in the timely administration of these agents. The selection of antimicrobial therapy should take into account the patient's history of drug allergies, recent antimicrobial exposure, suspected source of infection, and hospital-specific antibiograms. When choosing empiric antimicrobial therapy, a few general rules should be applied. First, the initial antimicrobial coverage should be broad enough to cover all potential pathogens. Convincing evidence shows that administering inadequate initial antimicrobial coverage is associated with increased morbidity and mortality. Second, any antimicrobial that the patient has recently received should be avoided. Third, vigilant monitoring of culture data and de-escalation of the antimicrobial regimen based on culture results and sensitivities will reduce the risk of superinfection and the emergence of resistant organism. The link between early administration of antibiotics for suspected infection and antibiotic stewardship remains an essential aspect of high-quality sepsis management. If infection is subsequently proven not to exist, then antimicrobials should be discontinued.

Within the author's trauma/emergency surgery ICU, a multidisciplinary sepsis team has developed antimicrobial regimens based on suspected source of infection and the current institution-specific antibiogram. Of course, all potential sites should be considered, but the most likely site of infection in a polytrauma patients to cause sepsis (with attributable organ dysfunction) or septic shock are pneumonia and intra-abdominal infection. Table 34.1 depicts empiric antibiotics for pneumonia and intra-abdominal infections (other sites of infections not included in this table for brevity) and show (1) the preferred regimen and (2) the regimen for patients with severe β lactam allergies.

Unfortunately, the clinical diagnosis of pneumonia in polytrauma patients is very inaccurate. CXR abnormalities and the signs of SIRS are commonly present but may not be due to pneumonia. Therefore, in intubated patients bronchoscopic examination with bronchoalveolar lavage (BAL) is utilized [35]. If the presumptive diagnosis is pneumonia than the time of onset will dictate which agents to employ. For most early pneumonias (<5 days), the single agent ceftriaxone is used and vancomycin added if Gram-positive organisms seen on BAL Gram stain [36]. For most late pneumonia (≥5 days), a combination of cefepime and vancomycin are the initial agents. A second agent covering Gram-negative organisms from a different class (e.g., tobramycin) would be used in patients a high risk for multi-drug-resistant (MDR) pathogens or in those in septic shock [37]. In general, pneumonia are treated for 5 days and then reassessed [38]. If WBC and fever curve have not normalized, then treatment is extended for 7 days. In immunocompromised patients and those with specific MDR pathogens treatment is extended for 10 days.

In critically ill ventilated patients, it is easy to misdiagnosis pneumonia and thus when empirically treating pneumonia, other sources need to be considered. The most likely alternative infection to causes sepsis (with attributable organ dysfunction) is an intra-abdominal infection. The risk for this is high in trauma patients who have undergone a previous laparotomy especially those who had a hollow viscus injury. A discussion with the operating surgeon is important assessing this risk and computerized tomography scan of the abdomen/pelvis is the most informative diagnostic study. A combination of cefepime plus metronidazole is generally the initial empiric therapy. Vancomycin will be added for patients who have been in the ICU for a prolonged period and fluconazole will be added for those who had an upper GI perforation. Once source control (discussed below) has been accomplished duration of therapy is 4 days [39].

**Initial Fluid Resuscitation**: Crystalloid versus colloid resuscitation has been debated for decades [40]. Numerous clinical trials (analyzed by multiple meta-analyses) have not demonstrated a difference in important clini-

**Table 34.1** Empiric antibiotic selection for pneumonia and intra-abdominal infections. Other sites of infection not shown include urinary tract infection, central line, and wound/skin/soft tissue

| Indication | Antibiotic drug | Regimen | Duration |
|---|---|---|---|
| | 1. Preferred therapy<br>2. Severe β lactam allergy | (a) Monitor; adjust if renal dysfunction<br>(b) Kinetic monitoring | |
| Pneumonia | | | |
| Community acquired (CAP) | 1. Ceftriaxone + Azithromycin | 2 g IV q24h<br>500 mg PO/IV q24 | 5 days<br>3 days |
| | 2. Aztreonam + Azithromycin | (a) 2 g IV q8h<br>500 mg PO/IV q24 | 5 days<br>3 days |
| Early (<5 day) hospital acquired (HAP), healthcare associated (VAP), or aspiration pneumonia (not chemical pneumonitis) | 1. Ceftriaxone | 2 g IV q24h | 5 days |
| | 2. Aztreonam + Vancomycin | (a) 2 g IV q8h<br>(a, b) See nomogram | 5 days |
| Late (≥5 day) or [a]risk factors for multi-drug-resistant (MDR) pathogen HAP, HCAP, VAP, or aspiration pneumonia (not chemical pneumonitis) | 1. Cefepime + Vancomycin | (a) 2 g IV q8h<br>(a, b) See nomogram | 5 days then reassess—if WBC and fever curve have not normalized, then<br>7 days |
| | 2. Aztreonam + Vancomycin | (a) 2 g IV q8h<br>(a, b) See nomogram | 5 days then reassess—if WBC and fever curve have not normalized, then<br>7 days |
| Intra-abdominal | | | |
| Pseudomonas low risk | 1. Ceftriaxone + Metronidazole | 2 g IV q24h<br>500 mg IV q8h | 4 days after source control achieved |
| | 2. Aztreonam + Metronidazole + Vancomycin | (a) 2 g IV q8h<br>500 mg IV q8h<br>(a, b) See nomogram | |
| Pseudomonas high risk (previous hosp or broad-spectrum antibiotic exposure); (+) Pseudomonas culture result | 1. Cefepime + Metronidazole<br>OR<br>Pip/tazo<br>Can add vancomycin if MRSA risk factors are present | (a) 2 g IV q8h<br>500 mg IV q8h<br>(a) 3.375 g q6h<br>(a, b) See nomogram | 4 days after source control achieved |
| | 2. Aztreonam + Metronidazole + Vancomycin | (a) 2 g IV q8h<br>500 mg IV q8h<br>(a, b) See nomogram | |
| | 3. Aztreonam + Clindamycin | 2 g IV<br>600–900 mg | |

[a] Risk factors for MDR pathogens: antimicrobial therapy in preceding 90 days; current hospitalization ≥5 days; hospitalization ≥2 days in preceding 90 days; residence in nursing home or extended care facility; chronic dialysis within preceding 30 days; immunosuppressive disease or therapy

cal outcomes (i.e., pulmonary dysfunction and mortality). In the absence of any clear benefit and given the added expense of albumin, an initial bolus of crystalloids (1000 mL over 30 min) is administered as soon as possible after sepsis diagnosis. In patients with hemodynamic instability (systolic blood pressure <90 mmHg or a decrease of >40 mmHg) or when the serum lactate >4 mmol/L, the total initial recommended volume is 30 mL/kg. This volume has been observed to be the usual standard practice in the control groups in clinical trials [26–28]. Most patients will require more than 30 mL/kg of resuscitative fluid, but additional fluid should be given based on hemodynamic assessments that predict fluid responsiveness (discussed below). Historically, 0.9% sodium chloride (saline) was commonly used fluid (especially in medical ICUs); however, saline has been associated with a hyperchloremic metabolic acidosis and increases risk for acute kidney injury (AKI) as well as mortality [41]. In the trauma ICU patients, we prefer to use a balanced crystalloid solution (such as lactated Ringer's or Plasma-Lyte) [42, 43].

**Addition of Vasopressor Agents**: Restoring adequate perfusion pressure to the vital organs is a key first step in resuscitation. If mean arterial pressure (MAP) of ≥65 mmHg is not achieved after initial fluid resuscitation, then vasopressors should be started within the first hour. Increased MAP is thought to result in augmented tissue perfusion although the optimal threshold is unknown. Single center studies looking at MAPs higher than 65 mmHg have yielded variable improvements in physiologic endpoints but have not adequately studied clinical outcomes [44]. However, a recent multicenter trial that compared norepinephrine dose titration to achieve an MAP of 65 mmHg versus 85 mmHg found no difference in mortality at 28 days or 90 days [45]. Targeting an MAP of 85 mmHg resulted in a significantly higher risk of arrhythmias, but the subgroup of chronic hypertensive patients targeted the higher MAP had a reduced need for renal replacement therapy. The discussion of physiologic effects of different vasopressors or combined inotrope/vasopressors in septic shock is the beyond the scope of this chapter [46–48]. In brief, sepsis usually causes vasodilation associated with a high cardiac output (CO) and a low systemic vascular resistance (SVR). Therefore, initial vasopressor therapy should be targeted at restoring vascular tone. Norepinephrine is the preferred vasopressor agent for treatment of septic shock and should be administered through a CVL. It is primarily an alpha-receptor agonist that promotes widespread vasoconstriction to increase MAP and has little effect on heart rate or stroke volume. Norepinephrine is preferred over dopamine because it is more effective at reversing hypotension in septic shock and its use is associated with lower mortality. Dopamine increases MAP and CO, primarily due to an increase in stroke volume and heart rate. It can be very useful in patients with compromised ejection fraction but causes more tachycardia and arrhythmias. In septic shock patients who are adequately volume resuscitated and refractory to first-line vasopressors, the addition of vasopressin may be beneficial. Vasopressin is a stress hormone with vasoactive effects, and it is believed that septic shock patients have a relative deficiency of vasopressin [49]. The addition of vasopressin improves responsiveness to norepinephrine and potentially reduces the dose needed to maintain MAP [50, 51]. It is the author's current practice to initiate a vasopressin infusion at a rate of 0.03 U/min in patients requiring norepinephrine infusion at ≥15 mg/min. The dose of vasopressin should not increase because at higher doses it can decrease cardiac output as well as cause cardiac, digital, and splanchnic ischemia [52]. Finally, phenylephrine use is not recommended because clinical trial data of its use in sepsis are limited. It is pure α-adrenergic agonist that potential to produce splanchnic vasoconstriction [53].

**Addition of Inotropic Agents**: Although most patients with sepsis initially present with increased CO, a subset of patients will develop myocardial depression from sepsis. The exact

mechanism for this reversible myocardial dysfunction is still under investigation. For patients with suspected or known cardiac dysfunction, the addition of inotropic therapy is recommended. Dobutamine is the first-line agent for treatment of cardiac dysfunction in patients with sepsis [46, 53]. However, it will cause hypotension in hypovolemic patients. The management of patients with a poor CO in septic shock presents a unique challenge to the clinician because they require the titration of vasopressors and inotropic agents. In this subset of patients, a pulmonary artery catheter can be useful. This allows for the specific titration of vasopressors based on systemic vascular resistance and inotropic agents based on cardiac output. There is no evidence to support increasing CO to supranormal levels [54]

**Steroids**: The use of steroids for the management of sepsis has been debated for decades. The benefits of reducing early SIRS (with decreased organ dysfunctions) must be weighed against the risk of amplifying delayed immunosuppression (with increased secondary infections) and impairing wound healing (especially in polytrauma patients). In recent years, the concept of using low-dose steroids to treat relative adrenal insufficiency in septic shock has gained popularity [55–58]. One major source of confusion is how to diagnose relative adrenal insufficiency. Previously, it was common practice to obtain random cortisol levels and to treat if the level was low (which was variably defined). Subsequently, it became popular to perform a cosyntropin stimulation test in patients with septic shock as a means to identify those patients with relative adrenal insufficiency. To perform this test, a baseline serum cortisol is drawn which represents time zero (T0). The patient is then given 250 mg of IV cosyntropin and blood samples were obtained 30 and 60 min later. If the maximal change in serum cortisol from T0 to T30 or T60 was ≤9 mg/dL (called the "delta 9"), then the patient is considered to have relative adrenal insufficiency and steroids are initiated. However, there were several problems with this approach. First, obtaining three timed blood samples in patients in septic shock is logistically difficult to perform and it takes time to get the results. Second, "delta 9" definition was proven to be inaccurate in patients who had a low serum albumin (which binds cortisol). Third, etomidate (commonly used for emergency intubations) causes a temporary suppression of the hypothalamic-pituitary-adrenal axis. This results in transient adrenal insufficiency that is of uncertain clinical significance. To simplify this decision, starting in 2008 SSC EGB recommended that IV hydrocortisone was recommended in adult septic shock patients with hypotension that responds poorly to adequate fluid resuscitation and vasopressors. The literature indicates that low-dose hydrocortisone (200 mg/day) decreases the dose of vasopressors, the time to cessation of vasopressors, but its effects on reducing mortality remain uncertain. The author currently gives hydrocortisone (as an intermittent dose of 50 mg every 6 h) after adequate fluid resuscitation and norepinephrine plus vasopressin have failed to restore hemodynamic stability. A continuous infusion of 9 mg/h is used in patients with difficult to control hyperglycemia [59]. The duration of steroid administration also remains controversial [60]. The current recommendation is that steroids be tapered once vasopressors are no longer required.

**Blood Transfusions**: Based on the Rivers et al. EGDT 2001 publication, the SSC EBG recommended a target hemoglobin of [Hb] of 10 g/dL in severe sepsis/septic shock patient [22–25]. However, in the 2016 SSC EBG, the target [Hb] was reduced to 7 g/dL (in the absence of extenuating circumstances, such as myocardial ischemia, severe hypoxemia, or acute hemorrhage) for two reasons. First, the three large EGDT multicenter PRTs (ProCESS, ARISE, ProMISe) trials discussed above showed that targeting a [Hb] of 10 g/dL in EGDT was not associated with improved outcomes [26–28]. Second, the Transfusion Requirements in Septic Shock (TRISS) trial published in 2014 that compared a transfusion [Hb] threshold of 7 versus 9 g/dL in patients

with septic shock patients found no differences in 90-day mortality, ischemic events, or use of life support and significantly fewer red blood cell transfusions in patients targeted for a 7 g/dL [61]. In patients with known poor CO and a [Hb] of 7–9 g/dL, we will obtain blood from an SC or IJ CVL to measure $ScvO_2$ and will transfuse to a [Hb] >9 g/dL to augment oxygen delivery if $ScvO_2$ is <65%.

**Ongoing Fluid Resuscitation**. To avoid unnecessary (potentially harmful) fluid administration, fluid beyond initial resuscitation is based the assessment that the patient will be fluid responsive [62]. The goals of resuscitation are an MAP goal of ≥65 mmHg, and urine output (UO) goal of >0.5 mL/kg/h. Insuring adequate UO is important in the early stages of sepsis. Acute kidney injury (AKI) is quite common and reversible. Our studies have shown that persistent AKI portends poor short- and long-term outcomes [63, 64]. We also monitor CVP if a CVL is in SC or IJ positions. CVP, however, is only of value when it is low (<5 mmHg). When CVP is in a normal range, its ability to predict a response to a fluid challenge is limited [65]. We have found bedside transthoracic echocardiography is valuable in assessing volume status and cardiac contractility to predict fluid responsive. Passive leg raising is another valuable technique [66]. However, we have not found monitors that assess variations in systolic pressure, pulse pressure, or stroke volume in response to changes in intrathoracic pressure induced by large tidal volume mechanical ventilation to be of much value in the setting of sepsis and low SVR. Serum lactate is indirect measure of the adequacy of resuscitation. In the setting of shock, increased serum lactate levels most likely represent inadequate tissue perfusion [67]. However, in critically ill patients elevated lactate levels can also be due to accelerated aerobic glycolysis driven by excess beta-adrenergic stimulation, or other causes (e.g., liver failure, hyperglycemia, alcohol intoxication). In the setting of early sepsis, RCTs have demonstrated a significant reduction in mortality with lactate-guided resuscitation [68, 69]. If initial lactate is elevated (>2 mmol/L), it should be remeasured within 2–4 h to guide resuscitation to normalize lactate.

**Source Control**: This involves rapid identification of the site of infection and determining whether it is amenable to a source control interventions. Optimal timing of source control is poorly studied and depends upon the scenario. In the setting of septic shock, this should be done as soon as possible after initial resuscitation. This could be as simple as removing an infected CVL, opening an infected wound or bedside drainage of a superficial abscess. However, polytrauma patients who are undergone previous operative procedures are at high risk to develop deep infections that require operating room (OR) or interventional radiology (IR) interventions. Obtaining diagnostic imaging and performing OR or IR procedures outside the ICU presents a unique challenge. It is important to insure adequate volume loading prior transport out of the ICU to perform these diagnostic or therapeutic interventions. The in-depth discussion of the concept of damage control surgery is beyond the scope of this chapter [70–75]. In brief, the concept was developed for trauma patients who arriving with severe bleeding, but has been extended to emergency surgery patients who present in persistent septic shock with vasodilation, hypotension, and myocardial depression (see Fig. 34.4). This, combined with endothelial activation and diffused intravascular coagulopathy, causes ongoing endothelial leak, cellular shock, and microvascular thrombosis. The clinical manifestation is septic shock with worsening AKI and progressive MOF. The crucial question is the timing of OR source control to break this cycle. These patients need 2–3 h of preoperative optimization, during which time the airway is secured, CVL and A lines are placed, volume resuscitation, and broad-spectrum antimicrobial agents

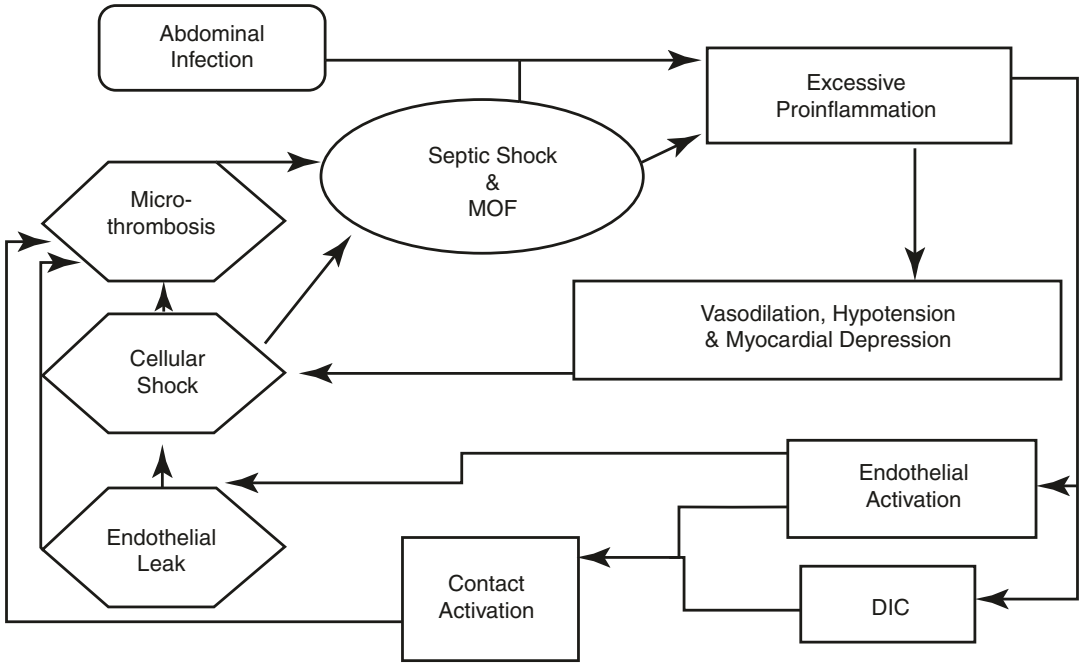


**Fig. 34.4** Abdominal infection causing persistent sepsis shock

are administered, and, if needed, vasopressors are titrated to attain MAP goals. Once in the OR and the patient is under general anesthesia, the surgeon needs to assess the degree of physiologic derangement and vasopressor use. If severe physiologic derangements exist or high-dose vasopressors are required, the OR interventions need to be abbreviated. The primary aim is to control the source of infection. Ostomies are not formed. Bowel resections remove necrotic or perforated bowel, but the bowel is left in discontinuity. Abdominal closure is with a temporary abdominal closure device and the patient is returned to the ICU for physiologic optimization. This includes optimizing volume resuscitation and mechanical ventilation, correction of coagulopathy and hypothermia, and monitoring for ACS. Over the next 24–48 h, abnormal physiology is corrected so that the patient can safely return to the operating room for a definitive operation and abdominal closure which may need to be staged.

## 34.5 Conclusion

Polytrauma patients are at high risk to develop sepsis which substantially worsens short- and long-term outcomes. Early recognition of sepsis is imperative to improving these outcomes. Unfortunately, the diagnosis of sepsis after polytrauma is especially challenging and the recent changes in sepsis definitions from the Sepsis-2 to Sepsis-3 criteria has added confusion. However, performance improvement programs that insure early diagnosis and rapid optimal implementation of the Surviving Sepsis Campaign (SSC) evidence-based guidelines have been consistently shown to reduce in hospital mortality. Key interventions in the early ICU management of sepsis in polytrauma patients include establishing effective IV access, simultaneous administration of broad-spectrum antimicrobial agent(s) and initial fluid resuscitation, administration of vasoactive medication as needed to insure vital organ perfusion, source control, and optimizing ongoing resuscitation.

**Key Concepts**

- The diagnosis of sepsis in polytrauma patients is confounded by the initial traumatic insult which activates innate immunity through similar mechanisms as in sepsis and as a result both cause similar SIRS and organ dysfunctions.
- Local infections and resulting inflammation can progress to a dysregulated systemic immune response. If this is not interrupted, sepsis will progress to severe sepsis and then to septic shock leading to refractory shock, MOF, and death.
- Performance improvement programs that utilize sepsis screening to diagnosis sepsis early and optimize implementation evidence-based care of sepsis substantially reduced in hospital mortality.
- Key interventions in the early ICU management of sepsis in polytrauma patients include establishing effective IV access, simultaneous rapid administration of initial fluid resuscitation and broad-spectrum antimicrobial agent(s), administration of vasoactive medication as needed to insure vital organ perfusion, optimizing ongoing resuscitation and timely source control.

**Take Home Messages**

- Utilize sepsis screening to insure early diagnosis of sepsis.
- Develop processes of care (e.g., protocols, order sets, etc.) that insure optimal implementation of evidence-based care that are pertinent to early management of sepsis in polytrauma patients.
- As soon as possible after diagnosing sepsis, administer a 1 L bolus of a balanced crystalloid solution over 30 min. In hypotensive patients or those with a serum lactate >4 mmol/L additional fluid should be administered to achieve 30 mL/kg of initial volume resuscitation.
- In patients who do not achieve an MAP ≥65 mmHg with initial volume resuscitation within 1 h, start a norepinephrine infusion and titrate as needed.
- Simultaneously, identify the most likely site of infection and to administer within 1 h broad-spectrum antimicrobial agent(s) to cover potential pathogens.
- If the norepinephrine infusion increases to ≥15 mg/min, add low-dose vasopressin at infusion rate of 0.03 U/min. Do not increase this dose of vasopressin.
- Start low dose steroids (e.g., hydrocortisone 50 mg q 6 h) in patients requiring ongoing high doses of norepinephrine and vasopressin to achieve MAP ≥65 mmHg.
- Additional fluid resuscitation (beyond the initial 30 mL/kg) will likely be needed but should be based on the assessment that the patient will be fluid responsive.
- Bedside transthoracic echocardiography is valuable in differentiating hypovolemia versus impaired cardiac function in non-responding patients. Patients with impaired cardiac function should inotropic agent started. Dobutamine is the preferred agent but will cause hypotension in hypovolemic patients.
- Start low-dose steroids (e.g., hydrocortisone 50 mg q 6 h) in patients requiring ongoing high-dose norepinephrine and vasopressin.
- Source control is a crucial intervention, but optimal timing is poorly studied. Patients who required operative intervention should have preoperative optimization and those who remain in septic shock after induction of anesthesia should undergo damage control. The goal is to insure adequate resuscitation to prevent or reverse acute kidney injury.

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# Polytrauma and Multiple Organ Dysfunction

35

Barclay T. Stewart and Ronald V. Maier

**Learning Objectives**

- Describe MOD, its phenotypes, and common clinical manifestations.
- Highlight key pathophysiological features of MOD, including those related to the host response to injury, complement, leukocytes, platelets, cytokines, the gut, and secondary insults.
- Explain strategies to prevent MOD, including use of damage control resuscitation and surgery, minimizing ventilator-induced lung injury, eliminating excess transfusion of blood and blood products, and use of immunonutrition.

## 35.1 Introduction to Multiple Organ Dysfunction

### 35.1.1 Overview

Multiple organ dysfunction (MOD) is the manifestation of an excessive, dysregulated immune-inflammatory response directed by a genomic storm induced by serious injury and/or infection. MOD describes an array of phenotypes that are poorly understood and carries several pseudonyms—multiple organ failure (MOF), multiple systems organ failure (MSOF), or one of its more conspicuous components, such as acute respiratory distress syndrome (ARDS), acute kidney injury (AKI), or trauma-induced coagulopathy (TIC). More specifically, MOD is the result of dysregulated immune and inflammatory responses driven by both the innate and adaptive immune systems and the inadequate endogenous responses that aim to restore homeostasis. The syndrome phenotypes represent a spectrum of degree of dysfunction (e.g., severe and multiple organ systems involved versus mild and a single organ system involved) and timing (e.g., early and rapidly progressive to death versus late and prolonged).

Improvements in injury prevention and control, trauma system enhancements, and surgical and critical care delivery have reduced the incidence and overall severity of MOD. However, these advances have not markedly changed the high mortality rate associated with severe MOD

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from extensive polytrauma, sepsis, or other overwhelming insults nor the intensity of resources required to manage it. Most interventions designed to treat MOD have not proven efficacious and therapy consists largely one of organ function support until resolution occurs. Therefore, prevention remains paramount. In addition, the impacts of MOD on survivors, while incompletely understood, affects all domains of recovery, including physical and mental functioning, independence and community integration, and the ability to return to work or school.

### 35.1.2 Definitions of Multiple Organ Dysfunction

Eiseman was one of the early investigators to describe "multiple organ failure" in 1977 by reporting progressive organ dysfunction among 42 patients and calling attention to, "this new man-made syndrome, which has both important scientific and social implications" [1]. Despite its ubiquity and impact on the outcomes of injured patients since 1977, there has not been consensus on a single definition of MOD. Broadly, MOD is the development of life-threatening, potentially reversible, physiological derangements that involve two or more organ systems that were not directly caused by the original injury.

There are two distinct patterns of MOD:

- Primary MOD—a consequence from a specific insult that causes organ dysfunction early and can be directly attributed to the insult itself (e.g., acute kidney injury and cardiovascular dysfunction due to rhabdomyolysis or acute hypovolemia).
- Secondary MOD—a manifestation of the host's primarily immunologic response (e.g., acute respiratory distress syndrome and cardiovascular dysfunction due to massive innate inflammation from polytrauma, hypovolemic shock, reperfusion-induced oxidant injury, and secondary coagulopathy).

Although the overall processes are limited, the degree of dysfunction and number of organs potentially affected generate remarkably heterogenous patterns of signs and symptoms that comprise the MOD syndrome. Practically, organ dysfunction has been defined and described generally in one of two ways—as the physiologic derangement that requires organ support (e.g., respiratory failure, kidney failure, shock) or as the clinical intervention deployed to support the dysfunctional organ system(s) (e.g., mechanical ventilation, hemodialysis, inotrope or vasopressor support, parenteral nutrition) [2]. Early definitions were weighted toward the number of dysfunctional organs. Current definitions attempt to incorporate the degree of dysfunction of the affected organ(s) to better delineate the disease extent and potentially predict the clinical trajectory. Proposed definitions differ in the specific parameters utilized to measure dysfunction, progression of dysfunction, and weighting of specific measures [3, 4].

### 35.1.3 Scoring Systems

Although a number of scores have been proposed, three are commonly used to define MOD: Marshall Multiple Organ Dysfunction Syndrome (MODS) Score, Sequential Organ Failure Assessment (SOFA) Score, and Denver Score (Table 35.1) [3, 5–7]. MODS Score grades the dysfunction of six organ systems (pulmonary, renal, hepatic, cardiovascular, hematologic, and neurologic systems). The SOFA score is also composed of scores from six organ systems, which are graded from 0 to 4 according to the degree of dysfunction. SOFA Score has been secondarily validated among injured patients [8]. The Denver Score grades four systems (pulmonary, renal, hepatic, cardiovascular). These scores do not grade other commonly involved systems, such as the endocrine, gastrointestinal and immune systems. Fröhlich et al. compared the classification and diagnostic accuracy of the MODS, SOFA, and Denver Scores among injured patients [6]. They delineated five grades of organ dysfunction severity using the degree of derangement of biomarkers that represent each organ system scored (Grade 0–4) (Table 35.1). Although

**Table 35.1** Marshall Multiple Organ Dysfunction Syndrome (MODS) Score, Sequential Organ Failure Assessment (SOFA) Score, and Denver Score components and proposed grades of multiple organ dysfunction (MOD) syndrome severity

| | Biomarker | Unit | Grade 0 | Grade 1 | Grade 2 | Grade 3 | Grade 4 |
|---|---|---|---|---|---|---|---|
| *Denver Score* | | | | | | | |
| Pulmonary | $PaO_2/FIO_2$ | mmHg | >208 | 208–165 | 164–83 | <83 | |
| Renal | Creatinine | µmol/L | <159 | 160–210 | 211–420 | >420 | |
| Cardiovascular | Blood pressure and inotrope dose[a] | mmHg and µg/kg/min | No inotropes | Only 1 inotrope at a small dose | Any inotrope at moderate dose or >1 agent at small dose | Any inotrope at large dose or >2 agents at moderate dose | |
| Hepatic | Bilirubin | µmol/L | <34 | 34–68 | 69–137 | >137 | |
| *SOFA Score* | | | | | | | |
| Pulmonary | $PaO_2/FIO_2$ | mmHg | >400 | ≤400 | ≤300 | ≤200 | ≤100 |
| Renal | Creatinine | µmol/L | <110 | 110–170 | 171–299 | 300–440 | >440 |
| Cardiovascular | Blood pressure and inotrope dose | mmHg and µg/kg/min | No hypotension | Mean arterial pressure <70 mmHg | Dopamine ≤5 or any dobutamine dose | Dopamine >5 or epinephrine or norepinephrine ≤0.1 | Dopamine >15 or epinephrine or norepinephrine >0.1 |
| Hepatic | Bilirubin | µmol/L | ≤20 | 20–32 | 33–101 | 102–204 | >204 |
| Central nervous system | Glasgow Coma Score | – | 15 | 13–14 | 10–12 | 6–9 | <6 |
| Coagulation | Platelet count | $10^3/\mu L$ | >150 | ≤150 | ≤100 | ≤50 | ≤20 |
| *MODS Score* | | | | | | | |
| Pulmonary | $PaO_2/FIO_2$ | mmHg | >300 | 226–300 | 151–225 | 76–150 | ≤75 |
| Renal | Creatinine | µmol/L | ≤100 | 101–200 | 201–350 | 351–500 | >500 |
| Cardiovascular | PAR[b] | | ≤10.0 | 10.1–15.0 | 15.1–20.0 | 20.1–30.0 | >30.0 |
| Hepatic | Bilirubin | µmol/L | ≤20 | 21–60 | 61–120 | 121–240 | >240 |
| Central nervous system | Glasgow Coma Score | – | 15 | 13–14 | 10–12 | 6–9 | <6 |
| Coagulation | Platelet count | $10^3/\mu L$ | >120 | 81–120 | 51–80 | 21–50 | ≤20 |

Table adapted from Frölich et al. *Which score should be used for posttraumatic multiple organ failure? - Comparison of the MODS, Denver- and SOFA-Scores.* Scand J Trauma Resusc Emerg Med. 2016; 24: 130

[a] Inotrope doses (in µg/kg/min): vasopressin: small <0.03, moderate 0.03–0.07, large >0.07; dopamine: small <6, moderate 6–10, large >10; dobutamine: small <6, moderate 6–10, large >10; epinephrine: small <0.06, moderate 0.06–0.15, large >0.15; norepinephrine: small <0.11, moderate 0.11–0.5, large >0.5

[b] Pressure-adjusted heart rate (PAR) = Heart Rate × Central Venous Pressure/Mean Arterial Blood Pressure

these scores have adequate predictive performance for MOD, intensive care requirements, and MOD-related mortality, MODS and SOFA Scores were more sensitive and the Denver Score was more specific [4, 6]. The authors concluded that the incidence of MOD depends on which score is used. Therefore, the definition and scoring systems used in clinical practice, quality improvement, and research still need to be harmonized. Regardless of scoring specifics, one thing is clear—the risk of death increases with increasing number of dysfunctional organ systems and increasing degree of dysfunction within each organ system.

### 35.1.4 Epidemiology

MOD is common in the hours, days, and weeks after severe injury. Reports from the Glue Grant project, a prospective study at trauma centers in the United States that included adults with severe blunt injuries and hemorrhagic shock, offer insight to the incidence of and mortality attributable to MOD [9, 10]. Nearly 15% of patients in the dataset developed MOD, one-third of whom died. Age- and injury severity-adjusted incidence rates suggest that MOD occurs significantly less frequently than it did 20 years ago due to improved trauma systems, resuscitation, and surgical and critical care practices. However, improvements in MOD-related mortality have not been realized. This trend has been reported by several retrospective studies of MOD after injury in high-income countries [11–14]. This inability to improve survival once MOD occurs argues that prevention of MOD through improvements in early care should remain the primary focus of ongoing research, diagnostic test development, and therapeutic interventions.

There are a number of risk factors that increase the odds of acquiring MOD. These risk factors include advanced age, male sex, obesity, higher injury severity, and worse early physiologic derangement (e.g., higher transfusion requirements; or acidosis, hypothermia, and coagulopathy—the "Lethal Triad"). For example, a recent observational study of severely injured adults (i.e., Injury Severity Score >15) reported a fivefold increased risk of MOD in patients >55 years of age compared to younger adults [15].

There are also organ-specific differences in MOD epidemiology. The lungs are the most commonly affected organ (>50% of patients with MOD) although significant reductions in progression and extent of pulmonary dysfunction have been achieved through damage control resuscitation, ventilator-associated pneumonia (VAP) prevention bundles, and lung protective ventilation strategies [16]. MOD without pulmonary dysfunction is uncommon (<10%). However, MOD-related mortality is highest for patients with dysfunction of the cardiovascular system (39%), kidneys (38%), liver (19%), and lungs (12%) [10].

### 35.1.5 Phenotypes

The early host response to injury is commonly exhibited by the systemic inflammatory response syndrome (SIRS) (Fig. 35.1). SIRS is the clinical manifestation of innate immune system activation and is defined as the presence of two or more of the following conditions:

1. Temperature greater than 38 °C or less than 36 °C
2. Pulse rate greater than 90 beats/min
3. Respiratory rate greater than 20 breaths/min or $PaCO_2$ less than 32 mmHg
4. White blood cell counts greater than 12,000/$mm^3$ or less than 4000/$mm^3$ or greater than 10% immature (band) forms

Patients with SIRS typically follow one of three phenotypes: rapid recovery, early MOD with recovery or death, or chronic critical illness with persistent inflammation and/or immunosuppression. Patients also simultaneously develop a suppression or exhaustion of the adaptive immune response (Fig. 35.1). Similar to persistence of an overly aggressive immunoinflammatory state causing ongoing diffuse organ injury, patients experience a simultaneous, persistent, and overzealous response that leads to adaptive immunosuppression and an increased risk of infection,

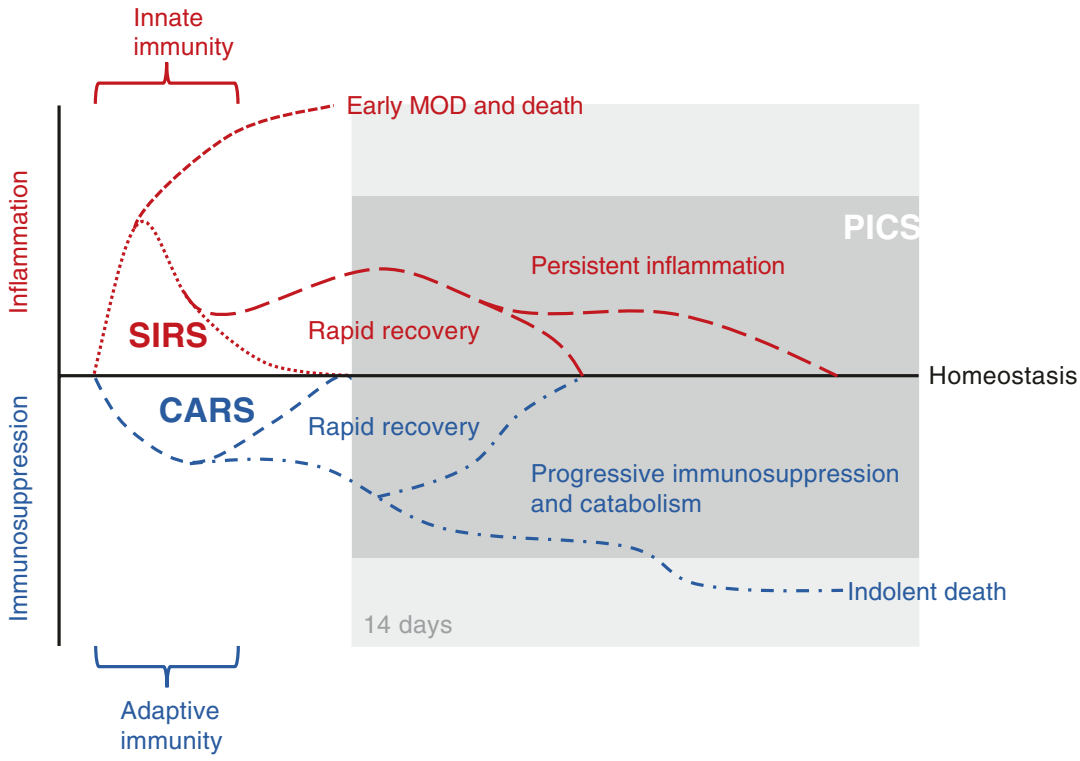


**Fig. 35.1** Conceptual phenotypes within the immunoinflammatory model of multiple organ dysfunction syndromes. *SIRS* systemic inflammatory response syndrome; *PICS* persistent inflammation, immunosuppression, and catabolism syndrome. Blue represents the adaptive immunity genomic response, and red represents the innate immunity genomic response. (Figure adapted from Vanzant et al. *Persistent inflammation, immunosuppression, and catabolism syndrome after severe blunt trauma.* J Trauma Acute Care Surg. 2014 Jan;76(1):21–9)

poor wound healing, catabolism, and other clinically important complications. Among those who develop early MOD and fulminant death, 60% die within 48 h. Patients who develop MOD within 3 days of injury are more likely to die than patients who develop MOD later in their hospitalization.

Although most patients return to a balanced immune and inflammatory state, some remain in a persistently proinflammatory, immune-dysregulated and catabolic state. Regardless of whether experiencing a predominantly pro-inflammatory or immunosuppressive response, patients can experience chronic critical illness (≥2 weeks) and a persistent inflammation-immunosuppression catabolism syndrome (PICS) that can last for weeks to months after critical injury and leads to particularly poor outcomes despite diligent and prolonged critical care (Fig. 35.1) [17]. PICS is defined as:

1. Protracted intensive care requirement (>14 days)
2. Persistent inflammation (C-reactive protein concentration >150 μg/dL and retinol binding protein concentrations <10 μg/dL)
3. Immunosuppression (total lymphocyte count <800/mm$^3$)
4. A catabolic state (serum albumin <3.0 mg/dL, creatinine height index <80%, and weight loss >10% or BMI <18 kg/m$^2$ during the index hospitalization)

Genomic analyses of bluntly injured patients who experience complicated clinical outcomes have demonstrated persistent genomic expression patterns consistent with defects in the adaptive immune response and increased inflammation [18]. When genomic expression and clinical data are linked, it is clear that some patients experi-

ence persistent inflammation, immunosuppression, and protein depletion consistent with PICS. Phenotypically, patients with PICS are unable to achieve homeostasis and typically suffer a prolonged and complicated clinical course characterized by recurrent infections, loss of lean body mass resistant to nutritional support, unsatisfactory wound healing, and other complications [19]. Given these adversities, patients with PICS are often unable to experience functional recovery and assume an indolent course until death [4, 20]. PICS is particularly common in older patients with multiple comorbidities and significant baseline frailty [21]. The aging nature of our global populations will make PICS a common challenge for all who work in critical and acute care, recovery and rehabilitation, palliative care, ethics, and health economics.

A recent prospective point-prevalence study of 440 critically injured patients reported on the MOD phenotypes in the post-damage control resuscitation and surgery era [22]. Nearly 60% of the patients developed MOD and was strongly associated with mortality (22% compared to 0.5% of those without MOD). One quarter of deaths occurred within the first 48 h of injury. Three trajectories of MOD were identified but were all present on admission. Phenotype 1 MOD resolved early with a median time to recovery of 4 days and a mortality rate of 14.4%. Phenotype 2 had a delayed recovery (median 13 days) and a mortality rate of 35%. Phenotype 3 had a prolonged recovery (median 25 days) and high mortality rate of 46%. Distinct clinical associations were identified for each MOD phenotype: 24-h crystalloid administration was associated strongly with phenotype 1, traumatic brain injury with phenotype 2, and admission shock severity with phenotype 3.

### 35.1.6 Intensive Care Utilization and Cost

Patients with MOD require markedly more intensive care than their similarly injured peers. Sauaia et al. reported that MOD survivors accounted for 20% of intensive care unit and mechanical ventilation days despite representing only 9% of the critically ill population [10]. National estimates of critical care costs suggest that the care required for patients with MOD totaled 22% of critical care costs for all critically ill patients [23]. The estimated median cost per patient with MOD was US$ 77,000, which is more than double the cost of caring for patients without MOD (US$ 38,000).

## 35.2 Pathophysiology

### 35.2.1 Historical Context

Improvements in injury prevention and organized trauma care have markedly reduced mortality in the minutes and hours after injury [24, 25]. As a result, more patients survive to experience MOD, which remains one of the leading causes of late trauma-related deaths alongside hemorrhage, traumatic brain injury, and sepsis [26]. One of the earliest pathophysiological hypotheses was proposed by Moore et al., which hinged on the observation of a bimodal distribution of MOD [27]. The initial peak (i.e., a "one-hit" model) was attributed to a massive insult that induced profound systemic inflammation that precipitated MOD. The later peak (i.e., a "two-hit" model) was attributed to a second reactivating event (e.g., infection, transfusion, surgery) in an already primed or vulnerable host (e.g., adaptive immunity suppressed state).

Much has been learned from the study of the pathophysiology of post-traumatic MOD. The culmination of these findings suggests that injury triggers two simultaneous, opposite responses: proinflammation and immune suppression. Analyses of the Glue Grant database confirmed that the genomic expressions of pro- and anti-inflammatory responses were simultaneous (i.e., not compensatory) and not necessarily equivalent [28]. Pro-inflammation manifests as systemic inflammatory response syndrome (SIRS) that results from activation of the innate immune system and is associated with early MODS. Suppression or inhibition of the adaptive immune system and apoptosis limits pro-inflammation and manifests as a preconditioned homeostasis to protect against additional insults and promote healing.

However, excessive and/or prolonged inhibition can degenerate into a severe systemic immunosuppression that is associated with immunoparalysis, impaired healing, sepsis, and late MOD (i.e., PICS) [19, 28]. Ultimately, MOD is related to the intensity, duration, balance, and interplay between these basic immunoinflammatory responses (Fig. 35.2). These responses do not simply cancel one another out but interact, disrupt, sustain, and even amplify one another [29].

### 35.2.2 Pathophysiologic Mechanisms and Host Responses to Injury

The proinflammation response is activated and propagated predominantly by ischemia-reperfusion and oxidant-induced injury, as well as primary and secondary release of numerous inflammatory "danger signal" mediators displaced from injured tissues [4]. In the absence of tissue injury or infection, the release of these otherwise potential inflammatory mediators is prevented by homeostatic clearance of inflammatory cells (e.g., neutrophils) by apoptotic cell death, which does not trigger an immune response [30]. However, in the presence of tissue injury (e.g., polytrauma with significant soft and bone tissue injury) or infection the mediators released by cell lysis or apoptosis amplify the danger signal and trigger both innate and adaptive immune responses [31]. These mediators that result in a primed environment are called damage-associated molecular patterns (DAMPs). Examples of DAMPs include high mobility group box protein-1 (HMGB1), heat-shock proteins, uric acid, and DNA. Injured cells also release mitochondrial DAMPs (mtDNA, residu-

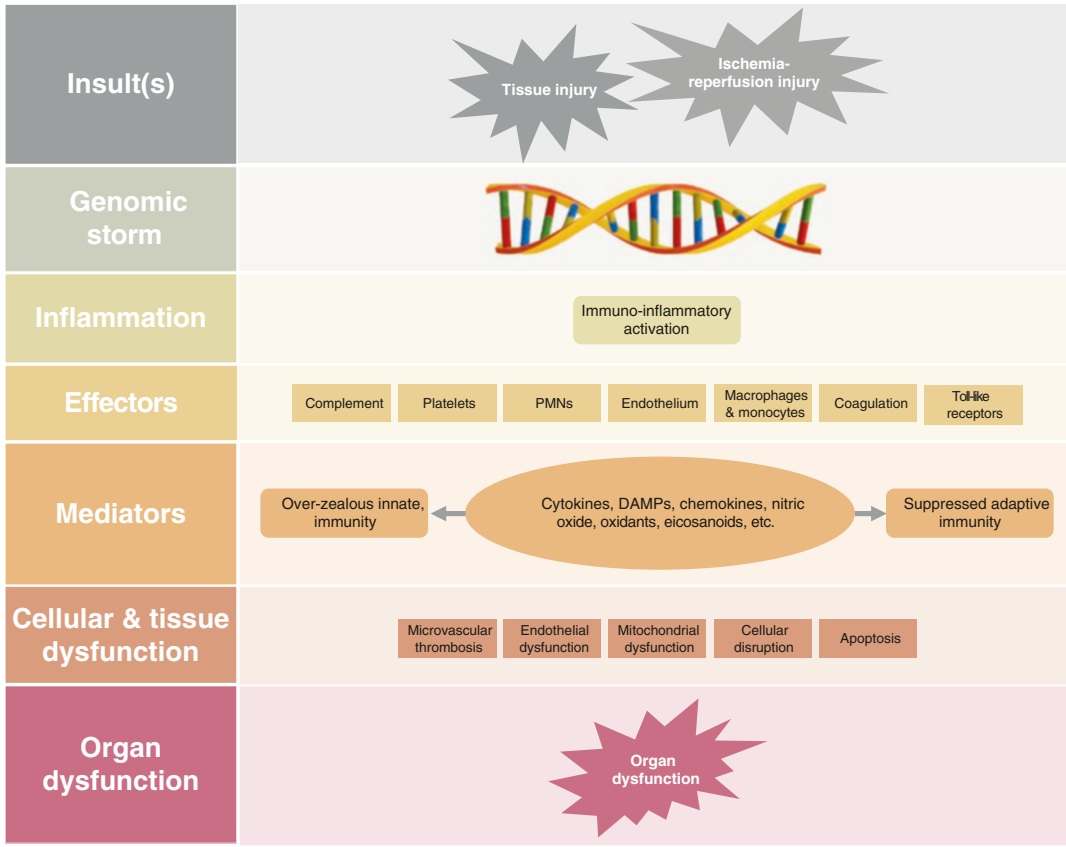


**Fig. 35.2** Schematic review of the pathophysiology of multiple organ dysfunction

als of intracellular evolutionary bacterial DNA) into the systemic circulation, which trigger an inflammatory state analogous to sepsis [32, 33]. Elegant studies of the proteomes of injured human lymph demonstrate a multitude of intracellular molecules, mitochondrial proteins, DNA, markers of hemolysis, extracellular matrix components, and damaged tissue factors [34, 35]. These mediators both trigger and potentiate the innate immune response.

A "genomic storm" is now known to occur after severe injury. More than 80% of the entire human transcriptome in the circulating leukocyte is significantly altered producing changes in genomic activity that commonly persist for at least a month following injury. These changes are qualitatively similar but quantitatively markedly greater and more prolonged than the genomic alterations induced in healthy controls receiving an infusion of endotoxin [28]. Approximately one-third of the most overexpressed genes (>2-fold increase in activity) are associated primarily with innate immunity activation, while approximately two thirds of the genes most altered are suppressed and involve primarily pathways of adaptive immunity. Genes related to T-cell function and antigen presentation are uniformly less frequently expressed, including the PD-1 pathway, which may explain, in part, the increase in malignancy recurrence after severe injury and major operations with significant hemorrhage and multiple transfusions. The genomic storm in response to blunt injury is also highly analogous to that which occurs after major burn injury and during sepsis [36, 37]. In addition, complications frequently experienced by critically injured patients and overall poor outcomes were associated with a higher degree and greater duration of altered gene expression and concomitant immune dysfunction. Of note, there are not differences in specific gene expressions that predicted particular outcomes, but rather a similar qualitative gene expression pattern in both survivors and those who died. The primary difference predictive of outcome was in the trajectory of the genomic response. Those who were able to achieve immunoinflammatory homeostasis and return to a normal genomic expression profile recovered, quickly. Patients who were unable to achieve homeostasis experienced a prolonged and complicated critical illness associated with a high mortality rate. Thus, there are no discreet genomic products for therapeutic intervention identified, which explains why all isolated gene targeted therapies to date have failed clinically. Importantly, far less is known about immune gene expression patterns in specific dysfunctional tissues or organs, such as the lung, liver, or kidneys, which may demonstrate unique gene expression patterns not present in the circulating leukocytes measured to date [28].

## 35.3 Actors Implicated in MOD Pathophysiology

There are a number of genomic-controlled effectors and mediators of the immune response that contribute to MOD, including complement, leukocytes, platelets, cytokines, the gastrointestinal (GI) tract, and others. Each of these is briefly discussed.

### 35.3.1 Complement

Complement is one of the predominant effectors of the innate immune response and is immediately activated after injury. Once activated, complement enhances the adaptive immune response and couples the immune and coagulation systems [38, 39]. The degree of complement activation informs its functions. At low levels of activation, complement catalyzes the production of its pro-inflammatory components (i.e., C3a, C3b, C5a, terminal C5b–C9 membrane attack complex) that lead to lysis of target cells and recruitment of leukocytes to clear damaged tissue and enable normal healing. As the stimulus for activation increases, complement results in the production of strong pro-inflammatory mediators including oxygen free radicals, arachidonic acid, and cytokines. Thus, excessive complement activation can lead to collateral bystander injury of normal tissues and organ function and lead to leukocyte paralysis,

which prevents neutrophils from responding to C5a or other chemotactic signals [40].

Activation of the complement cascade is regulated by cell-surface proteins (e.g., CD55, CD46), the C5a receptor (CD88) and several inhibitors (e.g., C4b-binding protein, factor I) [4]. Together, these receptors function as checkpoints to limit complement-activated collateral tissue destruction and progressive, uncontrollable coagulopathy. In severe injury, the expression of these receptors is altered and incompetent regulation of the complement cascade ensues [41]. Trauma-induced complementopathy has been associated with SIRS and poor outcomes in patients who sustained blunt trauma, traumatic brain injury, and burn injuries [42, 43].

### 35.3.2 Leukocytes

Polymorphonuclear leukocytes (PMNs) and macrophages are central actors in the immune response and inflammation that occurs after injury. Injury stimulates massive release of neutrophils and immature band cells from the bone marrow into the systemic circulation and induces a wide variety of PMN functions and phenotypic markers [44]. Concomitantly, both the direct and secondary hypoxic-ischemic and reperfusion-induced oxidant tissue injury results in a marked increase in cell-to-cell adhesion molecules (e.g., L-selectin, CD18) that cause PMNs to slow in microcirculation, roll along the endothelium, and migrate into adjacent uninjured tissues [45]. Patients who experience a rapid and mass sequestration of PMNs in the hours and days after injury are more likely to develop MOD than their counterparts with less PMN margination [46]. This is likely due to the degranulation of toxic products of PMNs sequestered in organs that then release pro-inflammation cytokines (e.g., IL-6, TNF-α), which amplify the dysregulated immune response. PMNs also release reactive nitrogen and oxygen species when they degranulate, which cause direct cytotoxic injury and potentiate local and systemic inflammation and organ dysfunction [4]. As support for this dysregulated process, studies of antibodies that targeted neutrophil surface CD18 reported minimal neutropenia-associated sequestration and attenuation of pulmonary dysfunction by reducing PMN adhesion and migration across the pulmonary capillary endothelium [47, 48]. When PMNs are activated in the vasculature, they also extrude a meshwork of chromatin fibers that produce cloud-like neutrophil extracellular traps (NETs) that aid in pathogen trapping [49]. However, NETs have been implicated in propagating diffuse microthrombosis and tissue hypoxia, which further complicates the ischemia-reperfusion injury that instigates and augments the innate immune response [50]. In an experimental mouse model of traumatic brain injury (TBI), NET formation was associated with cerebral hypoperfusion and brain hypoxia [50]. When mice with TBI were given recombinant DNAse-I to degrade NETs they experienced improved neurologic function.

Circulating monocytes and tissue macrophages also become primed and activated by complement proteins, multiple cytokines, and DAMPs through a family of membrane receptors called Toll-like receptors (TLRs). TLRs are responsible for recognizing DAMPs, pathogen-associated molecular patterns (PAMPs), and viral surface proteins (e.g., CoV-2), which cause release of a multitude of highly active pro-inflammatory mediators that disrupt the integrity of the microvascular endothelium and further potentiate the overall innate inflammatory response [51]. For example, monocytes release large quantities of TNF in response to pro-inflammation mediators and endotoxin. TNF has effects that are nearly identical to those of endotoxin itself, including fever, altered tissue perfusion, lactic acidosis, intravascular coagulation, and capillary permeability. TNF causes the release of other pro-inflammation mediators (e.g., IL-2) that amplify the immune response and risk of MOD [52]. Macrophages and monocytes are long-lived cell lines and appear to be central mediators orchestrating the host inflammatory response; once activated they become self-perpetuating actors in MOD and probably the prime director of the longer lasting effects,

such as the PICS syndrome. Of note, endogenous and exogenous steroids are well-known suppressors of macrophage activation and may explain their potential benefit in explosive inflammatory conditions (e.g., COVID-19).

### 35.3.3 Platelets

Platelets become activated by complement directly, via complement-induced activation of the coagulation cascade, and secondary to endothelial injury. Activated platelets potentiate microvascular thrombi and local tissue hypoxia that further complicates the ischemia-reperfusion injury common after traumatic shock. Circulating neutrophils patrolling the vasculature are stimulated by activated platelets and initiate an inflammatory response when they are encountered [53]. Activated platelets enhance neutrophil phagocytosis, production of oxygen-free radicals and NETs, and affinity for cell adhesion molecules (CAMS; e.g., P-selectin, β2 integrin).

Much of our understanding of the role of platelets in local and systemic inflammation has come from the study of what happens when platelets are inactivated or low in number. For example, acute lung injury in rat models can be attenuated through interruption of platelet-neutrophil interactions with a P2Y12 receptor antagonist [54, 55]. Further, pre-injury antiplatelet therapy in people who sustained blunt injuries was associated with a lower risk of acute lung injury, MOD, and death and better outcomes among patients with ARDS [56, 57]. Transient and persistent thrombocytopenia is a predictor of postinjury organ dysfunction [58]. However, a multicenter, double-blind, placebo-controlled, clinical trial that randomized 390 patients at risk of ARDS to 325 mg of aspirin in the emergency department and for the following 7 days found no significant difference in ARDS or other outcomes (e.g., ventilator days, mortality) [59]. This again highlights that interruption of one of the multitude of arms involved in the complex immune response is unlikely to produce a clinically relevant change in the overall inflammatory phenotype.

### 35.3.4 Cytokines

Cytokines can be pro-inflammatory (TNF-α, GM-CSF, IFN-γ, IL-1, IL-2, IL-6, IL-8, IL-17) or anti-inflammatory (IL-4, IL-10, IL-13) [4]. Injured patients who develop MOD are more likely to have a relative abundance of pro-inflammatory cytokines (e.g., IL-1, IL-8, GM-CSF, monocyte chemotactic protein-1, macrophage inflammatory protein-1) compared to patients who do not develop MOD [60]. Differential early expression of pro-inflammatory cytokines and their receptors is associated with increased risk of MOD and death even months after injury [61]. Among 352 patients with severe TBI or polytrauma with Injury Severity Score ≥6, patients with late MOD (i.e., ≥4 days after injury) were more likely to express a biphasic elevation of IL-6 and significantly higher TNF concentrations compared to patients with early MOD or no MOD [62]. Further, TNF expression levels accurately predicted the development of late MOD.

However, other cytokines may be crucial to reverse the adaptive immunoparalysis. As an example, in response to injury or infection, IL-17 produced by γδ T cells, natural killer T cells, and innate lymphoid cells induces the production of GM-CSF and chemokines such as CXCL1 and CXCL2 and is a cytokine that acts as a predominantly macrophage and T-cell pro-inflammatory mediator. IL-17 is needed to eliminate extracellular bacteria and fungi by inducing antimicrobial peptides such as defensin [63]. IL-17 may play a role in the pathogenesis of MOD. Administration of exogenous IL-17 appears to be able to recover the paralyzed adaptive immune response and shows promise in restoring antimicrobial potential, preventing complications of infection, and mitigating further aggravation (i.e., a "second-hit") of the innate immune system [64, 65].

Similarly, IFN-γ is produced by a variety of immune cells (e.g., natural killer T cells, innate

lymphoid cells, helper, and cytotoxic T cells) and is induced by other cytokines (primarily IL-12 and IL-18), following the activation by TLRs or other broadly reactive antigen receptors during infection and/or tissue injury. As a result, an early burst of IFN-γ production occurs early, during infection to help initiate the emergence of an antigen-specific adaptive immune response. Importantly, IFN-γ modulates macrophage activity causing these cells to be primed for not only pro-inflammatory responses but also resistance to suppressive mediators and reversal of immune tolerance and paralysis, thus restoring a normal adaptive immune response.

### 35.3.5 The Gut

The gut conceptually consists of an epithelium, innate and adaptive immune systems, and a microbiome. Each plays a vital role in maintenance of health and in the pathophysiology of MOD. Decreased intestinal blood flow after traumatic shock disrupts the epithelial integrity and intestinal immune function. These changes allow toxic gut-derived mediators to traverse the otherwise protective epithelium, travel through the mesenteric lymphatic system and gain access to the systemic circulation through the thoracic duct where they instigate distant inflammation and damage. Given that these mediators traverse the pulmonary circulation before that of other organs, it is postulated that this process may be one of the reasons why pulmonary dysfunction and ARDS is often seen in isolation or prior to the onset of MOD. Pre-clinical experiments that include thoracic duct ligation in animal models of critical illness have reported decreased rates of pulmonary dysfunction [66].

Study of the intestinal microbiome in critically ill humans has demonstrated pathologic shifts in the relative abundance of specific microbial taxa, decreased taxa diversity, and overgrowth of pathogenic bacteria and yeast [67]. For example, even slight variations of intestinal pH (i.e., ±1) in critically ill patients are associated with a threefold incidence of bacteremia and a twofold increase in mortality [68]. Similarly, shifts in the relative abundance of obligate or facultative anaerobes and decreased taxa diversity more broadly are associated with a higher risk of developing MOD and death [69].

Several biomarkers of dysfunctional gut health and function have been associated with MOD [70]. In an observational study of critically ill patients, decreased plasma citrulline (a marker of enterocyte functional metabolic mass) and elevated intestinal fatty acid-binding protein (released from damaged enterocytes) on admission to the intensive care unit were associated with need for vasopressor support, coagulopathy, and MOD [71]. Abnormal values of both biomarkers were associated with higher mortality [72].

### 35.3.6 Secondary Insults

Several insults (second hits) that commonly occur after injury have been linked to the development of MOD, including blood transfusions, infections, and additional tissue trauma (i.e., major surgical procedures).

#### 35.3.6.1 Transfusion

Early blood transfusion is strongly and independently associated with the development of MOD. Blood products are highly immunogenic and contain pro-inflammatory cytokines, passenger leukocytes, activated platelets, complement components, and lipids that activate endothelial cells and the innate immune system [73]. Blood transfusion further drives an indiscriminate activation of the innate immune system while creating the simultaneous adaptive immune suppressed state that predisposes already high-risk patients to infections, sepsis, and MOD [74]. The risk of transfusion can be somewhat mitigated by use of fresh whole blood or blood products stored less than 2–3 weeks instead of older blood products [75]. Leukodepletion has not eliminated the attributable risk of transfusion because red blood cells themselves also release and contain pro-inflammatory mediators and cell membrane breakdown products are similarly proinflammatory.

#### 35.3.6.2 Infection and Sepsis

Infections and sepsis have long been implicated in the development of MOD. The Third International Consensus Definitions for Sepsis and Septic Shock (Sepsis-3) redefined sepsis as a dysregulated host response to infection leading to life-threatening single or MOD [76]. In its attempt to eradicate the pathogens, the innate and adaptive immune systems elaborate a wide array of potentially toxic mediators and activate multiple cell types. These mediators enhance effector mechanisms for macrophage and neutrophil killing, increase procoagulant-induced microcirculatory thrombosis to localize invading pathogens, and increase surrounding microvascular blood flow to enhance delivery of bactericidal mediators to the area of invasion. However, when this response is overzealous or becomes systemic rather than localized, manifestations of sepsis become evident. MOD can arise from systemic infection but is more commonly propelled by the overwhelming pro-inflammatory response and resulting tissue inflammation, bystander cell injury, and MOD. During sepsis, cardiovascular dysfunction, including dysfunction of the heart, large blood vessels, and microvasculature, is common and typically precedes MOD and death. The effects of infection on the microvasculature are especially profound. Sepsis-related microvascular dysfunction is characterized by vasomotor paralysis, neutrophil adhesion, thrombosis, and loss of the normal endothelial permeability barrier, which leads to a massive capillary leak and neutrophil transmigration [77]. This microvascular dysfunction has been characterized as the "unifying syndrome in response to intravascular or extravascular microbial agents that cause MOD" [78].

#### 35.3.6.3 Surgery and Damage Control

Surgical procedures can be thought of as controlled trauma. Damage control surgery, which aims to minimize surgical trauma and the ongoing physiologic insult experienced by the injured patient, results in a less activated immune system and lower risk of sepsis, ARDS, and MOD than conventional surgical strategies that aim for early definitive repairs [79]. Damage control orthopedics (DCO) originally consisted of the staged immobilization of femur fractures in order to achieve the benefits of early treatment and to minimize the risk of complications, such as fat embolism, hemorrhage, and coagulopathy, and a second hit inflammatory insult in a primed, pro-inflammatory host. Additional fractures and fracture patterns have been added to the DCO concept, such as injuries to the pelvis, spine, and upper limbs. However, some believe the indiscriminate application of DCO might produce less than optimal functional outcomes and produce substantial and unnecessary expense [80].

As an example of these underlying mechanisms, the degree of complement activation has been shown to be positively correlated with the invasiveness of early femur fracture treatment in a large animal model [81]. Once activated, C3a and C5a act detrimentally on cardiac function. Similar perturbations in valvular insufficiency and myocyte damage have been reported after reaming and intramedullary nailing of femoral diaphyseal fractures [82]. The severity of extremity polytrauma in humans has been associated with significant elevations of lactate, base deficit, and creatine phosphokinase and circulating inflammatory mediators [83]. Additionally, the complexity of the inflammatory response (e.g., number and density of inflammatory mediators measured by dynamic network analysis) is also positively correlated with extremity injury severity. A study of 472 bluntly injured patients determined that the relative differences in the early expression of multiple inflammatory mediators and their dynamic networks seem to separate patients with regard to divergent inflammatory trajectories and risk of experiencing late MOD [84].

One of the earliest controlled studies of damage control surgery in humans randomized 35 patients to early external fixation followed by delayed conversion to intramedullary instrumentation or primary intramedullary nailing [85]. A sustained inflammatory response was measured after primary intramedullary femoral nailing, but not after initial external fixation or after secondary conversion to an intramedullary nail. Harwood et al. studied 174 polytrauma patients who underwent either damage control femoral

shaft fracture management or early intramedullary nailing. Despite having more severe injuries, patients who underwent damage control surgery had a smaller and shorter SIRS and less MOD. Interestingly, patients who had damage control surgery and who later underwent conversion to intramedullary nail while their SIRS score was elevated had the most pronounced inflammatory responses and highest rates of MOD [86]. However, a systematic review and meta-analysis of 38 studies that reported on the timing of definitive treatment of femoral shaft fractures determined that there was no difference in ARDS, MOD, or mortality between patients who were treated with damage control and those treated definitively [87]. Overall, there may be a subgroup of patients with significant and/or persistent inflammation that might benefit from damage control surgery or delayed fixation to mitigate the risk of a "second insult" and MOD [18]. Pape and colleagues have surmised that the inflammatory status of the patient may be a useful biomarker for clinical decision-making regarding the timing of definitive surgery [86].

A recent polytrauma expert opinion survey was conducted to evaluate the suitability of the indications and interventions for damage control orthopedic surgery that aim to reduce the risk of MOD while maintaining a significant focus on satisfactory functional outcomes [88]. The consensus-based indications and initial surgical interventions for both isolated musculoskeletal injuries (i.e., musculoskeletal temporary surgery) and polytrauma (i.e., damage control orthopedics) are provided in Tables 35.2 and 35.3, respectively. Since the advent and global uptake of damage control surgery, there has been a general reduction in the incidence and severity of MOD [22, 89]. However, some major polytrauma centers have described an increase in AKI, ARDS, and MOD, in part, due to concomitant reductions in mortality [90]. Thus, while there may be an increase in MOD with early definitive orthopedic repair, there is no proven impact on overall survival but may impact the potential for optimal repair and result in increased resource utilization. Currently, there is no proven definitive answer for the best timing for definitive fixation. Consensus-based recommendations may be considered to help guide decisions regarding DCO versus early definitive care (Tables 35.2 and 35.3) [80, 88]. It should be noted that the highest priority in the patient with polytrauma is the immediate control

**Table 35.2** Consensus-based indications and surgical interventions for isolated musculoskeletal injuries to mitigate the risk of multiple organ dysfunction

| Location | Indication | Intervention |
|---|---|---|
| Spine | Unstable thoracic and lumbar spine fractures | Percutaneous dorsal instrumentation |
| Pelvis | Complex pelvic ring injuries with nerve or vascular injuries | External pelvic fixation |
| | Open pelvic injuries | External pelvic fixation |
| | Stabilization of the pelvis for pelvic packing | C-clamp |
| | Posterior pelvic ring injuries | Percutaneous screw fixation |
| | Hemodynamic instability with unstable pelvic fracture | Pelvic packing |
| Extremities | Open fractures with soft tissue contamination | External fixation of long bones |
| | Open fractures with large soft tissue defects | External fixation of long bones |
| | Large bone defects | External fixation of long bones |
| | Complex intra-articular fractures | External fixation of long bones |
| | Fractures with concomitant vascular injuries | External fixation of long bones |
| Soft tissues | Morell-Lavallee lesion | VAC therapy |
| | Soft tissue contamination | VAC therapy |
| | Large soft tissue defects | VAC therapy |
| | Compartment syndrome | Fasciotomy |
| | Mangled extremity with uncontrollable hemorrhage | Amputation |

Adapted from Pfeifer, R. et al. *Indications and interventions of damage control orthopedic surgeries: an expert opinion survey.* European Journal of Trauma and Emergency Surgery 2021 Dec;47(6):2081–2092

**Table 35.3** Consensus-based indications and surgical interventions for damage control surgery of musculoskeletal injuries in polytrauma to mitigate the risk of multiple organ dysfunction

| Location | Indication | Intervention |
|---|---|---|
| Spine | Occipito-cervical dissociation | Halo fixation |
| | Unstable thoracic and lumbar spine fractures | Percutaneous dorsal instrumentation |
| Pelvis | Unstable pelvic ring fractures | External pelvic fixation |
| | Complex pelvic ring injuries with nerve or vascular injuries | External pelvic fixation |
| | Open pelvic injuries | External pelvic fixation |
| | Posterior pelvic ring injuries | Percutaneous screw fixation |
| | Type C pelvic fracture disruption of SI joint and sacrum fracture | C-clamp |
| | Hemodynamic instability with unstable pelvic fracture | Pelvic packing |
| | Exsanguinating hemorrhage related to pelvic injuries | REBOA |
| Extremities | Open fractures with soft tissue contamination | External fixation of long bones |
| | Open fractures with large soft tissue defects | External fixation of long bones |
| | Large bone defects | External fixation of long bones |
| | Complex intra-articular fractures | External fixation of long bones |
| | Fractures with concomitant vascular injuries | External fixation of long bones |
| | Complex peri-prosthetic fracture | External fixation of long bones |
| Soft tissues | Morell-Lavallee lesion | VAC therapy |
| | Soft tissue contamination | VAC therapy |
| | Large soft tissue defects | VAC therapy |
| | Compartment syndrome | Fasciotomy |
| | Mangled extremity with neurologic injury | Amputation |
| | Vascular injury with ischemia more than 6–8 h | Amputation |
| | Mangled extremity with uncontrollable hemorrhage | Amputation |

Adapted from Pfeifer, R. et al. *Indications and interventions of damage control orthopedic surgeries: an expert opinion survey.* European Journal of Trauma and Emergency Surgery 2021 Dec;47(6):2081–2092
*SI* sacroiliac joint, *REBOA* resuscitative endovascular balloon occlusion of the aorta, *VAC* vacuum-assisted closure

of significant hemorrhage to prevent the ongoing or repeated sequence of hypoperfusion and ischemia leading to reperfusion-induced oxidant injury and the additional consequences of unnecessary blood transfusions. As such, utilization of emergency external bleeding control (e.g., pressure, packing, tourniquet, surgical control), preperitoneal packing for pelvic fractures or endovascular treatment for pelvic or other fracture-associated bleeding (e.g., resuscitative endovascular balloon occlusion of the aorta (REBOA), embolization) in addition to stabilization to control ongoing bleeding is critical in the care of the patient with polytrauma.

## 35.4 Interventions to Prevent MOD

No targeted intervention has been shown to safely and effectively treat MOD in humans other than well planned and optimal resuscitation, immediate control of blood loss, early debridement of devitalized tissue, and organized critical care. However, several avenues have been and continue to be investigated (e.g., immunomodulation with TLR antagonists, mesenchymal stem cell therapy, artesunate treatment, DAMPs-targeted immunotherapy, C1 and C3 inhibition, CD59 inhibitor, CCR2-selective antagonist, statin therapy, tranexamic acid, and valproate) [91]. Until more targeted treatments become proven and available, prevention of MOD remains our most effective strategy. There are a number of opportunities to reduce the risk of MOD, including practice of damage control resuscitation and surgery, judicious use of blood transfusions, avoidance of ventilator-induced lung injury (VILI), and strategic immunonutrition.

### 35.4.1 Damage Control Resuscitation

The goal of resuscitation is to restore tissue perfusion. Resuscitation with isotonic crystalloids

during and after the Vietnam War in the 1960s markedly decreased mortality, primarily from renal failure, but contributed to the emergence of "Đà Nẵng lung," which became characterized as ARDS [92]. The management of patients in shock had been focused on aggressive fluid resuscitation with crystalloid or colloid solutions to rapidly restore circulating blood volume, maintain "optimal" vital organ perfusion, and prevent occult hypoperfusion from splanchnic vasoconstriction and subsequent organ injury and MOD. However, carrying this principal to a supraphysiologic strategy (and again confirming the adage, "The enemy of good is better.") created associated unwanted effects including worsening coagulopathy and increased tissue edema. This massive increase in edema played a direct role in the occurrence of worsening TBI, compartment syndromes, ARDS, and MOD [93–96]. Concerns about the effect of large volume isotonic crystalloid resuscitation led to experimentation with small volume resuscitation using hypertonic saline (e.g., 3%, 5%, and 7.5% sodium solutions). Initially, the use of low-volume hypertonic saline among patients who underwent damage control surgery resulted in a lower incidence of ARDS, sepsis, MOD, and mortality [97]. Additionally, a randomized trial of hypertonic saline resuscitation demonstrated a transient inhibition of PMN activation and partial restoration of normal monocyte phenotypes among patients in hypovolemic shock [51]. However, the Resuscitation Outcomes Consortium (ROC) trials for both shock and traumatic brain injury were halted after preliminary data showed no beneficial effect of hypertonic saline in the clinical trials [98, 99]. In addition, use of hypertonic saline appears to increase the coagulopathy seen in severe hemorrhagic shock and risk of MOD [100].

After nearly half a century of trauma resuscitation research since the description of ARDS, it has become clear that the best resuscitative strategy for a person in hemorrhagic shock to prevent MOD is not based on crystalloid nor colloid solutions but a balanced infusion of blood components or, preferably, fresh whole blood to mimic replacement of lost whole blood [101]. Damage control resuscitation was developed by the Tactical Combat Casualty Care Committee of the U.S. Military, and utilized for combat casualties in Iraq and Afghanistan [102]. The principles of damage control resuscitation include:

1. Permissive hypotension
2. Restriction of excess crystalloid resuscitation
3. Earlier blood transfusion with balanced plasma and platelet to red blood cell transfusion ratios
4. Goal-directed correction of coagulopathy

A balanced transfusion strategy of fresh whole blood or PRBCs, fresh frozen plasma (FFP), and platelets (at or near a 1:1:1 ratio) has been shown to enhance hemostasis and reduce the incidence of ARDS, acute kidney injury, MOD, and death [103, 104].

### 35.4.2 Judicious Use of Blood and Blood Product Transfusion

Although balanced blood and blood product transfusion has clear benefits over crystalloid during damage control resuscitation, transfusions are associated with immune dysregulation and MOD. A large body of evidence has confirmed the clinical equivalence and safety, and in some cases advantages, of a restrictive transfusion strategy for critically ill patients [105, 106]. Healthcare systems that have adopted restrictive transfusion protocols in intensive and acute care units have reported decreases in rates of transfusion and MOD [107, 108]. Other techniques that can be used to reduce the risk of MOD from transfusion of blood and blood products, include washing packed red blood cells, filtration, irradiation, pre-storage leukoreduction, and use of whole blood [105]. However, these techniques have not been associated with marked reductions in MOD or death among injured patients [109]. Regardless, a restrictive transfusion strategy for critically injured patients is cost-effective, reduces the risk of MOD, and introduces no harm. In anemic patients with ongoing hemor-

rhage, with risk of significant bleeding, or with concurrent ischemic brain, spinal cord, or myocardium, the optimal transfusion strategy remains unknown [110].

### 35.4.3 Timing of Secondary Interventions

Timing for re-exploration and definitive management of the open abdomen is 24–72 h after initial laparotomy to avoid the secondary inflammatory insult of an open abdomen and packing used to control non-surgical bleeding while allowing time for optimal resuscitation and normalization of physiologic responses. The timing for definitive care of non-life-threatening injuries in the polytrauma patient is less well established [80]. The balance between adequate recovery to tolerate a major operative intervention and the risk of a secondary insult that triggers an excessive inflammatory response due to inadequate recovery and persistent priming of the innate immune response that leads to MOD is still a debated topic without definitive data to inform decision-making.

### 35.4.4 Prevention of Ventilator-Induced Lung Injury

Ventilator-induced lung injury (VILI) occurs from extremes of mechanical forces applied to the lung parenchyma. Ventilation of areas of the lung with low compliance (e.g., pulmonary contusion, pneumonia, edema) direct administered tidal volumes to areas of the lung with high compliance. This results in increased alveolar pressure, over-distension, and injury to otherwise healthy lung parenchyma (i.e., barotrauma). Conversely, when alveoli in areas of the lung with high compliance repeatedly collapse at end expiration and then re-open with inspiration leads to a damaging shear stress injury (i.e., atelectotrauma). VILI results in an inflammatory reaction that causes release of pro-inflammation mediators, recruitment of activated leukocytes, and further pulmonary dysfunction; the results of VILI are functionally and histologically indistinguishable from ARDS [4]. The effects of VILI are not localized—hypoxemia exacerbates distant tissue ischemia-reperfusion injury, pro-inflammation cytokines join the systemic circulation, and the immune system becomes increasingly dysfunctional.

VILI can be reduced by a lung protective ventilation (LPV) strategy. LPV employs lower tidal volumes, higher positive end expiratory pressure (PEEP), and lower inspired oxygen fraction than conventional ventilation strategies. Functionally, LPV restricts plateau and driving pressures and prevents barotrauma and atelectotrauma. Although LPV reduces mortality in patients with ARDS, there is currently insufficient evidence to support the use of LPV in an attempt to prevent ARDS and MOD in high-risk patients [111].

### 35.4.5 Immunonutrition

Malnutrition occurs in up to 50% of critically ill patients due to a deterioration of nutritional status in the setting of pronounced metabolic demands and systemic inflammation. Malnutrition that occurs in the setting of critical injury and hypermetabolism leads to muscle wasting, delayed wound healing, failure to wean from ventilator support, higher rates of nosocomial infection, and greater risk of MOD and death. Critical injury-related malnutrition can be mitigated by targeted nutrition therapy and immunonutrition. Immunonutrition aims to maintain the integrity of the intestinal epithelium, support the innate mucosal immunity and mitigate local and systemic inflammation by incorporating interventions related to the route (i.e., enteral vs. parental), timing, and contents of feedings.

Early enteral feeding is safe (even in the presence of an open abdomen) and effective in maintaining intestinal mucosal integrity and modulating the mucosal immune response [112]. Enteral nutrition has been shown to support the mucosal-associated lymphoid tissue (MALT) that produces the majority of the body's IgA [113]. In turn, MALT and gut IgA prevent over-

growth of pathologic bacteria and limit release of toxic by-products into mesenteric lymphatic system and systemic circulation, which is associated with reduced risk of ARDS and MOD. Early enteral feeding also maintains the gut microbiome, which may further reduce the risk of pathogenic bacteria and yeast overgrowth, and MOD.

One of the major constituents in nutritional support that appears to impact outcomes in polytrauma is the provision of high levels of protein. Protein supplementation preserves lean body mass and acts as a direct nutritive source for the metabolically challenged polytrauma patient, particularly for patients who also have a significant TBI or burn injury. Published guidelines recommend providing at least 2 g/kg/day of protein for critically injured patients [114]. Although it is difficult to achieve this level of intake using standard enteral formulas without protein or amino acid supplementation, it can be done safely with protocolized feeding strategies [115].

In addition to early enteral feeding with adequate protein concentrations, some intensivists suggest administration of probiotics and synbiotics (e.g., probiotics with prebiotic fiber) to maintain a healthy microbiome and buffer against the impacts of the frequent need for antibiotics (e.g., perioperative prophylaxis, surgical site, and nosocomial infections). There is marked confusion and lack of clear data as to the benefits of probiotics. However, meta-analysis of available randomized trials suggests that probiotics and synbiotics can reduce the rate of nosocomial infections (e.g., VAP) and total antibiotic days but not intensive care utilization or mortality [116].

A number of pharmaconutrients have been studied for immunonutrition, including arginine, glutamine, branched chain amino acids, n-3 fatty acids, selenium, vitamins A, C, and E, and nucleotides. There have been inconsistent results from clinical trials of pharmaconutrient supplementation. Broadly speaking, the findings suggest that the mechanism by which immunonutrition modulates the risk of MOD is likely selective and depends on genetic, injury and/or environmental influences [117]. However, a meta-analysis of 74 controlled trials and 7574 surgical patients demonstrated that immunonutrition (i.e., enteral nutrition with pharmaconutrients) was associated with significant decreases in infections, anastomotic failures, sepsis, and mortality [118]. Immunonutrition is evolving and the gaps in our understanding of pharmaconutrient–host interactions, the metabolic basis for immune modulation, and the dosage and routes required to achieve risk reduction is improving.

## 35.5 Long-Term Outcomes

The impacts and burden of critical injury and MOD persist long after hospitalization for trauma survivors, their families, and their communities. Long-term follow-up of 322 critically injured patients reported that those who experienced MOD were four times more likely to require assistance during activities of daily living at 2 and 7 years after discharge compared to those who did not experience MOD [20]. However, long-term survival and functional status were the same for patients who suffered single organ failure and no organ failure. Almost half of patients who experienced MOD achieved complete recovery to pre-injury functional status.

Recent and current study of long-term, patient-reported outcomes among injured and burned populations have facilitated better understanding of physical, mental, and social health after discharge [119]. In general, trauma and burn survivors experience persistent long-term sequelae that effect their physical and mental functioning, community re-integration and return-to-work or -school [120, 121]. However, the added impacts of MOD on long-term outcomes has not been well defined.

The heterogeneity in outcome measures and instruments used to study long-term outcomes creates a major barrier in the synthesis of results to inform a comprehensive understanding of MOD survivorship and opportunities for system improvement. Future work in this field should focus on patient, family, and provider consensus-based outcome measures, including survival, physical function, cognition, mental health, strength, pulmonary function, health-related quality of life, and pain [122]. A better under-

standing of life after MOD can be used to inform goals of care discussions, shared decision-making, and interventions and services that promote a fuller recovery.

## 35.6 Conclusion

MOD is the result of dysregulated immune and inflammatory responses driven by both the innate and adaptive immune systems. Additionally, the endogenous responses that aim to restore homeostasis are inadequate and potentiate the immunoinflammatory dysregulation and often act in synergy to produce the characteristic syndromes associated with MOD. Despite large reductions in the incidence of MOD globally, the mortality associated with MOD has minimally changed. Therefore, preventing MOD is critical, and hinges on damage control resuscitation and surgery, minimizing further organ injury caused by ischemia-reperfusion injury, avoiding ventilator-induced lung injury, eliminating unnecessary blood and blood product transfusion, and systematic but individualized use of immunonutrition. Survivors of MOD often face considerable and long-term recovery challenges that should be identified and managed in a multidisciplinary manner.

**Key Concepts and Take Home Messages**

- Multiple organ dysfunction (MOD) is the manifestation of an excessive, dysregulated immune-inflammatory response directed by a genomic storm induced by serious, injury and/or infection. More specifically, MOD is the result of dysregulated immune and inflammatory responses driven by both the innate and adaptive immune systems and the inadequate endogenous responses that aim to restore homeostasis.
- The MOD syndrome phenotypes represent a spectrum of degree of dysfunction (e.g., severe and multiple organ systems involved versus mild and a single organ system involved) and timing (e.g., early and rapidly progressive to death versus late and prolonged).
- Improvements in injury prevention and control, trauma system enhancements, and surgical and critical care delivery have reduced the incidence and overall severity of MOD. However, these advances have not markedly changed the high mortality rate associated with severe MOD from extensive polytrauma. Most interventions designed to treat MOD have not proven efficacious, and therapy consists largely one of organ function support until resolution occurs. Therefore, prevention remains paramount.
- Strategies to prevent MOD include damage control resuscitation and surgery, minimizing ventilator-induced lung injury, eliminating excess transfusion of blood and blood products, and use of immunonutrition.

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# 36 ICU Management: General Management in the Elderly in ICU

Basil Andreas Hatz, Franziska Ziegenhain, and Kai Oliver Jensen

**Learning Objectives**

- Highlight the need for special SOP for elderly.
- Know about the therapeutic options on ICU.
- Value the need for debate the admission to ICU with the patient/relatives prior to surgery.

## 36.1 Background

### 36.1.1 Frailty

Different approaches to describe the vulnerability of the geriatric patient can be found in literature. The most frequently applied terms are "frailty" and "biological age" [1, 2]. Frailty refers to a loss of the ability of an individual to cope with external stressors due to preexisting conditions. Frailty is not primarily defined by age; nevertheless, older people tend to have a higher incidence for frailty. Different scores have been developed to estimate the frailty of patients [2–4]. Most of them include parameters like nutritional status, ability to care for oneself, mobility, and comorbidities [1, 5, 6]. Frail patients are considered to have a higher biological age and are more likely to have adverse outcomes [5, 7]. For elderly patients who are administered to the ICU, a high frailty is a negative predictor for survival [5].

### 36.1.2 Preexisting Conditions

The majority of elderly trauma patient suffers from comorbidities. These preexisting conditions tend to complicate diagnostic processes and therapeutic decisions. When deciding if a patient needs intensive care, these comorbidities should be taken into consideration. A patient with a severe renal insufficiency might need perioperative intensive care to enhance the chances of survival. Furthermore, regular medication might alter the ability of the body to cope with trauma. For example, reactive tachycardia might be absent due to beta blockers [8, 9]. The prevalence of different comorbidities varies between countries. Nevertheless, the most frequently found diseases are very similar and are listed in Table 36.1 [10–12].

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**Table 36.1** Most frequent comorbidities in geriatric trauma patients

| Most common preexisting conditions [13–15] |
|---|
| • Cardiovascular diseases |
| • Hypertension |
| • Diabetes mellitus |
| • Neurodegenerative diseases |
| • Cancer |
| • Arthritis |
| • Chronic pulmonary diseases |

### 36.1.3 Trauma Mechanism

The trauma mechanism in elderly patients does not necessarily indicate the severity of the injury. In younger trauma patients, severe multiple injuries occur from high energy trauma mechanism such as traffic accidents or falls from more than 3 m. In elderly multiple injured patients, low energy trauma mechanisms such as falls from less than 3 m results in severe injuries [16–18]. Most of these are domestic falls from a standing height. This leads to other injuries being suspected in elderly polytrauma patients than the injuries found in young polytraumatized patients with similar severity of the injuries [19–21].

### 36.1.4 Injury Severity

Elderly trauma patients mostly suffers severe injuries from low energy trauma mechanism [22]. The comorbidities and slower protective reflexes of geriatric patients rises the risk for severe injuries from minor trauma like tripping domestic falls. Younger patients mostly do not have severe comorbidities and can compensate stumbling falls with their reflexes. This makes severe injuries unlikely from minor trauma. Elderly patient may in same cases sustain multiple fractures or severe traumatic brain injury after a same-level fall [8].

## 36.2 ICU Treatment for Geriatric Polytrauma

### 36.2.1 General Considerations

Physiological changes in elderly patients greatly affect critical care management. Physiological reserve decreases by aging and seems to be an explanation for the higher mortality and long-term outcomes compared to younger patients [23]. Elderly trauma patients need different treatment approaches and options. Specific geriatric treatment systems with high-volume of geriatric patients seems to improve to overall outcome [10, 16, 17, 21, 22, 24]. A high index of suspicion for injury may help to recognize further impairment. Preexisting comorbidities may worsen small injuries. Thoracic contusions with rib fractures worsening a reduced lung function and rises the risk for pneumonia [11]. In addition, the risk for solid organ injury when rib fractures are present seems to be higher. Considering these conditions in intensive care treatment by consequent treatment adaptations can improve the outcome of elderly multiple injured patients [11]. Ethical considerations should also be noticed. For example, due to the high probability of adverse outcomes, an ICU admission with maximum medical care in a severely injured, frail, and unwilling geriatric patient may be ethically contraindicated [11, 12].

However, many critically injured elderly patients benefit from intensive care, and this option should not be ruled out based on patient age alone. We therefore recommend initiating intensive care when indicated, while closely defining and then frequently reevaluating what therapeutic option is best for the patient. Whenever possible, these options should be discussed with the patient directly. If this is not possible due to the patient's condition, the medical team should act according to the patient's health care directive if available. Family members are also an important resource to help determine the presumed will of the patient. If none of these options are available, the medical team must reach consensus on the treatment objective. For these reasons, the development of an SOP for assessing ICU admission and intensive care treatment in elderly polytraumatized patients would in our opinion be of tremendous help in every institution. In summary, before treatment can be initiated in critically injured geriatric patients, an assessment should be made to underline the need for it and reach a consensus within the treatment team and the relatives.

### 36.2.2 Development of Consensus Group

An interdisciplinary team approach improves the outcome in treatment of severely injured trauma patients. Primarily, the goal is to develop evidence-based SOPs for the trauma care of critically ill elderly patients in the ICU. An interdisciplinary international consensus group comprised of traumatologists, orthopedic surgeons, intensivists, anesthesiologists, medical ethics experts, and geriatricians experienced in the treatment of severely injured geriatric patients, and with previous experience in guideline development was therefore created (Table 36.2). This taskforce of the German trauma association section for geronto-traumatology (Sektion Alterstraumatologie der DGU®) has now begun the development of a guideline for the ICU admission for severely injured geriatric patients.

At the same time, the DGU consensus group started to generate an SOP for the treatment of severely injured geriatric patients in the ICU. In order to create a guideline which is easy to follow and understand, the group decided to organize the SOP into organ-based rather than problem-based chapters (Table 36.3). Since ethics play an especially important role in geriatric care, ethical considerations with different therapeutic options based on those considerations form a substantial component of the SOP.

**Table 36.3** SOP chapters for the treatment of severely injured geriatric patients in the ICU

| SOP chapters | |
|---|---|
| CNS | Delirium |
| | Reduced brain volume |
| Cardiovascular system | Volume management |
| | Transfusions |
| | Catecholamines |
| | Cardiovascular diseases |
| Coagulation | |
| Pulmonary system | Ventilator-associated pneumonia |
| | Thoracic trauma |
| | Tracheotomy |
| | Pulmonary diseases |
| Nephrology | Dialysis |
| Liver | |
| Pharmacology and medication | |
| Infectiology/ immunologic system | |
| Gastrointestinal tract | Nutrition |
| | Digestion |
| Musculoskeletal system | Frailty/preexisting condition |
| | Physiotherapy/ergotherapy |
| Skin | Decubitus |
| Externa | Pacemakers |
| | Catheter |
| Ethical problems | Therapy limitations |
| | Reanimation |
| | Comfort therapy |

### 36.2.3 Therapeutic Options

Therapeutic decisions are based on the patient's desired therapeutic goals and the burdens and risks of potential treatment options. Advanced care planning, designed to ensure that patients receive their desired emergency care in the event of a life-threatening crisis, has been further developed in recent years. In Germany, a one-paged sheet with detailed patient wishes in the setting of acute illness or injury, referred to as Physician Orders for Life-Sustaining Treatment (POLST or ÄNo, in German) can be added to an advanced directive [12]. Based on these choices, three treatment options exist:

**Table 36.2** Participating subspecialties of the interdisciplinary international consensus group

| Participating subspecialties |
|---|
| Traumatology |
| Geriatric medicine |
| Intensive care medicine |
| Anesthesiology |
| Orthopedic surgery |
| Medical ethics |

#### 36.2.3.1 Option A

Option A is the standard option for patients without a known advanced directive. This treatment plan has the aim to keep the patient alive with all the medical interventions that are necessary. Mechanical resuscitation, intubation, necessary escalation of the therapy as well as the treatment of complications are included. Maximum care

should be administered to patients in this treatment group [12].

#### 36.2.3.2 Option B

Option B represents a restricted version of Option A. This means, that due to the patient's situation, medical conditions and personal wishes, certain restrictions are formulated. A common limitation is the prohibition of mechanical resuscitation while still allowing drug resuscitation. Surgeries with a high risk or mortality are normally not a valid option. Smaller procedures with a clear benefit for the patient might be a good option and should be taken into consideration.

The four major treatment options that are patient can exclude are cardiopulmonary resuscitation, invasive ventilation, and ICU admission. In palliative situations, some patients might also exclude a hospital admission [12].

#### 36.2.3.3 Option C

This last option refers to patients who are in a palliative situation. The care that they receive should be designed to maximize the comfort and quality of life. Extending the remaining life span is not a primary goal. To ensure the best possible supportive care, an admission to the ICU might still be an option and should be discussed [12].

## 36.3 Summary

The rising age in multiple injured trauma patients requires adapted treatment patterns. The elderly polytrauma patient on the ICU has other requirements, starting with the trauma mechanism which may be very low energy with yet a high impact on the severity of the injury. Although mostly minor trauma leads to a high injury severity score, the accompanying comorbidities and the reduced reflexes enhance the effect of an accident. These physiological changes must be considered in the treatment of elderly polytrauma patients. Therapeutic options from "full intervention" to "no intervention" with deep ethical considerations have great importance especially on the ICU.

**Key Concepts**

- Preexisting conditions, frailty, and ethical aspects influence treatment decisions in geriatric patients a lot.
- Admission to ICU is worth to debate with patients/relatives prior to interventions.
- There are different therapeutic options for geriatric patients on ICU.

**Take Home Messages**

- Treatment in the ICU has shown to improve outcomes despite older age.
- The indication for admission to the ICU should be addressed prior to any surgery with patients and/or relatives.
- SOPs should be available.
- Most principles of organ support require more subtle treatment than in younger patients.

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# ICU Management: Clearing Patients for Surgery

# 37

Max Lempert and Hans-Christoph Pape

**Learning Objectives**

- Understand the requirements for secondary major reconstructive surgeries in polytrauma patients.
- Understand the incidence and major causes of associated complications.
- Understand the relationship between surgical timing, magnitude of surgery, and complications during the days of intensive care, i.e., the secondary period after major trauma.
- Understand the direct and indirect sequelae of ICU complications after severe trauma.

## 37.1 Introduction

In the early setting after injury, several physiological changes are well described when it comes to decision-making [1]. Four different cascades (shock (oxygenation and ventilation), coagulopathy, acid base changes, and soft tissue injuries) have to be assessed [2].

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During the further stay of the patient on the ICU, some of the issues to be considered in the early stages of resuscitation are usually solved. Within 24 h, there is usually normalization of hypothermia, acidosis, and usually coagulopathy as well. If these are not under control, it may be a sign of ongoing undetected hemorrhage, or other causes that might be stimuli for inflammation.

This summary deals with the factors to be addressed during the secondary period after major trauma, which may be caused by infection, pulmonary complications, a second hit phenomenon, and lead to issues of a safe definitive surgical management [3, 4].

## 37.2 Clinical Status After 24–48 h After ICU Admission

Usually, many nonsurgical causes of bleeding should be controlled at the secondary period after injury. Among them are correction of hypothermia and coagulopathy. As these belong to the physiological changes described in the triad of death (shock, hypothermia, coagulopathy), they may help control acidosis as well. In general, hypothermia is known to affect coagulation, if addressed rapidly [5]. Coagulopathy affects several other pathways, such as the cellular energy turnover, the cardiac effects induced by hypothermia. The parameter used the most to describe hem. Shock is lactate. However, care should be


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taken not to rely on lactate alone, as various metabolites may affect the measurement of metabolic acidosis [6]. Also, chronic diseases are associated with pathological lactate values [7] and can contribute to the general inflammatory response after trauma.

Another associated factor is the volume status, namely the ratio of fluid input versus output (I/O ratio), which is an indirect indicator of inflammation, where volume is lost into the "third space," the interstitial space. In this situation, the patient frequently requires sustained amount of volume replacements and may require additional vasopressors in order to maintain a decent systolic blood pressure. In this situation, major surgeries should be avoided.

Several scores advocate perioperative assessment to be applied after completion of the initial resuscitation. One represents a recommendation to include the four pathophysiological changes cited above (*coagulopathy*, *acid base changes*, *indicators of acute hemorrhage*, *body temperature*, *and soft tissue injuries*). One focuses on parameters indicative of the acid base status (pH <7.25, BE <5.5, lactate >4 mmol/L) [8]. The most recent one utilized a nationwide trauma registry and the resulting parameters from a deductive calculation revealed admission BP, NISS of >50 points, or mass transfusion (pRBC of 15). A validation of all of them proved the most recent one to be the most sensitive. It used an independent database (3668 patients) and separated results for the prediction of early (e.g., death from hemorrhage) versus late complications (e.g., sepsis), in an ROC analysis. For early complications, the combination of indicators of shock, coagulation, and soft tissue injuries (AUC 0.77) was superior to acid base changes alone (AUC 0.67). Late complications were predicted reliably, when a similar combination was used as described above, while acid base changes had no predictive value [9].

It has also been suggested that patients at risk of adverse outcome, such as those with head injury, bilateral lung contusions, multiple long bone injuries, coagulopathy, hypothermia, or estimated operation time of >6 h, should be considered for sequential staged surgical management [10]. A new list of parameters to separate borderline from unstable patients has recently been made available (Table 37.1). Markers of the adequacy of shock reversal, such as serum lactate, are measured routinely in trauma centers. It is therefore easy to envisage the routine use of markers of pro- and anti-inflammatory systems such as IL-6, IL-10, and procalcitonin to aid in the decision to carry out damage control surgery. Delaying definitive surgery until the shock state is fully reversed would appear to be not only beneficial but imperative [8]. All these measures have led to a more flexible approach in fracture management (Table 37.2). While the recommendations were strictly based on phases following certain time frames of injury ("window of opportunity" during day 1 surgery [11], currently the patient's response is usually assessed and included in the decision-making and the techniques used for early fracture fixation.

## 37.3 Clinical Status Following Day 2 After ICU Admission

The factors discussed above that are monitored within the first 24 h after ICU admission continue to be relevant partly. As secondary hyperinflammation becomes more important and the relevance of the fluid balance is an additional issue. Histological studies in polytrauma patients have shown that their capillary leak can be detected in all organs [12]. By no means should patients undergo major surgeries in the lack of a balanced or negative I/O ratio, as this indicates an ongoing permeability disturbance, which includes the lung, regional perfusion of the extremities and the intestine, possibly supporting SIRS. This indicator usually goes along with a rise in the platelet count, which should be >95,000.

Another issue to respect even when the fluid balance is achieved, is to assess the intraoperative changes expected to occur. In this line, one should avoid prolonged prone or lateral positioning, as both may interfere with oxygenation. Therefore, lengthy spine surgeries, or lower extremity reconstructions should be avoided, unless the patient is completely normalized in terms of I/O, SIRS, and pulmonary function.

**Table 37.1** Revised parameters to assess the borderline trauma patient in 2020 [17]

| | | Parameters |
|---|---|---|
| Static parameters | Injury combination | • Polytrauma ISS > 20 and AIS chest >2<br>• Thoracic trauma score (TTS) > grade 2 |
| | Local injury chest | • Bilateral lung contusion: first plain film or<br>• Chest CT: – Unilateral bisegmental contusion<br>– Bilateral uni- or bisegmental contusion<br>– Flail chest |
| | Local injury trunc/extr. | Multiple long bone fractures + truncal injury AIS 2 or more |
| | Truncal | Polytrauma with abdominal/pelvic trauma RR, 90 mmHg) (Moore 3) and hem. shock |
| | Major surgery for non-life saving conditions | "Non-life saving" surgeries<br>Flexible (day 1, 2, 3) after reassessment according to individual patient physiology:<br>Safe definitive surgery (SDS) and damage control (DCO) |
| | Duration of first operative intervention | Presumed operation time >6 h<br>Intraoperative reassessment:<br>• Coagulopathy (ROTEM/FIBTEM)<br>• Lactate (<2.0–2.5 mmol/L)<br>• Body temperature stable<br>• Requirement >3 pRBC/h |
| Dynamic parameters | Blood transfusion requirements | Massive transfusion (10 units RBCs per 6 h)<br>Initiates "goal directed therapy" (massive transfusion protocols) |
| | Intra/perioperative | • ROTEM/FIBTEM<br>• Lactate clearance <2.5 mmol/L (24 h) |

**Table 37.2** Situations to clear a patient for major surgery while in the ICU

| Early changes | Early sec. changes | Late sec. changes |
|---|---|---|
| <24 h | 24/48 h | >48 h |
| Hypothermia | Cleared | |
| Acidosis | Cleared, if hem. controlled | |
| Coagulopathy | Cleared, if hem. controlled | |
| | | Hyperpermeability<br>(+I/O ratio, vasopressor req.)<br>**(I/O > −500 mL/25 h)** |
| | | II hit (hemorrhage, maj. surgery<br>**Platelet count > 95,000** |
| | | Infection (local wound/catheter/gen.) |
| | | Pulm. compl. (rep. pneumothorax) |

The value of intraoperative reassessment in the presence of multiple fractures has been discussed and it appears to be in widespread use [13]. The repeated use of parameters such as urine output, oxygenation, $pCO_2$ measurements, and requirement of vasopressors are important (Table 37.3). Also, serum lactate levels, obtained from a large data base, were predictive of mortality when lactate normalized within the first 24 h. It is an important additional finding although of limited use for the perioperative assessment [14].

While days 2–4 appeared to have been crucial in avoiding further surgeries [15], the current thinking is that normalized physiology may vary between patients despite similar injury severities. Thus, the best timing for major secondary surgery may lie between day 2 to any day within the first week to 10 days, as soon as the physiology is normalized [16]. Usually, the duration of any surgery should be adapted to avoid a second hit phenomenon. This usually means that in the case of multiple fractures, the duration of surgeries is limited to about 2–3 h per surgical session.

**Table 37.3** Factors to consider in the planning of a major reconstructive operation in an ICU patient

| | |
|---|---|
| Duration | (>3 h?) |
| Positioning | (Prolonged prone or lateral recumbency position?) |
| Sec. compromise lung function | (Dislocation of chest tube, pulm. compression) |
| Local pressure | (Pressure-induced compartment syndrome ass./w. positive fluid balance) |

**Table 37.4** Intraoperative reassessments during major secondary surgery while a patient is managed in the ICU

| Parameter group | Parameter | Criteria |
|---|---|---|
| Volume | Urine output | Stable |
| | Requirement of vasopressors | No increase |
| Lung function | Oxygenation | Stable |
| | $pCO_2$ measurements | Stable |
| Intra-op hemorrhage | HK | Rapid change |
| | HB (mostly too slow reacting) | |
| | ROTEM | Rapid change |

Further important factors to consider in the planning of a major reconstructive operation in an ICU patient are listed in Table 37.3. These should be discussed in a team effort by the treating ICU and surgical subspecialty (Table 37.4).

**Key Concepts/Conclusions**

- Decision-making should be performed rapidly and may be subject to revision before, during, or after the first surgical phase. Some trigger factors are known that require damage control or abbreviated surgeries. Among these are severe head and chest trauma, multiple fractures if the patient is unstable, or ongoing exsanguination. During the ICU period, the first day (<48 h after injury) is usually a time for completion of resuscitation, rewarming, and reversal of coagulopathy. If the associated parameters are not normalized by then, further issues should be considered (e.g., sec. splenic rupture, ongoing extremity bleeding). In the days thereafter, the second hit and infectious complications are crucial. The indication should respect a negative fluid balance, stable lung functions, limited intraoperative bleeding, and limited surgical time. Specific injury combinations for which a damage control orthopaedics approach should be considered are bilateral femoral fractures, and multiple injuries in elderly patients.
- This process of decision-making may be defined as "injury-patient tailored" to allow Safe Definitive Surgery.

**Take Home Messages**

- Respect patient physiology and response after completion of resuscitation.
- Respect negative I/O ratio and stable lung function.
- Respect the assumed surgical time (<3 h).
- Respect intraoperative changes (vasopressor, lung function, coagulopathy).

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# ICU Management: Venous Thromboembolism

38

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**Learning Objectives**

- To recognize the importance of VTE prophylaxis for polytrauma patients under ICU management.
- To describe the prevention of VTE in polytrauma patients under ICU management.
- To list chemical prophylactic solutions for VTE in polytrauma patients under ICU management.
- To explain the appropriate timing to start chemical prophylaxis for VTE to prevent bleeding complications in polytrauma patients under ICU management.
- To identify the contraindications for chemical prophylaxis in polytrauma patients under ICU management.

## 38.1 Definition and Epidemiology of Venous Thromboembolism

The definition of venous thromboembolism (VTE) includes both deep venous thrombosis (DVT) and subsequent pulmonary thromboembolism (PTE). DVT develops in the lower extremities before being transported to the lung by blood flow and, in turn, develop into an embolism. As PTE can be fatal, the diagnosis of VTE is of great clinical importance. PTE is more commonly referred to as pulmonary embolism (PE).

DVT is reported to occur in 40–80% of patients with major trauma without thromboprophylaxis. This statistic is based on objective diagnostic screening for asymptomatic DVT. An estimated 22% of trauma patients eventually develop PE. Symptomatic PE occurs in 0.25% of patients who have been treated with internal fixation surgery for femoral fractures. The overall mortality of patients who underwent any surgery and subsequently developed PE was 22.86%. The 30-day mortality after symptomatic PE in patients who underwent noncardiac surgery was 25.3%.

VTE is a preventable cause of death within the hospital setting. PE is the third major cause of death in trauma patients who survive the first 24 h after trauma. Approximately 80% of DVT cases have been reported to be clinically silent, and only 30% of fatal PE cases are detected prior to death. Only 1.5% of DVT patients presented with clinical characteristics suggestive of thrombosis prior to diagnosis using venography.

A recent systematic review published in 2018 [1] reported that PE was not associated with lower extremity DVT in adult trauma patients. The report suggested that new PE etiologies should be explored. Examples of this

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include considering the possibility of DVT originating in other veins (e.g., the vena cava and pelvic veins or within the pulmonary arteries) or that thrombi originating within the venous endothelium could develop via a different mechanism than those within the arterial vasculature. Whether the result of genetic variables or trauma, hypercoagulability, hyperinflammation, or autonomic dysfunction states should also be investigated as potential causes of PE in the trauma population remains to be determined.

## 38.2 Risk Factors of VTE

Virchow's triad is considered the most representative causative factor of VTE. It consists of venous stasis, intimal injury, and hypercoagulability. Venous stasis is caused by the immobility of the associated tissues. Intimal injury is caused by a local fracture or soft tissue injury. Hypercoagulability is induced by endothelial tissue injury. Trauma patients are highly likely to present with Virchow's triad. Polytrauma patients were reported to be more hypercoagulable than non-polytrauma patients in both the preoperative and postoperative periods. In addition, patients with major trauma were found to be hypercoagulable upon admission to the intensive care unit (ICU) and during recovery.

Polytrauma is a major risk factor of VTE. Other risk factors include increased injury severity score (ISS), lower extremity fractures, pelvic fractures, traumatic brain injury, acute spinal cord injury, chest injury, operative interventions, older age, male sex, and immobilization [2]. The incidence of VTE among adult trauma patients steadily increases with age until 65 years, after which the odds of developing VTE appear to level off or even slightly decrease [3]. Pelvic fractures have been found to be associated with a higher risk of VTE development [4, 5]. Among the patients with spinal cord injuries, the risk of VTE appears to vary. A higher index of suspicion for VTE is warranted in patients with upper thoracic spinal cord injuries (Table 38.1).

**Table 38.1** Risk factors of venous thromboembolism

| |
|---|
| • Polytrauma |
| • Increased ISS |
| • Pelvic fractures |
| • Lower extremity fractures |
| • Traumatic brain injury |
| • Acute spinal cord injury |
| • Chest injury |
| • Operative interventions |
| • Immobilization |
| • Increased age |
| • Male gender |

*ISS* injury severity score

## 38.3 VTE in Polytrauma Patients

In addition to a relatively high risk of VTE, other risk factors have been associated with polytrauma patients who are admitted to the ICU. Multiple fractures of the lower extremities and pelvis appear to increase the risk of PE. When thromboprophylaxis was not administered, 40–80% of patients with major trauma developed an objectively documented DVT. The incidence of DVT in patients with pelvic fractures was reported to be >50% when thromboprophylaxis was not administered [6]. Prior reports indicated that the incidence of death due to PE is between 0.4% and 2% and often occurs without warning in the postoperative period, making it the most common source of morbidity and mortality in patients who have survived the first 24 h after trauma. In the hospital setting, it is the most preventable cause of death in patients with major traumas [7].

The incidence rates of symptomatic DVT and PE in polytrauma patients have been reported to be 0.8% and 1.0%, respectively. Injury severity, major pelvic injury, and one or more operations were found to be independent risk factors for the development of symptomatic DVT, whereas age ≥60 years, male sex, and more than one operation were discovered to be risk factors for the development of symptomatic PE.

## 38.4 Goal of VTE Care for Polytrauma Patients

The primary goal of VTE care for polytrauma patients is to prevent symptomatic DVT/PTE and fatal PTE during hospitalization. In the chronic phase, the goal is to prevent the recurrence of VTE and, if applicable, to manage post-thrombotic syndrome. While outpatient clinics should be equipped to deal with the chronic phase, the short-term treatment of VTE will be the focus of this chapter.

## 38.5 Screening of VTE for Polytrauma Patients

Owing to the high incidence rate of asymptomatic clots, the rationale for screening is to detect any undiagnosed VTE. Screening with imaging modalities such as ultrasonography (US), magnetic resonance venography, computed tomography venography, and contrast venography are all used to identify asymptomatic DVT. However, serious practical limitations within the major trauma population make it difficult to routinely perform these imaging techniques. It is neither cost-effective (because asymptomatic clots are often found, and the means by which to address these are uncertain) or sensitive (because proximal clots are frequently missed). More than 25% of trauma patients are unable to undergo ultrasonographic examination of the proximal part of the affected lower extremities. DVT rates have been found to increase with surveillance, but the risk of PE did not decrease with surveillance in adult trauma patients, which suggests that the findings consist of asymptomatic DVT. In its guidelines on VTE prevention, the American College of Chest Physicians (ACCP) recommended against serial diagnostic US for asymptomatic DVT in the trauma population [8]. At present, no evidence supports the recommendation of the routine use of any particular screening tool as a method of reducing the risk of VTE in patients with pelvic and acetabular fractures. Moreover, the use of screening to exclude asymptomatic DVTs in patients with pelvic and acetabular fractures is currently not supported by evidence.

However, the screening of suspected VTE cases is considered meaningful in ICU-based management. D-dimer is a fibrin degradation product, a small protein fragment present in the blood after a blood clot is degraded by fibrinolysis. Its name is derived from the two D fragments of the fibrin protein that are joined together by a cross-link. The D-dimer concentration was measured using a blood test. D-dimer levels have frequently been used for VTE screening in patients with orthopedic trauma, but high D-dimer levels alone cannot be used to diagnose VTE. Most severely injured trauma patients without VTE have positive D-dimer levels. Measuring D-dimer levels might be of little value within the first 48 h of injury. The negative predictive value of D-dimer levels to exclude VTE in trauma patients was reported to be 100% after the first 4 days after the onset of injury. D-dimer levels are expected to decrease within a few days of trauma and that monitoring D-dimer levels in the ICU after the first few days could facilitate the early detection of VTE. Polytrauma patients may need repeated surgeries to fix multiple injuries, and it is important to understand that both trauma and surgery have significant effects on D-dimer levels. An increase in D-dimer levels following a decline is a potential sign of VTE development. D-dimer levels measured on the tenth post-injury day could be a useful predictor of VTE in major trauma patients (median ISS, 20). The cutoff that maximized the Youden index was 12.45 μg/mL [9]. The author of the article demonstrated the usefulness of D-dimer in predicting VTE in patients with pelvic or lower extremity fractures that required surgery. The cutoff D-dimer level was found to be 15.2 μg/mL on day 7 after injury [10]. If imaging examinations to detect VTE were repeatedly performed in all trauma patients, the financial and logistical burden on patients, medical staff, and technicians would soon become problematic. Using a D-dimer cutoff level as a reference is expected to reduce the number of imaging examinations performed in the future. Thrombin antithrombin III complex (TAT) is a protein complex consisting of throm-

bin and antithrombin that is formed in response to the high thrombin level caused by coagulation. As thrombin is rapidly bound by antithrombin, TAT is a good measure of thrombin level in the blood. One previous study used TAT as a screening tool for screening postoperative VTE in patients with lower limb and pelvic fractures [11], but the evidence of the usefulness of TAT in trauma patients is limited.

The definitive diagnosis of VTE requires imaging examinations. The author prefers to use US of the lower extremities to screen for DVT because this method is noninvasive, free from irradiation, and can be performed at bedside [12]. Contrast-enhanced computed tomography (CE-CT) scanning of the chest can also be used to detect PTE. Although CE-CT involves irradiation, it can be used to diagnose PTE. In addition, CE-CT can detect DVT during scanning of the lower extremities. It is recommended that all hospitals develop a formal strategy for diagnosing VTE.

## 38.6 VTE Prophylaxis for Polytrauma Patients

Omission of thromboprophylaxis during the first 24 h of ICU admission without obvious reasons is associated with an increased risk of mortality in critically ill adult patients, including those with multiple traumas. Every hospital should develop a formal strategy to prevent VTE in patients.

All polytrauma patients should receive VTE prophylaxis as part of their ICU management because of the increased risk of VTE in this population. The Antithrombotic Therapy and Prevention of Thrombosis, 9th ed: American College of Chest Physicians Evidence-Based Clinical Practice Guidelines (AT9) provides suggestions and recommendations on thromboprophylaxis use in major trauma patients and can be utilized as a reference [13]. Two approaches can be used for thromboprophylaxis, namely mechanical and chemical thromboprophylaxis. They can be used in combination if applicable (Table 38.2).

**Table 38.2** Prophylaxis of venous thromboembolism in polytrauma patients

| | |
|---|---|
| Chemical thromboprophylaxis | LMWH |
| | LDUH |
| | (Fondaparinux) |
| Mechanical thromboprophylaxis | IPC |
| | Venous foot pump |
| | GCS |
| Prophylaxis of PE | IVC filter |

*LMWH* low-molecular-weight heparin, *LDUH* low-dose unfractionated heparin, *IPC* intermittent pneumatic compression, *GCS* graduated compression stockings, *PE* pulmonary embolism, *IVC* inferior vena cava

## 38.7 Mechanical Thromboprophylaxis

The mechanical method of thromboprophylaxis is aimed at reducing the pooling of blood in the deep venous system that increases the venous flow of blood back to the heart. In addition, this method prevents microvascular damage of the veins caused by stretching during venous pooling. Mechanical prophylaxis does not affect coagulation, nor does it increase the risk of bleeding [14].

Mechanical methods of thromboprophylaxis are recommended primarily in patients with a high bleeding risk. Polytrauma patients fit this description; therefore, mechanical methods of thromboprophylaxis should be applied initially until hemostasis is achieved. The mechanical methods of thromboprophylaxis include intermittent pneumatic compression (IPC), venous foot pump, and graduated compression stockings (GCS). A multiple propensity score-adjusted analysis revealed that the use of IPC, but not GCS, was associated with a significantly lower risk of VTE in critically ill patients admitted to the ICU of a tertiary-care medical center [15]. Active and passive motions of the ankle are also recommended if the patient can manage it.

However, mechanical prophylaxis does have its limitations (Table 38.3). If a patient presents with lower extremity injuries, they may not be able to wear these devices. The presence of compartment syndrome and peripheral artery disease

**Table 38.3** Contraindications of thromboprophylaxis

| | |
|---|---|
| Chemical thromboprophylaxis | History of heparin-induced thrombocytopenia (Contraindications of using heparin) |
| | Active bleeding or risk of bleeding |
| | Intracranial hemorrhage |
| | Spinal injury |
| | Abdominal organ injury |
| | Coagulopathy |
| Mechanical thromboprophylaxis | Lower extremity injury |
| | Compartment syndrome |
| | Peripheral artery disease |

in the lower extremities of the patient are also contraindications to the application of mechanical prophylaxis. Moreover, the increased odds of peripheral nerve paralysis and compartment syndrome should be kept in mind when considering the use of these mechanical prophylactic devices. Poor compliance has also been observed to be a disadvantage of the mechanical method. Moreover, the risks of developing PE and DVT also do not appear to decrease when mechanical prophylaxis is utilized in adult trauma patients.

## 38.8 Chemical Thromboprophylaxis

The risks of developing DVT and PE can be reduced with chemoprophylaxis in adult trauma patients. Chemical thromboprophylaxis using anticoagulants is recommended once the initial bleeding caused by the trauma has been stopped. Approximately 2 days after the initial trauma, the thrombosis risk is considered to be greater than the bleeding risk. Therefore, the ideal period for commencing chemical prophylaxis with anticoagulant period is between ICU days 3 and 8. However, polytrauma patients admitted to the ICU are highly variable with regard to their general condition, site of injury (particularly in the case of head trauma), and injury severity. Therefore, a generic protocol for chemical thromboprophylaxis cannot be applied to all polytrauma patients.

Low-molecular-weight heparin (LMWH) or low-dose unfractionated heparin (LDUH) are recommended for patients with major trauma. The ACCP guidelines recommend the use of LMWH in patients with major trauma [13, 16]. A history of heparin-induced thrombocytopenia (HIT) is a contraindication for heparin use as chemical thromboprophylaxis. Instead, Xa (activated factor X) inhibitors such as fondaparinux may be considered as an alternative. Edoxaban is a direct-acting inhibitor of Xa and is utilized for VTE prophylaxis in hip fracture patients and patients receiving total joint arthroplasty [17]. However, evidence is lacking to support the use of these so-called direct oral coagulants (DOACs) for VTE prophylaxis in polytrauma patients. The use of aspirin alone is not recommended for thromboprophylaxis in any patient group. Warfarin should also not be used for thromboprophylaxis in hospitalized patients. The maximum effectiveness of anticoagulation is achieved after approximately 4–5 days, as it takes at least 36 h to produce a measurable effect.

Contraindications for chemical thromboprophylaxis include active bleeding or risk of bleeding, intracranial hemorrhage (ICH), spinal injury, abdominal organ injury, and coagulopathy (Table 38.3). After craniotomy or intracranial pressure monitoring, patients are advised to consult a neurosurgeon to discuss the necessity of chemical thromboprophylaxis. After undergoing open fixation of a spinal fracture, patients are sometimes given chemical thromboprophylaxis for 2 days to prevent paralysis induced by hematoma. The hemostasis of bleeding due to an abdominal organ injury should be confirmed, and any coagulopathy should be addressed before initiating chemical thromboprophylaxis [18]. Currently, no consensus has been reached among experts regarding the precise time at which chemical thromboprophylaxis is most safely and effectively administered in patients with traumatic brain injury. However, a comprehensive literature review on this topic that suggested that chemoprophylaxis should not be given within 3 days of injury for patients with a moderate or high risk of ICH may lend some insight.

Provided that chemoprophylaxis is administered 48 h post injury, its use is justified in low-risk patients who have not yet developed ICH expansion. If low-risk patients develop ICH expansion within 48 h post injury, chemoprophylaxis can be administered after day 3. In patients with diffuse axonal injury who have not developed ICH within 72 h, chemoprophylaxis can also be considered. DVT proportions significantly increase when chemoprophylaxis is withheld for longer than 7 days [19].

### 38.8.1 Heparins

Heparin is a natural mixture of mucopolysaccharides that potentiates the action of antithrombin. Administration of LMWH within 24 h or once hemodynamic stability is achieved lowers the incidence of VTE in patients undergoing surgical stabilization of acute pelvic and/or acetabular fractures. In trauma patients with pelvic or acetabular fractures, proximal (above knee) DVT with an elevated risk of PE is common. Chemoprophylaxis using LMWH is recommended for these patients. In contrast to fondaparinux, heparin has a much shorter half-life (the half-life of enoxaparin is 4.5 h), and its effect is at least partially reversible with protamine, unlike LMWHs, whose effects are less reversible. Therefore, when patients are potentially at risk of making multiple trips to the operating and interventional radiology suites in the early stages after trauma, the practicality of LMWH in terms of the reversibility of its effect and short duration of action make it an attractive option.

### 38.8.2 Fondaparinux

Fondaparinux is a synthetic pentasaccharide that acts as an indirect inhibitor of activated factor Xa. The downsides of fondaparinux are its half-life (which is 17 h) and irreversibility. Currently, no reversal agent has been approved, and the activities of reversal agents cannot be measured by any of the typical clotting parameters such as prothrombin time-international normalized ratio (PT-INR), activated partial thromboplastin time (APTT), and bleeding time. Ideally, an anti-factor Xa assay is required; however, this is not routine for most laboratories. Fondaparinux is also excreted renally and is therefore unsuitable for patients with renal impairment, particularly because it is difficult to monitor. Although well-powered studies have suggested that fondaparinux may be superior to LMWH in preventing VTEs (particularly proximal ones) in non-trauma patients, a few fundamental practical issues remain that make it unsuitable for many major trauma patients. Polytraumatized patients often have to make repeated and unscheduled return visits to the operating room, thereby conflicting with the long half-life and irreversibility of the effect of fondaparinux. The benefit of fondaparinux is that it eliminates the risk of HIT, a potentially serious complication related to thromboprophylaxis with heparins. Fondaparinux might be an alternative for anticoagulation treatment in patients with HIT [20].

## 38.9 Inferior Vena Cava Filter

An inferior vena cava (IVC) filter is a device that is aimed at preventing PTE in patients who have concomitant high risks of bleeding and PTE. Polytrauma patients often fit this description. Chemical thromboprophylaxis is possibly contraindicated in this population owing to the increased bleeding risk stemming from their injuries. In addition, lower extremity injuries do not allow for the application of mechanical thromboprophylaxis. An IVC filter is indicated in patients who have a high risk of VTE but are not suitable candidates for standard chemical and mechanical thromboprophylaxis. A patient who already had proximal DVT (above the knee) could benefit from an IVC filter insertion, especially if the patient has undergone multiple elective surgeries. IVC filter insertion can be considered for polytrauma patients during their ICU stay. Communication and consultation with

cardiologists and interventional radiologists are warranted.

To date, no randomized controlled trial has shown the efficacy of IVC filters. Therefore, their suitability for polytrauma patients remains a divisive topic [21–24]. Several guidelines exist, each with conflicting recommendations. The Eastern Association for the Surgery of Trauma (EAST) Practice Management Guidelines promotes the use of IVC filters in certain patients [25]. The guidelines recommend that insertion of a prophylactic IVC filter should be considered in very high-risk trauma patients who cannot receive anticoagulation because of the increased bleeding risk and have injury patterns that render them immobilized for a prolonged period. Examples of such injury patterns include severe closed-head injury (Glasgow Coma Scale <8), incomplete spinal cord injury with paraplegia or quadriplegia, complex pelvic fractures with associated long bone fractures, and multiple long bone fractures. However, guidelines from the American College of Chest Physicians (ACCP) advise against the use of IVC filters for primary prevention in patients, even if chemical and mechanical thromboprophylaxis are contraindicated [16]. However, this recommendation from the ACCP is targeted at patients who are undergoing major orthopedic surgery, a subgroup to which many trauma patients also belong. By contrast, the EAST Practice Management Guidelines are directed primarily to trauma patients. A report on the EAST guidelines explained that they are indeed useful but may overestimate the necessity of IVC filters [26].

Another controversial aspect of IVC filter insertion is the morbidity associated with the filter insertion itself. The risks include IVC thrombotic occlusion, IVC penetration by the filter, breakthrough PTE, and filter migration. A paradoxical increase in the DVT rate (fourfold to eightfold increase) has been reported. Filter retrieval is recommended by the CHEST Guidelines issued in 2012; however, the poor retrieval rates for retrievable filters are also a prominent concern.

## 38.10 The American College of Chest Physicians Guidelines, 9th Edition

The American College of Chest Physicians (ACCP) guidelines [13, 16] are evidence-based clinical practice guidelines that have been methodically derived from previous data. However, caution is needed because the existing evidence comprises heterogeneous populations consisting of various trauma injuries, a lack of data from well-designed studies, and only a relatively small number of studies. In the absence of prospective randomized controlled trials, VTE prevention policies will inevitably differ between institutions.

For major trauma patients, the ACCP guidelines suggest the use of LDUH (Grade 2C), LMWH (Grade 2C), or mechanical prophylaxis, preferably with IPC (Grade 2C) rather than no prophylaxis. For patients with a high risk of VTE (including those with acute spinal cord injury, traumatic brain injury, and spinal surgery for trauma), the guidelines suggest adding a mechanical to pharmacological prophylaxis (Grade 2C) when it is not contraindicated by lower extremity injury. If LMWH and LDUH are contraindicated, mechanical prophylaxis, preferably with IPC, rather than no prophylaxis is suggested (Grade 2C) unless contraindicated by lower extremity injury. The guidelines suggest adding a pharmacological prophylaxis alongside either LMWH or LDUH when the risk of bleeding diminishes or the contraindication for heparin therapy is resolved (Grade 2C). They suggest that an IVC filter should not be used for primary VTE prevention (Grade 2C). Lastly, they suggest that periodic surveillance should not be performed with venous compression ultrasonography (Grade 2C).

## 38.11 Treatment of VTE

The CHEST Guidelines and Expert Panel Report on Antithrombotic Therapy for VTE was published in 2016 [27]. New evidence suggests the use of direct oral anticoagulants (DOACs) such

as dabigatran (Grade 2B), rivaroxaban (Grade 2B), apixaban (Grade 2B), or edoxaban (Grade 2B) as long-term anticoagulant therapy for VTE in patients without cancer.

However, applying this guideline directly to polytrauma patients is decidedly inappropriate. Polytrauma patients that are managed in an ICU setting are still at risk of bleeding and require multiple surgeries to address their injuries. Surgeries to major injuries such as complex pelvic and acetabular fractures or long bone fractures become second hits and opportunities for secondary bleeding. Therefore, ICU physicians are likely to choose heparin (LMWH or unfractionated heparin) to treat VTE because it has been shown to effectively control bleeding. The CHEST guidelines recommend the use of an IVC filter in patients with acute DVT or PE who are being treated with anticoagulants (Grade 1B) [27].

The usefulness of DOACs for the treatment of VTE in polytrauma patients may be applied as a long-term modality of anticoagulant therapy after the polytrauma has been resolved, all surgeries have been completed, and the patient's general condition has stabilized. The treatment of VTE at this stage should be performed by a specialized physician outside the ICU.

## 38.12 Case Studies

### 38.12.1 Case 1: A 57-Year-Old Man

A man was injured in a traffic accident and diagnosed as having cranial and maxillofacial bone fractures, traumatic subarachnoid hemorrhage, cerebral contusion, left seventh and eighth rib fractures, a left clavicle fracture, a pelvic ring fracture, and bilateral tibia and fibula fractures. The ISS of the polytraumatized patient was 50. In addition to blood transfusion, transcatheter arterial embolization of the bilateral internal iliac arteries was performed to treat the shock. The pelvic and bilateral tibial and fibular fractures were stabilized with external fixation. The patient was treated in the intensive care unit. Internal fixation of the bilateral tibia fractures was performed 16 days after the injury. Anticoagulant therapy was not administered for the VTE prophylaxis because of intracranial hemorrhage. The CE-CT of the chest 2 days after the injury revealed asymptomatic PE (Fig. 38.1). Once the intracranial hemorrhage had subsided, the VTE was treated using unfractionated heparin followed by warfarin. After discharge from the hospital, the patient was given warfarin for approximately 4 months. Ten months after discontinuation of the warfarin therapy, he was diagnosed as having DVT of the bilateral femoral vein and inferior vena cava and was rehospitalized.

### 38.12.2 Case 2: A 71-Year-Old Man

A man was injured in a traffic accident. He was diagnosed as having an acute subdural hematoma of the head, flail chest with multiple rib fractures, a pelvic ring fracture, a right subtrochanteric fracture of the femur, and open fractures of the right tibia and fibula. The ISS of the polytrauma-

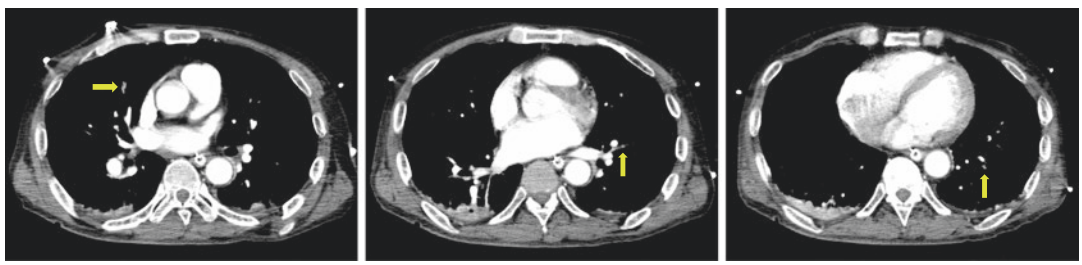

**Fig. 38.1** Contrast-enhanced computed tomography (CT) image of the chest displaying pulmonary embolism (PE). The arrows indicate the PE

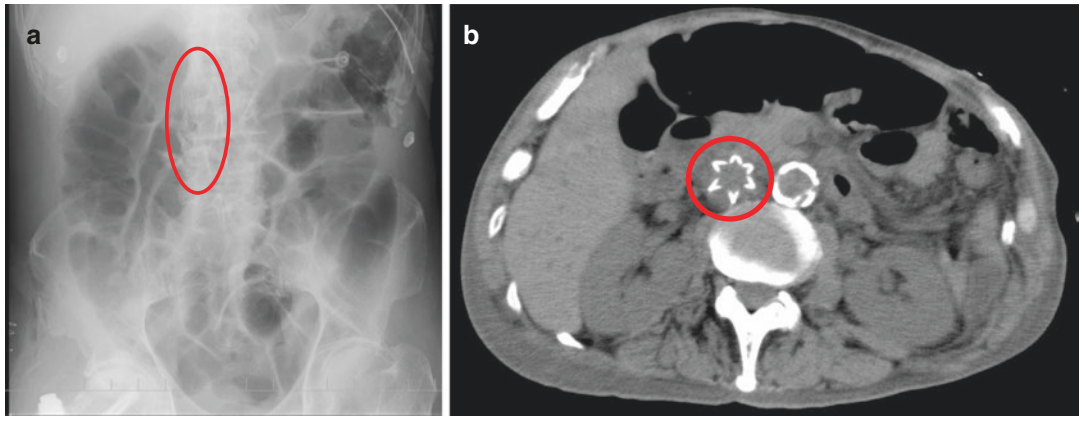


**Fig. 38.2** Inferior vena cava (IVC) filter inserted before the internal fixation surgeries to avoid PE. (**a**) Radiographic and (**b**) CT images. The circles indicate the IVC filter

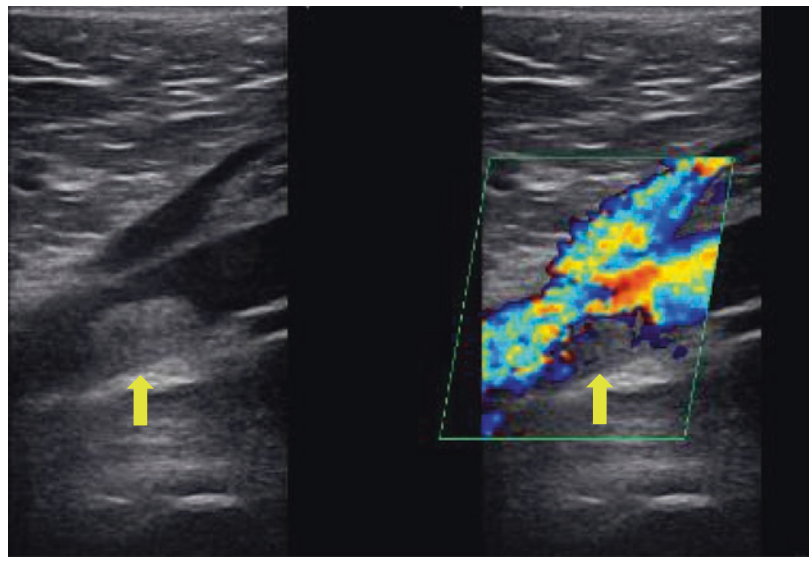

**Fig. 38.3** Ultrasonography image showing a deep vein thrombosis (DVT) of the lower extremities. The arrows indicate the DVT

tized patient was 41. The pelvic and right lower extremity fractures were stabilized by external fixation. He was treated in the intensive care unit. Anticoagulant therapy was not administered for VTE prophylaxis owing to intracranial hemorrhage. A free-floating DVT was found in the right leg on ultrasonography 12 days after the injury. An IVC filter (Fig. 38.2) was inserted before the internal fixation surgeries of the right leg to avoid PE. Internal fixation of the right femoral and tibial fractures was performed 15 days after the injury. PE was successfully avoided during hospitalization. The IVC filter was not removed (Fig. 38.3).

## 38.13 Conclusion

Care is needed to prevent VTE in polytrauma patients under ICU management.

**Key Concept**

- All polytrauma patients are at high risk of VTE, and prevention of fatal PTE is mandatory.

**Take Home Messages**

- All institutes should establish up-to-date guidelines and protocols to prevent VTE in polytrauma patients under ICU management.
- Chemical prophylaxis is the mainstream VTE prevention strategy.
- LMWH (also referred to as LDUH) is the recommended chemical agent for the prevention of VTE in polytrauma patients.
- Mechanical prophylaxis is less effective but may be useful when combined with chemical prophylaxis.

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# Part V

# Tertiary Period (After 8 Days)/ Rehabilitation

# 39 Rehabilitation Strategies in Polytrauma

Roman Pfeifer

**Learning Objectives**

- Understanding the major aim of rehabilitation in polytrauma patient.
- Understand the different clinical stages/phases in rehabilitation of severely injured.
- To understand factors and patient characteristics associated with negative outcomes.
- Understand the results obtained in a large follow-up study.

## 39.1 Introduction

Polytrauma victims are known to face limitations in their functional status, psychological outcome and quality of life. Moreover, trauma is associated with a large socioeconomic burden and significant health care costs due to the loss of economic opportunity and direct costs of treatment. Improvements in diagnostics and treatment over the last decades have led to a decrease in mortality in severely traumatized patients. Since a high number of patients survive their injuries, rehabilitation and quality of life have become more important.

Rehabilitation is described as a process of returning to a healthy and good way of life or of process of someone to do this (*Cambridge Dictionary*). After trauma, it is a problem-solving educational process aimed at reducing disability and handicap experienced by someone as a result of injury [1]. The main aim of rehabilitation is reduction of limitations and symptoms at the level of activity [1]. The complete restoration of functioning is very often not possible or requires a long process. Therefore, in polytrauma, rehabilitation is the most elaborate phase in treatment. However, only a few studies focus on this topic, and there is a huge lack of comparative studies investigating outcomes between different rehabilitation programmes [2]. Rehabilitation and outcome results acquired in monotrauma may be helpful; however, they do not consider the multidisciplinary rehabilitation approach required after polytrauma. Moreover, the presence of concomitant injuries, such as brain injury or upper and lower extremity injuries, may aggravate the rehabilitation process and need to be respected. The aim of this chapter is to describe the main aims in rehabilitation in severely injure patients, to discuss the present phases in rehabilitation and introduce the current results in this field.

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## 39.2 Aims of Rehabilitation in Polytrauma

Trauma rehabilitation clinics face several challenges in comparison to "classic" rehabilitation (general rehabilitation) centres and need to fulfil the following requirements in order to ensure the recovery of the patient [3–5]:

- There is a need for close cooperation and contact with acute hospitals due to high rates of re-operations or complications (e.g. infections) in the acute and post-acute phases.
- Trauma rehabilitation hospitals require a broad spectrum of therapists (e.g. physiotherapist, speech therapist, paint therapist, occupational therapist).
- Even in the post-acute phase, nursing may play a role in patients with multiple injuries.
- Psychological support during rehabilitation should have special consideration.

The reduction of the quality of life in trauma victims is related to reduced functional status, limitations, chronic pain, psychological disorders and social problems [6–8]. Long-term observations demonstrate that up to 30% of patients require medical aid for their disability and up to 20% report persistent disability after 10 years [7–9]. In particular, chronic pain and neurologic impairments were reported as factors that negatively influence the outcomes in patients who have sustained high-energy trauma [10, 11].

In addition to injury-related factors, such as injury severity and injury pattern, patients characteristics and socioeconomic factors have a strong impact on outcomes. Psychological disorders (post-injury depression 35–68%, anxiety 32–70%, and post-traumatic stress disorder 24–39%) were identified as factors that negatively affected the long-term functional outcome as well [12, 13]. Moreover, the self-efficacy of patients was the strongest predictor of the Sickness Impact Profile and return-to-work [12–14]. To address these issues, there is a need for concomitant post-traumatic psychological support and self-efficacy training [15]. Socioeconomic changes after injury may have consequences on a family, relationship or occupation. In general, long-term observation and follow-up studies in polytraumatized patients are sparse. The existing studies indicate that numerous factors have an influence on outcome. Age, educational level, pre-injury employment, and litigation are especially listed as relevant (Table 39.1) [16]. All these factors mentioned above indicate that a multidisciplinary rehabili-

**Table 39.1** Factors affecting the outcome of rehabilitation in polytrauma [3, 4, 6–9, 16, 25, 27, 28]

| |
|---|
| General outcome |
| • Not only injury-related factors, such as injury severity, injury site and treatment, play an important role for long-term outcome |
| • Specific characteristics of the patient, socio-economic factors and health habits are of immense importance too |
| • Authors reported high incidence of post-traumatic stress disorder (24–39%), anxiety (32–70%) and depression (35–68%) |
| • Women demonstrate high rate of psychiatric disorders and psychological support |
| • Long-term disability mostly due to head and lower extremity injuries |
| Upper extremity injuries |
| • Mainly low-energy mechanisms |
| • Better long-term results that after lower extremity injuries |
| • Concomitant vascular and nerve injuries are determinants of worse long-term outcome |
| Lower extremity injuries |
| • Injuries of the lower extremity cause significant impairments and loss of function |
| • 30–45% of patients report persistent pain |
| • 10–30% report disabilities and limited range of motion |
| • 7.5% received arthroplasty of the hip and 15.7% of the knee joint approximately 17 years after polytrauma |
| • Especially injuries below the knee injury are associated with worse long-term results |
| Pelvic injuries |
| • Mostly high-energy trauma with concomitant injuries of lower limb, spine, abdomen and head |
| • Associated injuries contribute to negative long-term results |
| • Neurologic impairments are major determinants for poor long-term outcome (peripheral nerve lesions, incontinence, sexual dysfunctions) |

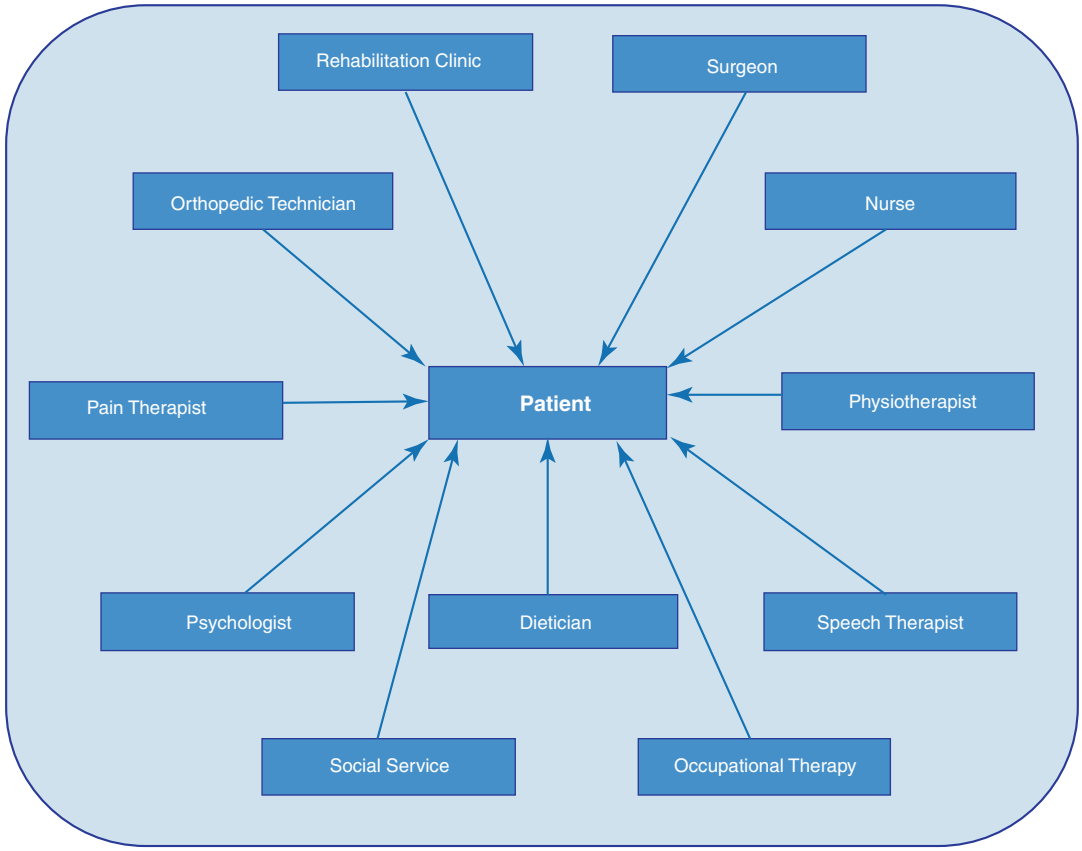


**Fig. 39.1** Trauma rehabilitation is a patient-oriented approach including multiple disciplines [3, 4]

tation approach appears to be the best way to improve outcome, potentially analogous to rehabilitation for stroke patients (Fig. 39.1) [17].

The identification of validated outcome parameters is difficult in polytraumatized patients. In general, literature indicates that effective re-integration with a focus on return-to-work or return-to-school, psychological support and quality of life are the main aims of trauma rehabilitation [18]. At the early stage, a close treatment relationship between the trauma surgeon and physiotherapist is required to allow the definition of individual concepts and aims [2]. Early transfer of patients to specialized trauma centres, early start with specific mobilization, training and non-weight bearing and involvement of psychologists and social workers are key concepts in multi-trauma rehabilitation [2]. Close communication with the patient is required to define individual aims with achievable goals of rehabilitation. Family members play a very important role and should be involved as soon as possible throughout the rehabilitation process [18]. The International Classification of Functioning, Disability and Health (ICF) allows a systematic analysis of existing disorders and communication between disciplines. It includes the basic aspects of function (joint function, coordination, pain, muscle strength, etc.), activity (re-integration, social situation, mobility, aids, etc.) and risk factors (weight, chronic pain, motivation, training, etc.). The ICF framework is successfully used in the rehabilitation of various neurological diseases [19, 20].

## 39.3 Phases of Rehabilitation

Based on the rehabilitation in patients with neurologic trauma and neurologic diseases, three to six phases in rehabilitation of severely injured patients can be distinguished (Fig. 39.2) [3–5].

1. In Hospital

   The "first phase" includes the acute treatment and early rehabilitation in the acute care hospital, which takes place directly after trauma. Already in the intensive care unit (ICU), early physical and physiotherapeutic measures are associated with improved mobility and activity in a post-traumatic course [21]. The main aim is the assistance of bodily function and reduction of secondary complications. Patients are often subjected to numerous acute operations and interventions; therefore, close cooperation with the treating trauma team is required. Moreover, these patients have very high care needs, psychological support, require monitoring and intense prophylactic measures [21, 22].
2. Primary rehabilitation

   Following the treatment in the acute care hospital and completed surgical treatment and monitoring, patients are transferred to post-acute rehabilitation/follow-up rehabilitation centres with the aim to recover from persistent limitations of functionality (phase two). The rehabilitation is predominantly aimed at treatment in this phase; however, acute problems (infections, need for re-operation or corrections) and secondary complications may arise and require close communication with the initial trauma team or even a return to an acute care hospital [21, 22]. Frequent radiological and clinical visits are still required. Further aspects are psychological support and early re-integration of patients to the job and social environments.
3. Outpatient

   In the third phase, the medical rehabilitation is to the greatest possible extent finished with residual deficits, limitations and dysfunctions. The main aim is the social and occupational re-integration of the patients. If further rehabilitation is required, patients are transferred to specialized, patient-oriented clinics with a main focus on residual problems, such as chronic pain treatment, psychiatric disorders, etc.

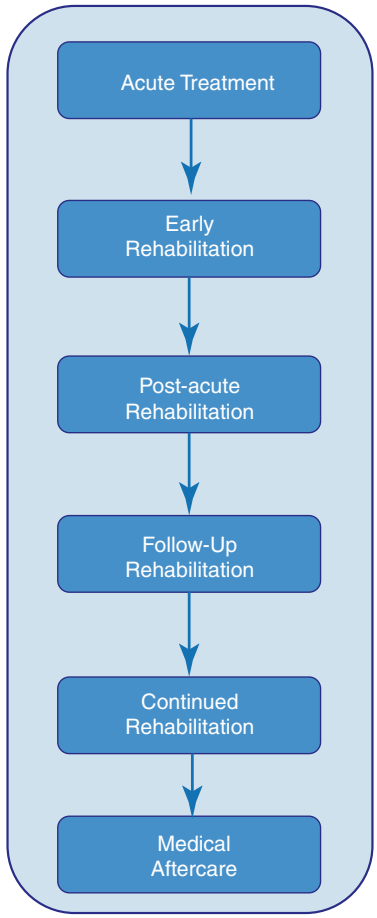


**Fig. 39.2** Phases in polytrauma rehabilitation [21]

## 39.4 Outcome

There is a lack of high-quality studies investigating the outcomes between different trauma rehabilitation programmes. Moreover, it is very difficult to compare the data in published studies due to differences in the trauma systems and rehabilitation strategies used. These data are of immense importance in order to improve the long-term outcome and quality of life in severely injured patients. Approximately one-third (32%)

of patients after severe trauma are transferred to a specialized rehabilitation clinic [23, 24]. Up to 50% are discharged home after treatment in acute care hospitals or 12% are relocated to other hospitals. Demographic parameters and injury patterns appear to play an important role in whether patients are further treated in rehabilitation centres or outpatient rehabilitation is performed. Aged and female patients are more frequently transferred to a rehabilitation hospital [23, 24]. Trauma victims with high Injury Severity Score (ISS) (35–49 points) and suicide attempts were treated significantly more often in a rehabilitation clinic [23, 24]. Finally, injury distribution appears to be relevant as well. Patients with severe brain injury and spinal trauma, especially showed the need for inpatient rehabilitation after trauma [23, 24].

According to a large polytrauma database study in Germany, up to 98% of trauma clinics have physiotherapists and 71% have occupational therapists available [23, 24]. However, only 20% of these clinics have the possibility to perform standardized early rehabilitation within an acute stay [23, 24]. Early rehabilitation is a relevant prerequisite for post-acute rehabilitation. A non-randomized clinical trial in the Netherlands compared an integrated multitrauma rehabilitation service approach with "Fast Track" rehabilitation concepts [2]. The "Fast Track" approach includes early coordination of treatment between trauma surgeon and rehabilitation physician with the aim of achieving a shorter stay in the acute care hospital and early transfer to a specialized rehabilitation centre. Moreover, individual goal-oriented treatment in physiotherapy and multidisciplinary approaches, including psychologists and social workers, should avoid long periods of immobilization and hospital admittance [2]. The abovementioned study revealed that the "Fast Track" strategy was an effective programme, leading to faster recovery in functional status at 6 months in comparison to the status as "usual" patients [2]. However, after 12 months of follow-up, no differences between treatment conditions were observed [2]. Other studies pointed out the role of psychiatric disorders in long-term follow-up in severely injured patients. Post-traumatic stress disorder, anxiety and depression appear to persist for a longer period after initial trauma [9, 25]. Patients more often have additional suicide attempts, further traumatic insults and higher mortality than the general population [26]. These and other studies indicate that psychiatric disorders are common in polytraumatized patients and long-term supervision is of immense importance.

**Take Home Messages**

- Three phases in rehabilitation of severely injured patients can be distinguished.
- Long-term observations demonstrate that up to 30% of patients require medical aid for their disability and up to 20% report persistent disability after 10 years.
- Post-injury depression (35–68%), anxiety (32–70%) and post-traumatic stress disorder (24–39%) are common.
- Effective re-integration with a focus on return-to-work or return-to-school, psychological support and quality of life are the main aims of trauma rehabilitation.
- There is a lack of high-quality studies investigating the outcomes between different trauma rehabilitation programmes.

**Conflicts of Interest** None of the authors has any conflicts of interests to declare.

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# Treatment of Fracture-Related Infections

# 40

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**Learning Objectives**

- Diagnostic criteria for FRI.
- Treatment aims in long-bone FRIs.
- Basic surgical and antimicrobial treatment principles.

## 40.1 Introduction

The risk of fracture-related infection (FRI) ranges from around 1% for low energy closed fractures up to 30% for high impact open extremity fractures [1]. In addition to the location and severity of the injury, the risk of developing an FRI depends on the extent of concomitant injuries and on pre-existing comorbidities. Polytraumatized patients are at high risk because severe trauma is commonly accompanied by complex musculoskeletal injuries and a compromised host immune response [2]. Infection prevention is pivotal in primary trauma care. In high-risk open fractures, preventive measures encompass an extensive debridement, fracture stabilization, early definitive soft-tissue coverage, and pre-emptive short-course antibiotic therapy [3–6].

An established FRI imposes a considerable burden on patients and health care providers. The

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median costs per patient are multiple times higher in FRIs compared to uneventfully healed fractures since FRIs are associated with prolonged therapy and multiple revision surgeries, delayed healing, and functional impairments [1, 3, 7, 8].

The correct diagnosis of an infection is the cornerstone of successful FRI treatment. However, diagnosis can be difficult, in particular when there are no obvious signs of infection, such as a fistula or pus [9]. The international FRI consensus group published evidence-based recommendations on diagnosis and treatment of FRI [3, 10–13], which are summarized in this chapter.

## 40.2 Pathogenesis

FRI most commonly occurs exogenously due to the initial trauma (in the case of an open fracture), during fracture fixation, or during disturbed wound healing or late soft-tissue coverage. Hematogenous seeding of microorganisms to the implant is an infrequent route of infection in FRIs [3, 14, 15]. The most common microorganisms involved in FRI include *Staphylococcus aureus* (30–42%), coagulase-negative staphylococci (20–39%), enterobacteriales (14–27%), anaerobes (16%), and streptococci (11%). Polymicrobial infections (20–35%) occur typically in patients with open fractures [1, 3, 16].

Bacterial biofilm formation plays an important role in the pathogenesis of implant-associated infections [14, 17]. Microorganisms form a biofilm rapidly on non-vital surfaces such as implants or necrotic tissue. In vitro data suggests a decreasing antibiotic susceptibility with increasing maturation of bacterial biofilms over time [17]. Hence, time is an important factor in the pathogenesis of FRIs. Since systemic antibiotics alone are not able to eradicate bacterial biofilms, successful management of FRI requires both surgical and antimicrobial treatment [3].

Due to the progression of fracture consolidation on the one hand and increasing biofilm formation and bone involvement (e.g., osteolysis, necrotic bone formation) on the other side, time is an important factor when developing a treatment strategy [1, 3, 18]. In order to reflect the pathophysiological changes, common FRI classifications include *time* as the single most important factor. *Willenegger* and *Roth* classified early-, delayed-, and late-onset infections, with a cut off at 3 and 10 weeks after fracture fixation [19]. Other authors proposed 6 weeks to differentiate between acute and chronic infections [20].

## 40.3 Definition and Diagnosis

The *FRI Consensus group*, an expert group composed of different scientific organizations, published (and recently updated) the FRI consensus definition based on diagnostic criteria [3, 11, 21]. Two levels of certainty of diagnostic features were defined and criteria could be either confirmatory or suggestive for FRI. In the presence of at least one of the five confirmatory criteria, an infection can definitively be diagnosed. The presence of suggestive criteria requires further investigations in order to look for confirmatory criteria. The diagnostic criteria are summarized in Table 40.1. The *International Consensus Group on Musculoskeletal Infections* accepted with a strong consensus the mentioned FRI definition [4].

### 40.3.1 Clinical Features

The clinical presentation depends on the localization, the initial trauma, and the type of osteosynthesis, the duration of infection, and the causative microorganism. The only clinical confirmatory signs of infection are purulent drainage and wound dehiscence or wound breakdown. In the latter criterion, the implant communicates with the skin microbiome (Fig. 40.1) [3, 11]. The classical inflammatory signs such as pain, redness, swelling are suggestive but not confirmatory for FRI. However, their presence should alert and prompt further investigation, especially when these signs are localized in the vicinity of the fracture [3, 11].

### 40.3.2 Laboratory Examination

Serum inflammatory makers such as C-reactive protein (CRP), erythrocyte sedimentation rate

**Table 40.1** Diagnostic criteria for fracture-related infection [11]

| | |
|---|---|
| *Confirmatory criteria* | |
| Clinical | • Sinus tract or wound breakdown (with communication to the bone or the implant) (Fig. 40.1) |
| | • Purulent drainage or presence of pus during surgery |
| Laboratory | • Phenotypically indistinguishable pathogens identified by culture from at least two separate deep tissue/implant specimens |
| | • Presence of microorganisms in deep tissue specimens confirmed by histopathological examination |
| | • Presence of >5 PMNs/HPF in chronic/late-onset cases (e.g., fracture nonunion) |
| *Suggestive criteria* | |
| Clinical | • Pain, redness, swelling, warmth, loss of function (dolor, rubor, tumor, calor, functio laesa), fever |
| | • Persistent, increasing or new-onset wound discharge |
| | • New-onset of joint effusion |
| Radiological | • Osteolysis |
| | • Implant loosening |
| | • Sequester (necrotic bone fragment, often within the cancellous part of the bone) |
| | • Failure of progression of bone healing (i.e., nonunion) |
| | • Presence of periosteal bone formation (at localizations other than the fracture site or in case of a consolidated fracture) |
| Laboratory | • Pathogenic organism identified by culture from a single deep tissue/implant specimen |
| | • Increased serum inflammatory markers (ESR, WBC, CRP) |

*ESR* erythrocyte sedimentation rate, *WBC* white blood cell count, *CRP* C-reactive protein, *PMNs* polymorphonuclear neutrophils, *HPF* high-power field

(ESR), and white blood cells (WBC) have a limited diagnostic value in the preoperative diagnosis of FRI and are suggestive criteria [3, 11, 22]. Nevertheless, they may provide information about the evolution of the infection [23].

### 40.3.3 Imaging Procedures

In the diagnostic workup of FRIs, the most commonly used imaging modalities are conventional radiography, computed tomography (CT), magnetic resonance imaging (MRI), and nuclear imaging techniques [3]. The different imaging modalities are all of value for different aspects of FRI. The indications to request diagnostic imaging for FRI include: (1) assessment of fracture healing, fracture reduction, and stability of the osteosynthetic construct; (2) to acquire more certainty regarding the presence or absence of FRI; (3) visualization of the anatomic details of the infection such as its extension, the presence of sequestra, sinus tracts, and subcortical abscess [11].

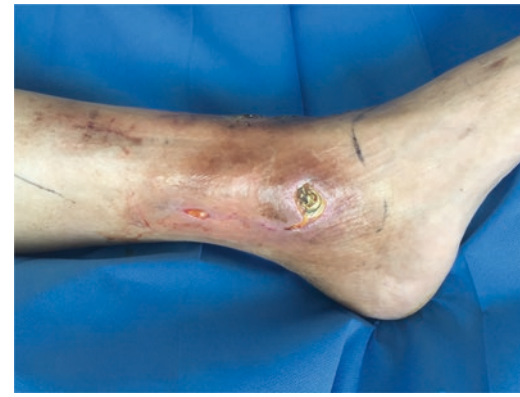

**Fig. 40.1** Confirmatory criterion for fracture-related infection: fistula/wound breakdown with surrounding unstable soft-tissue envelope after minimal-invasive plate osteosynthesis of the distal tibia

Serial plain radiographs are the investigation of choice to judge implant positioning, fracture reduction, progress or absence of osseous healing as well as osteolysis and implant loosening [9]. This modality is inexpensive, widely available, has a low radiation exposure and is therefore often the first-choice imaging modality. For more precise planning of the surgical procedure, CT allows a more detailed visualization of the bone architecture and delivers additional evidence for infection such as presence of sequestration, cortical bone reaction or intraosseous fistula, and abscess formation in the adjacent soft tissue [1]. Radiographic changes are not specific for infection and are categorized as suggestive in the consensus definition (Table 40.1) [21].

The method of choice for detecting soft-tissue involvement and intramedullary infection is MRI [1]. In postoperative and posttraumatic conditions, however, the value of MRI is reduced, as repara-

tive scar tissue may mimic an infection. Furthermore, scattering from metal implants can obscure certain imaging details despite metal artifact reduction techniques [9, 11, 24]. Nuclear imaging is using radioisotopes to visualize and trace physiological and pathophysiological changes, such as fracture healing, bone remodelling, and inflammatory response to an infection [1]. White blood cell scintigraphy and $^{18}$F-FDG PET/CT both present good satisfactory accuracy for the diagnosis of FRI [25, 26]. Despite a high diagnostic accuracy, nuclear imaging is still not a conclusive test to establish the diagnosis of FRI and is categorized as suggestive in the consensus definition [3, 11].

### 40.3.4 Microbiology and Histopathology

The appropriate, intraoperative sample collection is essential in the diagnostic process to allow interpretation of histological and microbiological analyses. It is important to detect the causative pathogen(s) for targeted antimicrobial therapy [9]. It is recommended to collect preferably five, representative deep tissue samples from the site of perceived infection and adjacent to implants [3, 9, 11]. Manipulation of the target area during sampling should be minimized and separate, unused surgical instruments should be used for each sample obtained to avoid cross-contamination [11, 27]. The samples should be numbered and labelled with the anatomical localization and sent for microbiological and histopathological investigation.

Swab cultures as well as bacterial cultures of sinus tracts and open wounds are not recommended, due to high risk for contamination [3]. Whenever possible (except septic patients), systemic antibiotics should be avoided 2 weeks prior to sampling to avoid false-negative culture results [3]. Sonication of removed implants are part of diagnostic procedure in several institutions. Sonication is a useful adjunct to conventional tissue culture in implant-associated infections. However, its diagnostic value in FRIs still needs to be established, and tissue cultures remain the gold standard [11, 28, 29]. The culture of phenotypically identical organisms from at least two separate deep tissue specimens is a confirmatory criterion of FRI (Table 40.1). A microorganism identified by a single deep tissue sample is a suggestive criterion for FRI and further investigation is required to confirm the diagnosis. In case a highly virulent pathogen (e.g., *Staphylococcus aureus*) is detected in one single deep tissue sample a high suspicion of infection should be risen [21].

A confirmatory sign for infection is the presence of microorganisms in deep tissue samples, as confirmed by histopathological examination using specific staining techniques for bacteria or fungi. Furthermore, in late FRIs an infection can definitively be diagnosed if more than five polymorphonuclear neutrophils (PMNs) per high-power-field are detected by histopathological examination (Table 40.1). The absence of neutrophils in any high-power field is diagnostic for aseptic nonunion [11, 30].

## 40.4 Treatment

### 40.4.1 General Considerations

The central aims of FRI treatment are: (1) fracture consolidation; (2) restoration of the soft-tissue envelope; (3) eradication of infection; (4) prevention of residual chronic infection; (5) restoration of function [1].

In contrast to prosthetic joint infections, osteosynthetic devices can be removed after bone healing and without loss of function. Therefore, complete eradication of infection is not always the primary goal and suppressive therapy can bridge the time to bony consolidation and removal of the internal osteosynthetic device [1].

The FRI consensus group published evidence-based recommendations on FRI treatment [3, 10, 12, 13]. These treatment recommendations are based on two surgical strategies and two antimicrobial concepts (Table 40.2). Surgery will be required for almost all cases of long-bone FRI. A suppressive life-long regimen of antibiotics alone is a last resort option in case of the following: (1) the patient is unfit for surgery; (2) limited life expectancy; or (3) surgical reconstruction is not possible [1].

**Table 40.2** Principle treatment concepts for fracture-related infections

| |
|---|
| *Surgical concepts* |
| • Debridement, antimicrobial therapy, and **implant retention (DAIR)** |
| • Debridement, antimicrobial therapy combined with:<br>– **Implant removal** (in case the fracture is consolidated) OR<br>– **Implant exchange** (one or two (multiple) stages) |
| *Antimicrobial concepts* |
| • **Infection eradication** |
| • **Infection suppression** |

Since FRI often occurs in patients with complex local and systemic impairments, management requires input from multiple specialties such as infectious diseases specialists, orthopedic trauma surgeons, plastic surgeons, microbiologists, clinical pharmacists, and radiologists. In complex cases, the reconstructive options are technically demanding, and therefore it is advised to treat these patients at specific bone infection centers [4, 13].

### 40.4.2 Surgical Concepts

The cornerstones of every surgical approach are: (1) judicious debridement combined with dead-space management; (2) stable osteosynthesis, and (3) sufficient vital soft-tissue envelope [1].

A well-planned and judicious debridement involves the excision of necrotic and infected (bone- and soft-) tissues, removal of foreign bodies (e.g., broken screws, sutures, bone grafts [31]), acquisition of multiple tissue samples for microbiology and histopathology from the site of perceived infection and evaluation of the osteosynthetic construct (stability and fracture reduction) [1].

Fracture stability is crucial for bone consolidation and infection eradication. Therefore, a stable osteosynthetic construct has to be warranted in unhealed fractures (both in implant retention and implant exchange) [6]. FRI animal models have shown that the advantage of implants for stabilization outweighs the increased susceptibility of a foreign body to infection [32, 33].

In addition to fracture stability, a vital and well-perfused soft-tissue envelope is mandatory for successful FRI treatment and significantly contributes to bone healing and infection eradication. It delivers essential growth factors, nutrients, host immune cells, and systemically applied antibiotics to the fracture area. Furthermore, it poses an antimicrobial barrier that prevents further contamination. In absence of a sufficient soft-tissue envelope (Fig. 40.1) optimal definitive soft-tissue coverage within an orthoplastic approach should be performed as soon as possible [34].

After an extensive osseous debridement local application of antimicrobials can be a treatment option for dead-space management. They offer the advantage of achieving very high local antibiotic concentrations in an environment of impaired blood supply [35]. Furthermore, these local antibiotics are not associated with systemic adverse events. Although local antibiotics can be used as an adjunct in the management of FRI, local delivery of antibiotics is not a substitute for thorough debridement [12].

The most commonly used compounds for local antibiotic delivery are gentamicin, tobramycin, vancomycin, and clindamycin. They are incorporated in resorbable or non-resorbable carriers. Although, polymethylmethacrylate (PMMA) remains one of the most commonly used delivery vehicles for local antibiotic therapy, the variable antibiotic elution rates, and the requirement for removal has led to the investigation of alternative carriers. More recently, bioabsorbable materials such as ceramics (e.g., calcium sulfates) and bioactive glass gained attention because they do not require surgical removal [35, 36].

The FRI treatment principles are summarized in a basic algorithm (Fig. 40.2) [3]. Surgical management is based on two basic questions: (1) Is the fracture healed? and (2) Is implant retention advisable?

In case of fracture consolidation, debridement is performed and the implant removed. In unhealed fractures, several factors have to be considered that influence the decision process toward the choice of the most optimal surgical strategy.

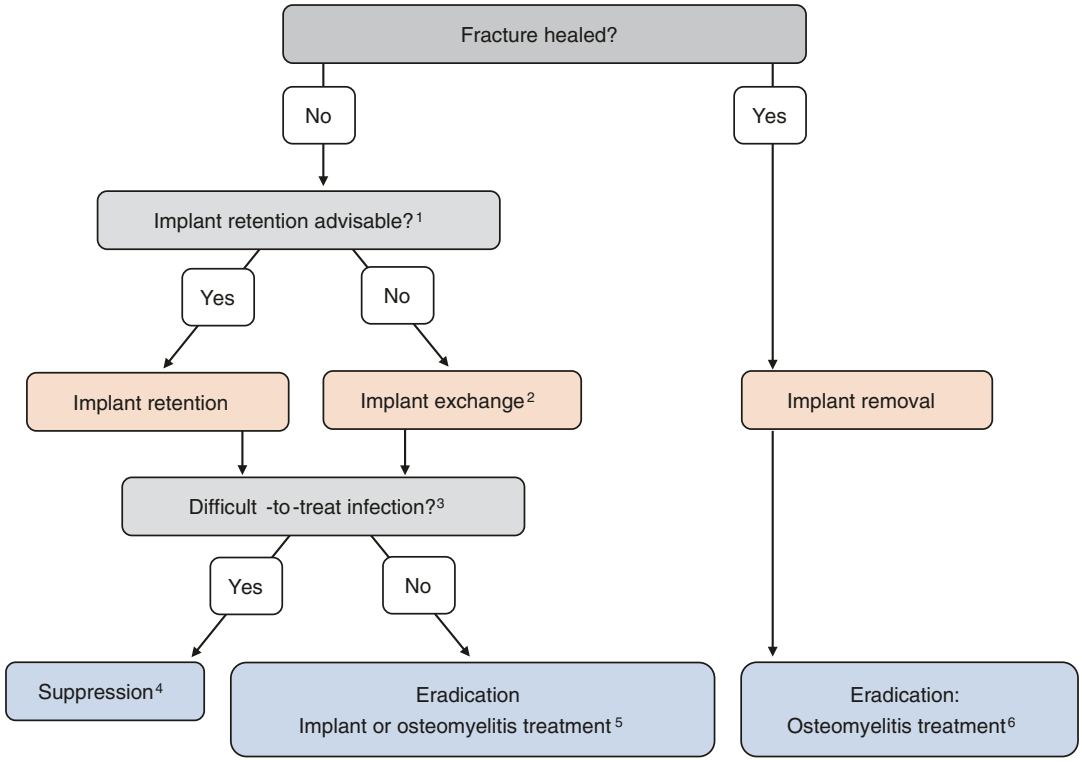


**Fig. 40.2** Algorithm describing the basic treatment principles for fracture-related infection (adapted from [3]). [1]Preconditions for implant retention are: (1) a stable osteosynthetic construct; (2) a vital soft-tissue envelope; (3) the ability to perform a proper debridement (with removal of necrotic bone and soft tissues) to reduce the bacterial load; (4) absence of relevant local or systemic comorbidities; (5) a short interval between fracture fixation and FRI revision surgery. [2]Implant exchange in one or two (multiple) stages. [3]Difficult-to-treat infection: no biofilm-active antibiotic available while implant in situ; due to antibiotic resistance of the pathogen, drug intolerance of the patient, or incompatible drug interactions. [4]Suppressive antibiotic therapy until implant is removed. [5]Implant treatment: 12 weeks antimicrobial therapy if internal fixation device present. Osteomyelitis treatment: 6 weeks antimicrobial therapy if no implants in the vicinity of infection. [6]Osteomyelitis treatment: 6 weeks antimicrobial therapy

Implant retention is a tempting approach, especially in early infections of complex fractures (i.e., articular fractures). In these cases, implant exchange may lead to loss of reduction, further devitalization of bone fragments and bone loss, making revision surgery even more challenging [18]. However, it is assumed that DAIR is only successful if certain preconditions are given (Table 40.3).

Assuming that FRIs are mainly acquired exogenously, the duration of infection can be regarded as the time interval between trauma/fracture fixation and FRI revision surgery. Data from a systematic review suggests that early FRIs with a short duration of infection (up to 3 weeks) can successfully be treated with implant retention if the other preconditions (Table 40.3) are present. Good results are reported in selected studies for delayed infections with a duration of infection of up to 10 weeks. A DAIR procedure in late infections (>10 weeks) with a mature biofilm is associated with a high failure rate [18].

An important precondition for successful DAIR is an adequate surgical debridement in order to reduce the bacterial load. In the presence of a nail, the intramedullary canal cannot be debrided, which may explain higher failure rates for DAIR procedures with intramedullary implants compared to plate osteosynthesis [18].

**Table 40.3** Preconditions for successful debridement, antibiotics, and implant retention (DAIR) [18]

| Preconditions for implant retention |
|---|
| 1. Presence of a vital soft-tissue envelope that contributes to bone healing and infection eradication |
| 2. Ability of sufficient debridement (which may not be possible in intramedullary nails) |
| 3. Presence of a stable osteosynthetic construct (and sufficient fracture reduction) |
| 4. Absence of relevant local or systemic comorbidities |
| 5. Short duration of infection |

### 40.4.3 Antimicrobial Concepts

#### 40.4.3.1 Empiric Antibiotic Therapy

In suspected infections, empiric intravenous antibiotics should be started after surgical debridement and sampling. If a new internal device is implanted, antibiotics can be given perioperatively. Data from prosthetic joint infections (PJI) showed that administering antibiotics at the start of the procedure does not compromise microbiological culture results significantly [3, 37]. The choice of empiric therapy depends on local epidemiology [3].

#### 40.4.3.2 Targeted Antibiotic Therapy

As soon as culture results and corresponding antibiotic susceptibility patterns from the intraoperatively collected samples are available, empiric antibiotics are tailored to a targeted therapy. The current recommendation is that IV therapy is switched to oral antibiotics after 1–2 weeks, when the soft tissues are stable and the wounds are dry [3, 10, 38]. In case of implant retention or exchange, a total treatment duration of 12 weeks is recommended. If the internal device is removed, antibiotics are given for in total 6 weeks [3, 10] (Fig. 40.2).

The presence of a difficult-to-treat infection (third question in the FRI treatment algorithm) is determining if the antibiotic regimen is curative or suppressive (Fig. 40.2) [3, 10]. In the latter case, the antimicrobial treatment controls the infection until the fracture is healed and the implant can be removed. In a difficult-to-treat infection, no biofilm-active antibiotics are available while an implant is in situ. These antimicrobials cannot be used because of resistance, drug intolerance, or incompatible drug interactions [3]. Biofilm-active antibiotics include rifampicin for staphylococcal infections and fluoroquinolones for Gram-negative bacteria, provide that they have been tested for susceptibility. To avoid emergence of resistant microorganisms, rifampicin should only be given with companion antibiotic, after thorough debridement and when wounds are dry. For staphylococci, fluoroquinolones such as ciprofloxacin or levofloxacin are the first-choice partners for rifampicin [3, 10, 39, 40].

## 40.5 Follow-Up

It is recommended to follow-up the patient in regular intervals for a minimum of 12 months after cessation of therapy in a specialized interdisciplinary outpatient clinic [13].

## 40.6 Conclusion

Fracture-related infection is a serious complication after musculoskeletal trauma surgery. An international consensus group, endorsed by multiple scientific organizations published diagnostic and treatment strategies. There is increasing evidence that multidisciplinary teamwork and collaboration between health care workers is essential to accurately diagnose and treat FRI.

**Take Home Messages and Key Concepts**

- An FRI can be definitively diagnosed in the presence of at least one of the five confirmatory criteria. The presence of suggestive criteria requires further investigation in order to look for confirmatory criteria.
- The aims of FRI treatment are: (1) fracture consolidation; (2) restoration of the soft-tissue envelope; (3) eradication of infection; (4) prevention of residual chronic infection; (5) restoration of function.
- The two main surgical strategies of FRI treatment are debridement, antimicrobial therapy and implant retention (DAIR) or debridement, antimicrobial therapy, and implant removal/exchange.
- Implant retention can be only successful under certain preconditions.
- The two main antimicrobial concepts are infection eradication and in certain cases infection suppression, until fracture union is achieved.
- Successful diagnosis and treatment of FRI requires the input of various specialties. If these are not available, transfer of the patient to a dedicated bone infection center providing a multidisciplinary team should be considered.

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# Management of Aseptic Malunions and Nonunions

41

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**Learning Objectives/Questions Covered**

- Describe evaluation of the patient with disordered bone healing.
- Discuss diagnosis of nonunion.
- Explain classification of nonunion.
- Enumerate non-operative treatments for nonunion.
- Identify surgical goals and steps.
- Elaborate upon the source and use of bone graft and substitutes.
- Remind the reader about the use of implantable bone stimulators.

## 41.1 Introduction

Disorders of skeletal healing after fracture take the form of malunion, nonunion and delayed union. Malunion is defined as healing of the bone in an abnormal shape that results in a clinically significant alteration in function. For diaphyseal locations, this can take the form of angulation, shortening, or rotation that alters the relationship of joints to each other and impairs the function of the limb. Nonunion refers to the situation in which bone healing has ceased without restoring the structural integrity of the bone. Practically, this is usually diagnosed after some period of time has passed, usually 3 months, without radiographic or clinical improvement, although in some cases of significant bone loss (designated *a critical defect*) healing is so unlikely that it could be considered an instant nonunion. The term delayed union refers to the situation in which the bony healing process is incomplete beyond the time which would be expected but is believed to be still active; or in which there is no radiographic or clinical progress, but it is still too soon to declare that it will not occur. This is a subjective assessment.

## 41.2 Patient Evaluation and Diagnosis

Patients with both malunion and nonunion may present with complaints of pain and/or deformity. As with any patient, a thorough history and physical exam should be performed. It is assumed that the readers of this chapter are familiar with that process, and so just a few of the relevant findings will be mentioned here as a reminder. Significant historical information includes details of the injury (open vs. closed; associated vascular or neurologic damage; other injuries; prior treatments, timing, outcomes; any history of signs, symptoms, or treatment of infection), as well as information about the patient (age and occupation; medical illnesses and medications; habits;

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compliance with previous treatments; social support situation; and psychological resilience). The treatment of these problems is complex and prolonged, so it is very useful at the outset to get to know the patients and their lives in order to help set realistic goals. A detailed history of the complaints and impairments takes time but is very useful in understanding what they hope to achieve by treatment and in managing expectations. It is rarely possible to make people "good as new" once they have developed a skeletal healing disorder, and that should be stated early in the process.

The physical examination, as always, should be thorough, which means that the patient should be adequately disrobed in order to examine the entire limb as well as the contralateral side. The location and status of previous scars should be noted, or even drawn in the chart, with an eye to vascularity of the soft tissues, skin changes suggestive of chronic infection, and possible location of surgical exposures needed. Do not forget palpation for tenderness, fluctuance, and soft tissue mobility. Deformities should be noted and quantified, particularly rotational variations from the contralateral side. Range of motion of adjacent joints, strength and size of musculature, motor and sensory function should be documented. Observe the function of the limb by having the patient walk in the hallway or perform functional activities with the upper extremity.

Radiographs should include the entire bone, with good orthogonal imaging of the joint above and below the fracture. In the case of malunion, contralateral films will usually be necessary. For the lower extremity, standing films of hip, knee, and ankle bilaterally are usually required to fully characterize the mechanical effects of the deformity; although occasionally a simple malunion will be confined to a single bone and that will be obvious. There is variation between people in the normal alignment and the goal should be to correct the person to a symmetrical alignment unless there is concomitant pre-existing abnormality, in which case correction of a malunion may be part of a comprehensive skeletal re-alignment process. Those are complex situations which should be referred to an experienced team. CT scans are helpful in delineating and locating rotational deformities that are identified on clinical examination. For the lower extremity, cuts through the femoral neck, distal femur, and distal tibia are usually obtained to compare rotational alignment to the unaffected side.

Laboratory evaluation will be guided by the patient's medical history. In almost all cases, any evidence of infection should be sought through assessment of the white blood cell count (WBC), C-reactive protein level (CRP), and erythrocyte sedimentation rate (ESR). ESR and CRP have been shown to be independently accurate predictors of infection; in one study of nonunion, if all three indices are elevated, 100% of patients turned out to be infected [1]. Most orthopedic trauma surgeons are aware of the high incidence of metabolic disorder or endocrinopathy in patients with unexpected nonunion. A high percentage (>80%) of patients with nonunion of low energy or nondisplaced fractures have been found to have endocrine abnormalities, most commonly vitamin D deficiency (~70%), but also abnormalities of calcium, thyroid or parathyroid function, diabetes, growth hormone, and hypogonadism [2]. Work-up includes a comprehensive endocrine and metabolic profile with serum and urine testing for abnormalities in a defined set of vitamins, minerals, and hormones [3].

## 41.3 Classification of Nonunion

Nonunions can be classified, primarily on the basis of radiographic appearance, and that classification may help guide treatment. The categories are: infected, atrophic, hypertrophic, oligotrophic, segmental bone loss, and synovial. Infected nonunions are not the focus of this chapter, but the presence of infection may not be known until the time of surgery or after, and so the possibility must always be kept in mind and discussed with the patient at each stage. A patient with an infected nonunion has two interrelated problems, nonunion and osteomyelitis, and both conditions require a treatment strategy. In many cases these coordinated plans will require staged surgical procedures with specific goals and tim-

ing. In patients with a "hot" infection (pain, erythema, purulent drainage, systemic symptoms), treatment may be initially directed at acutely controlling the infection, followed by attempts to achieve union. If the infection is more indolent, bony union may be the first goal. It is difficult to achieve long-term infection control if there is bony instability. Functioning, stable hardware rarely needs to be removed until union has been achieved, even in the face of infection, because instability is worse than the presence of foreign material, in terms of prolonging the infection. Ultimately, after bony healing is achieved, hardware may need to be removed for long-term definitive infection control.

The terms atrophic, hypertrophic, and oligotrophic refer to the radiographic appearance of reactive bone or callus at the fracture site. In atrophic nonunion, there is very little or no callus formation, and the ends of the bone are often tapered and wispy; they have been described as looking like the end of a sharpened pencil. Hypertrophic nonunions have an abundance of callus built up at the nonunion site, often on both sides, but not bridging across the fracture line. They have been described as having the shape of an elephant's foot. Oligotrophic nonunion is a rather vague and subjective category that falls in between the other two. The basic idea of this classification is the observation that hypertrophic nonunions usually heal easily when they are rigidly stabilized with internal fixation, while atrophic nonunions are felt to need some sort of additional biologic stimulation such as bone grafting in addition to rigid stabilization. While some have speculated that the difference between atrophic and hypertrophic nonunion results from a difference in vascularity, a histologic examination revealed that, on a microscopic level, atrophic nonunions are not avascular. Tissue sampled from human nonunions showed no difference in the blood vessel density between different types of nonunion [4]. In an animal model of atrophic nonunion, the number of blood vessels reached the same as in normal healing bone, but at a delayed time point, suggesting that avascularity in the first weeks of fracture healing may play a role in development of atrophic nonunion [5]. Anecdotally, atrophic nonunions do tend to occur in situations in which there is a less robust soft tissue envelope, such as open tibia fractures or cachectic patients.

There are additional concerns when there is a situation of segmental bone loss in the face of nonunion. In some situations, with short defects or in the upper extremity, shortening of the limb segment may be acceptable. The methods of reconstructing segmental defects include cancellous bone grafting, bone transport, and vascularized tissue transfer. Vascularized tissue transfer requires experience and expertise in microvascular techniques. Bone transport will be discussed in another chapter. Cancellous bone grafting indications, techniques, and outcomes will be discussed later in the chapter.

Synovial nonunions (true pseudo-arthrosis) are those which have developed a sterile fluid-filled, membrane-bound cavity between the ends of the bone, which often are covered with fibrocartilage, very similar to an actual synovial joint. Treatment of this type of nonunion is similar to an arthrodesis procedure, with debridement, apposition of bleeding bone, compression, and internal fixation.

## 41.4 Diagnosis of Nonunion

The diagnosis of nonunion is both clinical and radiographic. Although some nonunions are asymptomatic (e.g., clavicle), many cause symptoms of pain or instability. On physical examination, there may be tenderness or pain on manual stress. There may be gross instability of the bone and the appearance of an additional joint (hence the term "pseudo-arthrosis"), and this finding is more common in atrophic nonunion or cases of bone gap. In those cases, the diagnosis is not subtle or difficult. Examination using manual stress radiographs or fluoroscopy can document gross instability. The more controversial situation occurs in the hypertrophic (stiff) nonunion, or when there is internal fixation in place which both masks instability and obscures radiographic detail. Pain on weight-bearing has been considered a sign of nonunion, but can be multifactorial. Some well-united

fractures can have pain related to activity. A common definition of radiographic union is bony bridging of 3 out of 4 cortices of the diaphysis. This common usage definition was formalized into the Radiographic Union Scale for Tibia fractures (RUST) score by Whelan and coauthors [6]. The score is produced by using AP and lateral views of the tibia showing the fracture site and scoring each of the four cortices at the fracture site (anterior, posterior, medial, and lateral) on a scale of 1 to 3. A score of 1 means there is no bridging callus and the fracture line is visible, a score of 2 means there is bridging callus but the fracture line is still visible, and a score of 3 means there is bridging callus and the fracture line is not visible. The scores are then summed. Although there is no score that defines union, this has been determined in subsequent studies. This score has been shown to have a high interclass correlation coefficient (ICC) when used for diaphyseal fractures treated with intramedullary nailing [7] and moderate agreement for meta-diaphyseal fractures of the distal femur and proximal tibia [8]. The RUST score was modified in 2015 by Litrenta and colleagues with a slight improvement in ICC (6.8 vs. 6.3) [8]. Observers in that study assigned an average RUST score of 8.5 to fractures they considered united, while the average *modified* RUST for fractures considered united was 11.4.

Most textbooks suggest that if a healthy patient has pain, lack of three bridged cortices at 9 months and is showing no progressive improvement on radiographs over 12 consecutive weeks, they may be considered non-united. This definition has been adopted by the FDA [9] and by many insurance companies to evaluate payment for nonunion treatments, particularly bone stimulators. Some surgeons have a more aggressive approach to intervening earlier if they see no progress to healing. However, recent evidence suggests that, at least for tibia fractures, a significant portion of fractures that are judged nonunited at 3 months will go on to heal by 6 months, and caution is warranted prior to rushing to additional treatment [10]. Of course, some fractures are "instant nonunions" due to bone loss that exceeds a critical healing defect size.

CT scan is more accurate than plain radiography in diagnosing tibial nonunion. Several studies have shown a sensitivity of 100%, but lower specificity (~40–80%). The cost and radiation doses involved have limited the routine use of CT scans to evaluate healing of most fractures [11, 12]. Ultrasound has been used to evaluate healing of tibia fractures at an early stage with some promising results, particularly in terms of prediction of ultimate healing; however, it is felt to be highly operator dependent and is not in wide clinical use [11]. Current research involves evaluation of serologic and formal biomechanical methods to evaluate union, but for now, physical exam and plain radiographs form the mainstay of diagnosis for bone union.

## 41.5 Treatment of Nonunion

Treatment should always begin with a search for, and addressing, any correctible host healing factors. Metabolic and endocrine disorders have been mentioned and should be treated as necessary with optimization of diabetic control, renal function, vitamin D supplementation, and replacement of hormonal deficiencies. Peripheral vascular disease can be diffuse or focal, can contribute to the development of nonunion, and should be sought by history and physical examination. In appropriate patients, a formal vascular work-up may be indicated to identify correctable obstructions prior to any significant limb surgery. Certain medications have been shown to inhibit fracture healing, and they should be avoided when possible. Animal and cell culture studies suggest that certain antibiotics (fluoroquinolones, aminoglycosides, rifampin) may have negative effects on bone cell biology and fracture healing. Likewise, animal studies have demonstrated than anticoagulants (heparin and warfarin) significantly attenuated the process of fracture healing, but no human studies have shown this [13]. By far the most common and controversial issue revolves around non-steroidal anti-inflammatory drugs (NSAIDs). These drugs have been shown to inhibit fracture healing in cell culture,

multiple animal species, and many human studies [14–16]. However, the dosage, timing, and specific at-risk populations are not known with clarity. Due to the current opioid medication crisis, NSAIDs are promoted as a safer method of pain control following fracture, and proponents minimize the risk of nonunion or delayed union. It should be noted that there are no good studies demonstrating that addition of NSAIDs to pain medication protocols actually reduce the incidence of addiction and overdose although they can reduce the amount of narcotic medication used by patients. Many authors believe that the available literature does not prove that a short course of NSAID treatment will increase risk of bone healing problems in a normal healthy host, particularly a younger person. However, it seems prudent to avoid these medications in a patient with other risk factors for impaired bone healing. Dietary strategies for healing include vitamin and mineral supplementation, and addition of protein with conditionally essential amino acids [17, 18]. The addition of micronutrients important in the production of collagen (vitamin C, vitamin B6, proline, lysine) has been shown to speed tibial fracture healing in accelerate tibial fracture healing in a prospective, randomized, double blind, placebo-controlled trial [19]. Attempts should be made to address nicotine addiction, or other habits which may be detrimental. One should encourage the patient to see themselves as a partner in the healing process, and to take some responsibility for getting the bone united. There is undoubtably a psychological component to successful treatments of any injury and evidence of impairment in the psychosocial realm should lead to evaluation and treatment of depression, anxiety, or post-traumatic stress disorder. It is emphasized that the treatment on nonunion is often a long and difficult undertaking, in which surgery is only a small part, and the patient should be in the best possible state physically, mentally, and spiritually before undergoing the surgical portion. In some cases, particularly after a course of previous treatments that have failed, discussion of amputation as a reconstructive procedure may be in order.

## 41.6 Non-operative Treatment of Nonunion

Non-surgical treatments for nonunion include bone stimulators, functional bracing, systemic medications, and injections of platelet-rich plasma (PRP), mesenchymal stem cells, or bone marrow aspirate. Bone stimulators provide a physical signal to the bone that has a biologic effect. The signal can be electromagnetic in nature, or ultrasonic. The biologic effects of electromagnetic stimulation have been known for decades and include increased production of bone morphogenic protein 2, alkaline phosphatase, cytosolic calcium, and activated cytoskeletal calmodulin [20]. All electromagnetic stimulators function by production of a small electric current in the bone, but they do it by different mechanisms. The direct current stimulators are implanted surgically and apply the cathode and anode of a battery directly to tissues. This creates a current and induces chemical changes in the bone at the cathode wire that create conditions that promote differentiation of stem cells into bone. Noninvasive stimulators are of basically two types. Inductive coupling stimulators produce a current by creating a time-varying magnetic field which induces current flow in the conducting tissue. The electromagnetic field can be pulsed, sinusoidal, or combined static and sinusoidal. Capacitive coupling systems function by creating an electrical field with a voltage gradient between two charged plates, which in turn produces a current flow. The ultrasonic stimulator creates a mechanical signal using ultrasound, similar to but stronger than the sound waves used for diagnostic ultrasound. There is a large amount of literature on the effects of both electromagnetic stimulation and ultrasound stimulation on bone healing, including basic science, animal studies, and clinical studies [21]. Meta-analyses of this literature were performed in the early 2000s and resulted in differing conclusions. Three of them suggested a positive effect, and one did not [22–25]. A more recent meta-analysis of randomized, sham-controlled studies found moderate quality evidence from 15 studies that bone stimulation reduced radiographic nonunion

rates and reduced pain [26]. The use of a bone stimulator is relatively contraindicated in nonunions with a synovial cavity, with a bone gap greater than half the diameter of the bone, or with unacceptable malalignment. They seem to work better with hypertrophic nonunions, and in bones that are closer to the skin surface.

Functional bracing has been used to treat nonunions of the tibia. Sarmiento and coauthors treated 73 patients with tibial nonunion or delayed union with functional bracing, and followed 67 of them until outcome was determined. The nonunions were in the brace for an average of 4 months; six patients in the series failed to heal, five of which were in patients who had suffered open fractures. All of the patients had deformities that were considered "aesthetically acceptable" in the opinion of the authors, and 48 patients had fibular ostectomy (1 cm of bone removed at least 2 cm above or below the lesion), which was used when motion at the fracture site was more than "minimal." Bone grafting was performed in 10 patients who had a history of multiple failed previous surgical procedures. Weightbearing in the functional brace was an essential part of the treatment success [27].

Systemic administration of Teriparatide (human parathyroid hormone, N-terminal amino acids 1–34), given by weekly subcutaneous injection, has been used successfully to heal nonunion in case reports [28, 29]. Percutaneous injection of bone marrow aspirate at the nonunion site was first reported by Connolly in 1986, and since that time there have been many reports of the use of this technique with success rates varying from 75% to >90% [30–35]. Although most of the studies are small, retrospective series without control groups or blinded reviewers [33–35], the technique has low risk, and burns no bridges for later procedures. It is most useful in cases of aseptic NU or DU following internal fixation, where the hardware is stable and functional. Bone marrow aspirate injection has been combined with low-intensity ultrasound for treatment of recalcitrant long bone nonunion in one series, with 76% success after a year [36]. Bone marrow aspirate may be centrifuged to concentrate the nucleated cell fraction and increase the concentration of osteoprogenitor cells [32]. This may be combined with commercially available osteoconductive scaffolds to provide an optimal combination graft substitute [3].

Platelet-rich plasma (PRP) created by intraoperative processing of autologous blood has been used to stimulate healing in NU and DU, with reports being primarily small retrospective case series without control groups or blinded evaluation. Some studies have shown a promising effect [37, 38], while others have not [39].

## 41.7 Surgical Treatment of Aseptic Nonunion

When non-operative treatments have failed or are unlikely to succeed, the patient may choose surgical treatment. The goals of surgery are to provide increased stability in the correct alignment and to restart the healing process in a more favorable biologic and mechanical environment. The specific steps of the surgical treatment will depend upon the type of nonunion, the presence of deformity, and the details of previous treatments (Table 41.1). The simplest situation is an aseptic hypertrophic nonunion with acceptable alignment. In this case, the addition of mechanical stability alone, using internal fixation techniques (intramedullary nails or extramedullary plates), will lead to success in a high percentage of cases. The nonunion site does not need to be debrided or resected, because in the correct mechanical milieu, the scar and cartilage tissue will ossify. "Takedown" (debridement) of a nonunion is necessary only when there is excessive deformity, a true synovial pseudarthrosis, or an infected nonunion. If there is deformity that is outside acceptable ranges, correction of alignment usually occurs simultaneously to internal fixation and may involve surgical debridement or osteotomy through the nonunion site. In the atrophic or oligotrophic nonunion, some sort of biologic stimulation, such as bone grafting is required in addition to correction of alignment and provision of stability. The nonunion with bone loss will require stability, correction of alignment, biologic stimulation, and restoration

**Table 41.1** Surgical requirements for nonunion types

| Nonunion type | Enhance stability | Biologic stimulation | Debridement | Restore bony structure | Antibiotics |
|---|---|---|---|---|---|
| Hypertrophic | ✓ | | | | |
| Atrophic | ✓ | ✓ | | | |
| Synovial | ✓ | ✓ | ✓ | ± | |
| Bone loss | ✓ | ✓ | ✓ | ✓ | |
| Infected | ✓ | ✓ | ✓ | ± | ✓ |

All nonunions with unacceptable deformity will require correction of alignment

of structural integrity. A synovial nonunion will require increased stability, correction of alignment, and debridement of the synovial cavity. After that debridement, some cases will be improved with biologic stimulation and/or additional restoration of bony structure. Finally, the infected nonunion will need stability, correction of alignment, debridement, and antibiotics. Depending upon the extent of debridement, some of them may need grafting to restore structure to the bone.

The common basis for surgical treatment of each type of nonunion is restoration or enhancement of mechanical stability, and this is the role of internal fixation. Previous treatment may have resulted in inadequate stability from gaps or malreductions, or through failed fixation constructs. Analysis of mistakes that may have been made in previous treatments is essential and can guide the subsequent procedure. Common situations include plates that are too short, too thin, or improperly positioned or applied; screws that are too few, too many, or poorly placed; or intramedullary rods that are too short, too thin, or inadequately locked. These failed implant constructs must be removed, and appropriate fixation applied.

Removal of hardware can be challenging and the surgeon must be prepared for unusual or unfamiliar screw heads or nail extraction requirements. Identification of implants prior to surgery is ideal, in order to plan for having the correct extraction tools. In any event, sets for removal of broken screws should be available and the surgeon should be familiar with their use. Expect stripped threads and heads. In the case of intramedullary nails, long hooks are available and useful for removal of cannulated nails or nail fragments. The bone proximal to the nail or nail fragment should be over-reamed by 1–2 mm to facilitate extraction. If hooks are not available, one can sometimes use two ball tipped reaming rods to extract cannulated nails. The first reaming rod is inserted and advanced until the ball or bead is past the end of the nail. A second rod is inserted with the non-ball tip end leading, and this is advanced all the way to the end of the nail with light blows of the mallet. This forces the ball tip on the first rod into an eccentric position beyond the end of the nail and allows it to function as an extraction hook (Fig. 41.1).

Removed hardware should be cultured to evaluate for possible infection. Intraoperative Gram stain has a high specificity but a very low sensitivity for infection. Unfortunately, traditional culture-based methods for identification of infection may also be ineffective for implant-related infections caused by organisms producing a protective biofilm. Molecular diagnostic techniques are more sensitive than traditional techniques, but the role of these methods in medical microbiology has yet to be defined [40]. Sonication of explanted hardware using low frequency ultrasound increases the recovery of bacteria; however, the presence of microbes does not always indicate a clinically significant infection and does not necessarily warrant treatment. When hardware is removed with no clinical sign or symptom of infections, culture techniques show an unexpected rate of positive results [41].

In general, improvement of stability requires plates and nails that are longer and stiffer, and more firmly attached to bone, than those removed; and more than is often required for acute fracture. Compression of bone ends and fracture fragments should be achieved through plating and lag

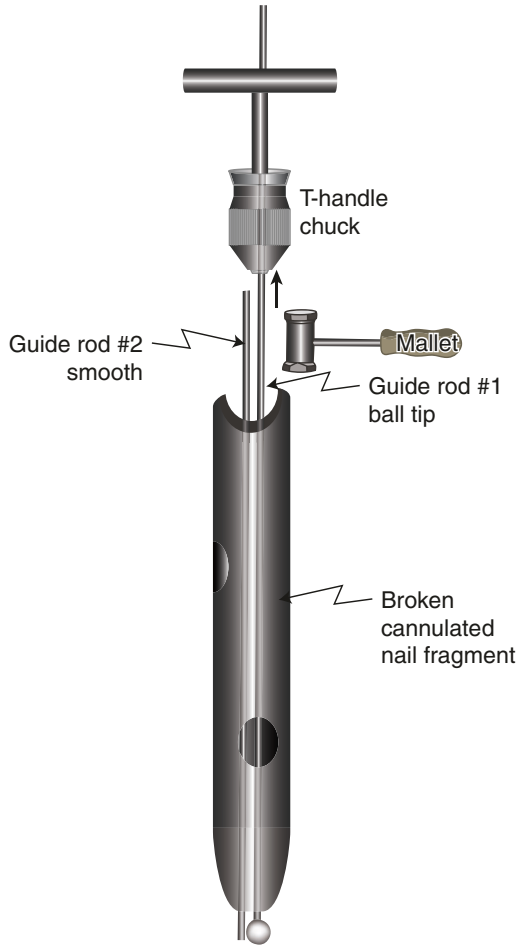


**Fig. 41.1** Diagram of the two guide rod technique for removal of a cannulated intramedullary nail when the nail is broken or the threads are stripped. The second, smooth guide rod forces the ball tip of the first rod to an eccentric location, where it functions as a hook on the end of the nail

screw technique whenever possible. Correct anatomic and mechanical alignment is important to allow the forces of muscle contraction and weightbearing to further compress and stabilize the nonunion. Figures 41.2, 41.3 and 41.4 illustrate these principles for the humerus, tibia, and femoral neck.

Dynamization of a nail construct by removing interlock screws and encouraging WB is occasionally successful (~50% of the time in femoral nonunion), but it likely is just a delaying tactic and does come with some risk—primarily shortening in fractures which are not axially stable [42]. In addition, it philosophically plays against the strategy of increasing stability. The same criticism is true regarding fibular osteotomy for tibial nonunion, another treatment of limited reliability when used by itself.

While it has been said that a failed nail should be treated with a plate, and a failed plate with a nail, that is an overly simplistic approach. The point is to do something different and better with the second operation rather than making the same errors again. Certain nonunion locations, such as the diaphysis of lower extremity long bones, lend themselves more easily to enhanced stability through intramedullary nail fixation, even if a previous nailing has failed. When performing an exchange nailing (removing an intramedullary rod used for initial fixation and placing a new one), it is important to identify and correct the deficiencies of the original nailing, by eliminating gaps, correcting alignments, using larger, stiffer implants (1–2 mm increase in diameter, thicker wall) and improving the interlocking. Success rates after femoral exchange nailing for nonunion have varied from 53% to 97%. It is more likely to be successful if clear deficiencies in the original nailing can be identified—excessive gaps, failure to interlock, unreamed, or undersized nails; and it is less likely to be successful in smokers [42]. In the tibia, exchange nailing is successful in a high percentage of aseptic tibial diaphyseal nonunions [43]. A recent report revealed a 97% success rate. Over half the patients (59%) underwent fibular osteotomy and 86% had dynamic compression used. An open surgical approach was used in 17%; when that was necessary, the authors utilized bone grafting and recombinant human bone morphogenetic protein rhBMP-7 [44]. A separate study with a significantly lower success rate (63%) found that presence of infection was a major risk factor for failure of exchange nailing, along with NU atrophic type or residual gap greater than 5 mm [45]. Exchange nailing is generally not successful for nonunions of the humerus.

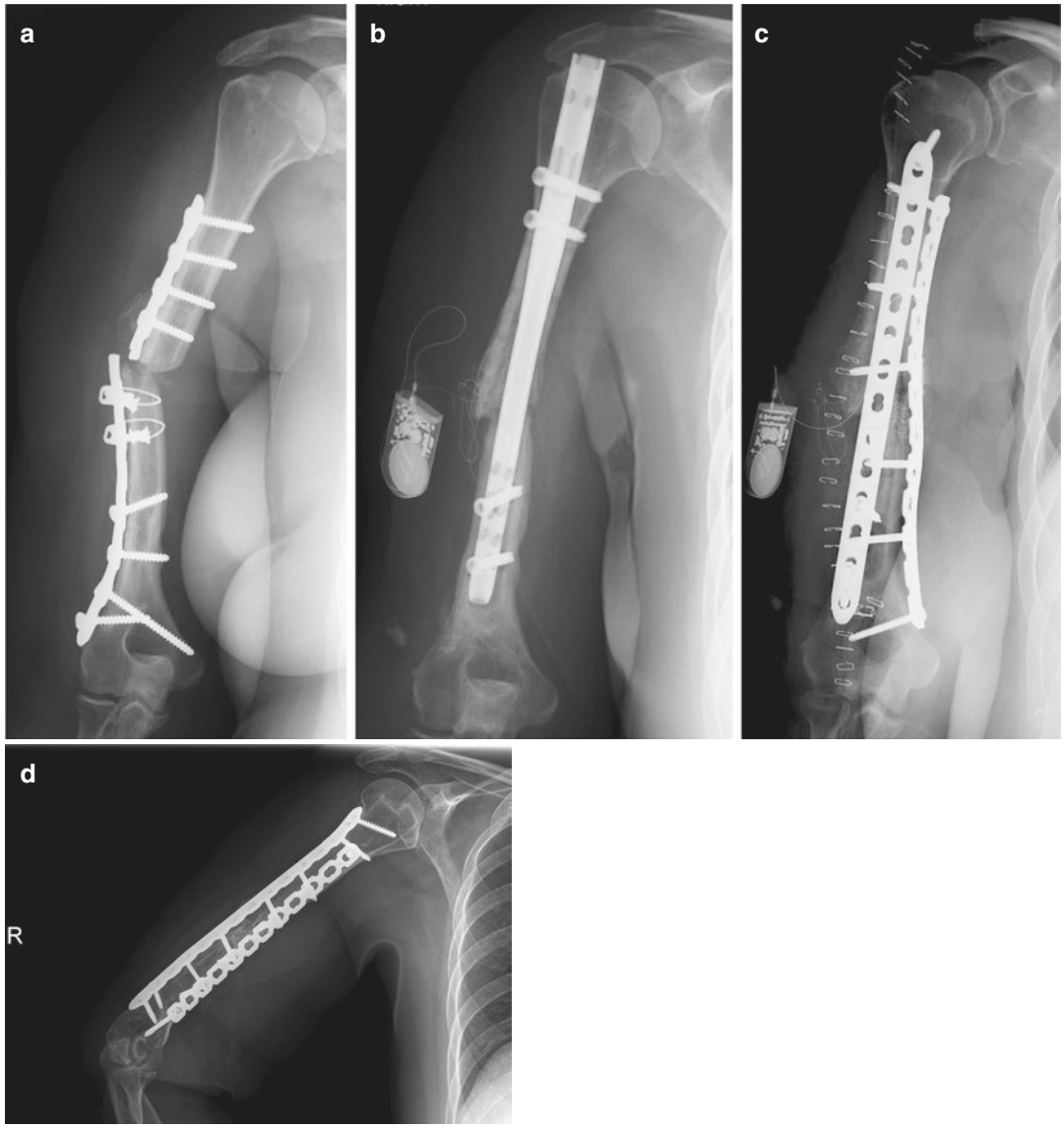


**Fig. 41.2** Nonunion of the Humerus. A 45-year-old female patient suffered an isolated midshaft humerus fracture in a fall, which was treated with plating. (**a**) Nonunion developed, possibly due to excessive soft tissue stripping (cables) and plating without compression; and eventually the plate broke. (**b**) The plate was removed and an intramedullary nail placed with bone stimulator. Unfortunately, the oversized nail was locked with a gap at the fracture site, and the nonunion persisted. Prominence of the nail proximally inhibited use of the arm. (**c**) Revision was performed with long 90-90 dual plating, closure of the gap, bone grafting, and repeat bone stimulation. (**d**) The fracture healed with the improved biomechanical environment. (**e**) A 45-year-old obese man had a distal humerus fracture in a motor vehicle accident. It was treated with olecranon osteotomy and Steinman pinning; atrophic nonunion was the predictable result. (**f**) Bicolumnar plating with bone graft led to predictable healing. (**g**) Another example of inadequate plating of the humerus: the plates are too short, and there is a gap at the fracture site. (**h**) Reliable healing following balanced, long, bicolumnar plating, bone grafting, and bone stimulator

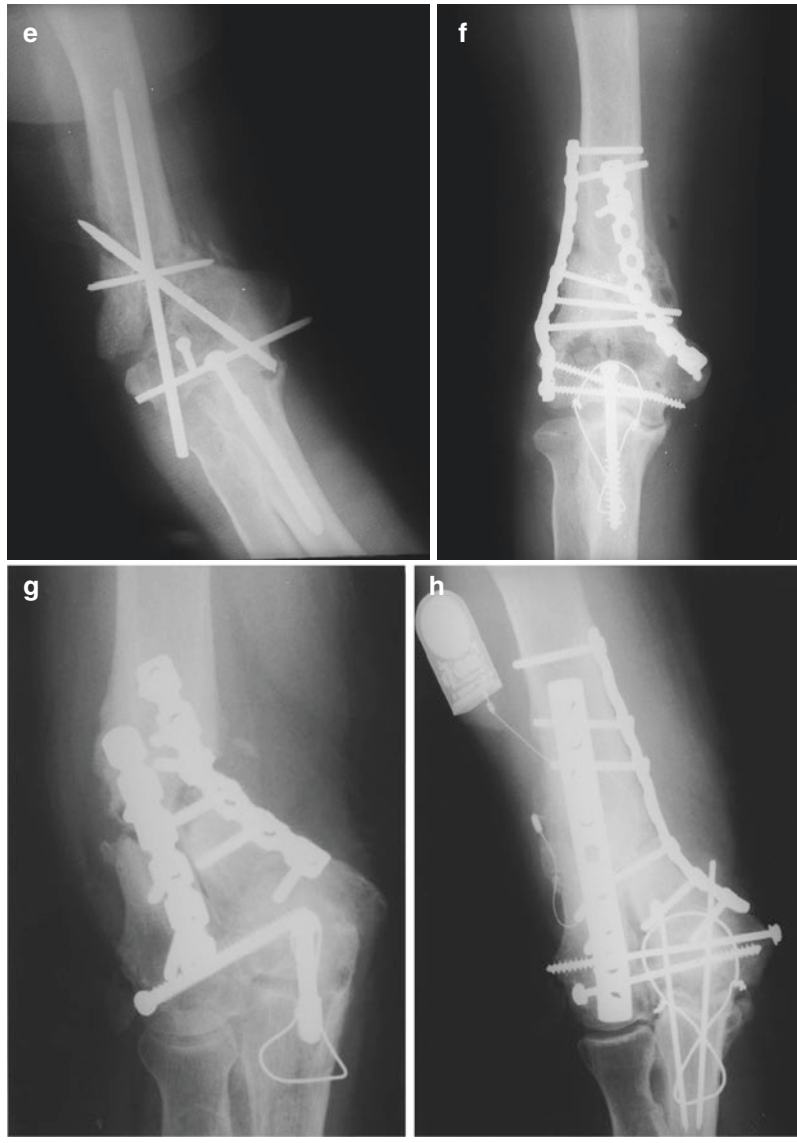


**Fig. 41.2** (continued)

Some locations, such as upper extremity and peri-articular nonunions, are better treated with plates. The length of plate necessary in treatment of nonunion is dependent upon the specific bone, location of the fracture, effects of previous hardware, and quality of the bone. Commonly repeated rules about the number of "cortices" of fixation required for plate stabilization of a particular bone are not evidence based, and biomechanical testing has shown that the length of the plate is more important to stability than the number of screw cortices used to attach it to the bone. When in doubt, go longer; but you do not need to fill every hole, particularly in good quality bone. Each screw hole in a plate is an opportunity, not an obligation. The use of locking plate technology is useful in obtaining stable fixation in osteoporotic bone, but always be careful not to compromise on fracture compression or the use of lag screw technique in favor of locking. Compress first, then lock if necessary.

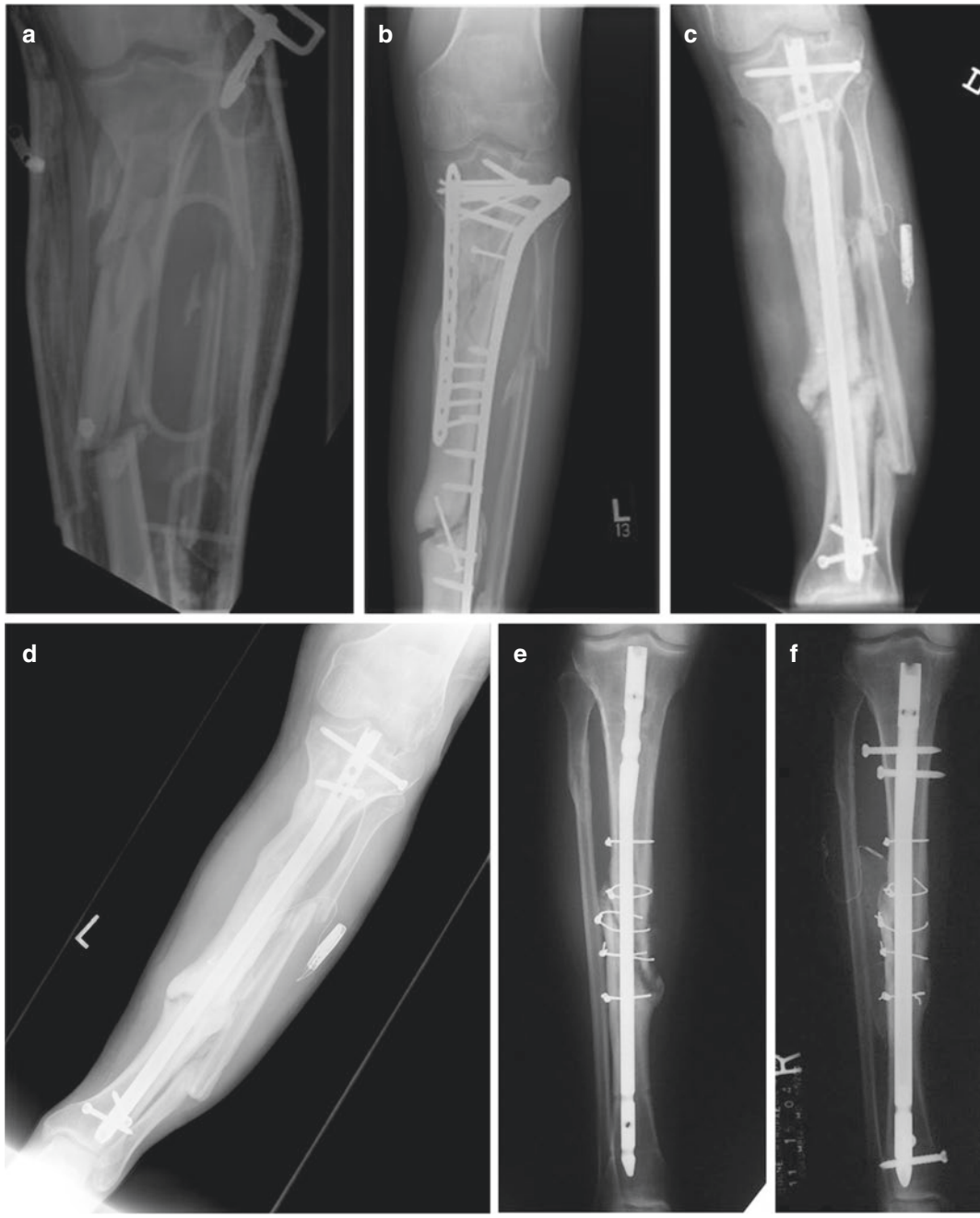


**Fig. 41.3** Nonunion of the Tibia. (**a**) A 42-year-old painter fell from a scaffold and suffered an open, segmental tibial fracture. (**b**) Treatment consisted of wound care and eventually, dual plating; however at 2 years after injury, he continued to have pain and inability to WB due to his 2 level atrophic nonunion. (**c**) Treatment consisted of hardware removal, creation of a tibial intramedullary canal, reamed interlocked nailing, bone graft, and bone stimulator. (**d**) By 5 months, he was FWB and had returned to work on a healed tibia. (**e**) This tibial nonunion in a 33-year-old rodeo clown, was treated with open cerclage and unreamed nailing. His atrophic nonunion was not solved by removing the distal interlocks. (**f**) The ultimate solution involved improving the stability with a larger, reamed, solidly interlocked nail, with posterolateral bone grafting and bone stimulator

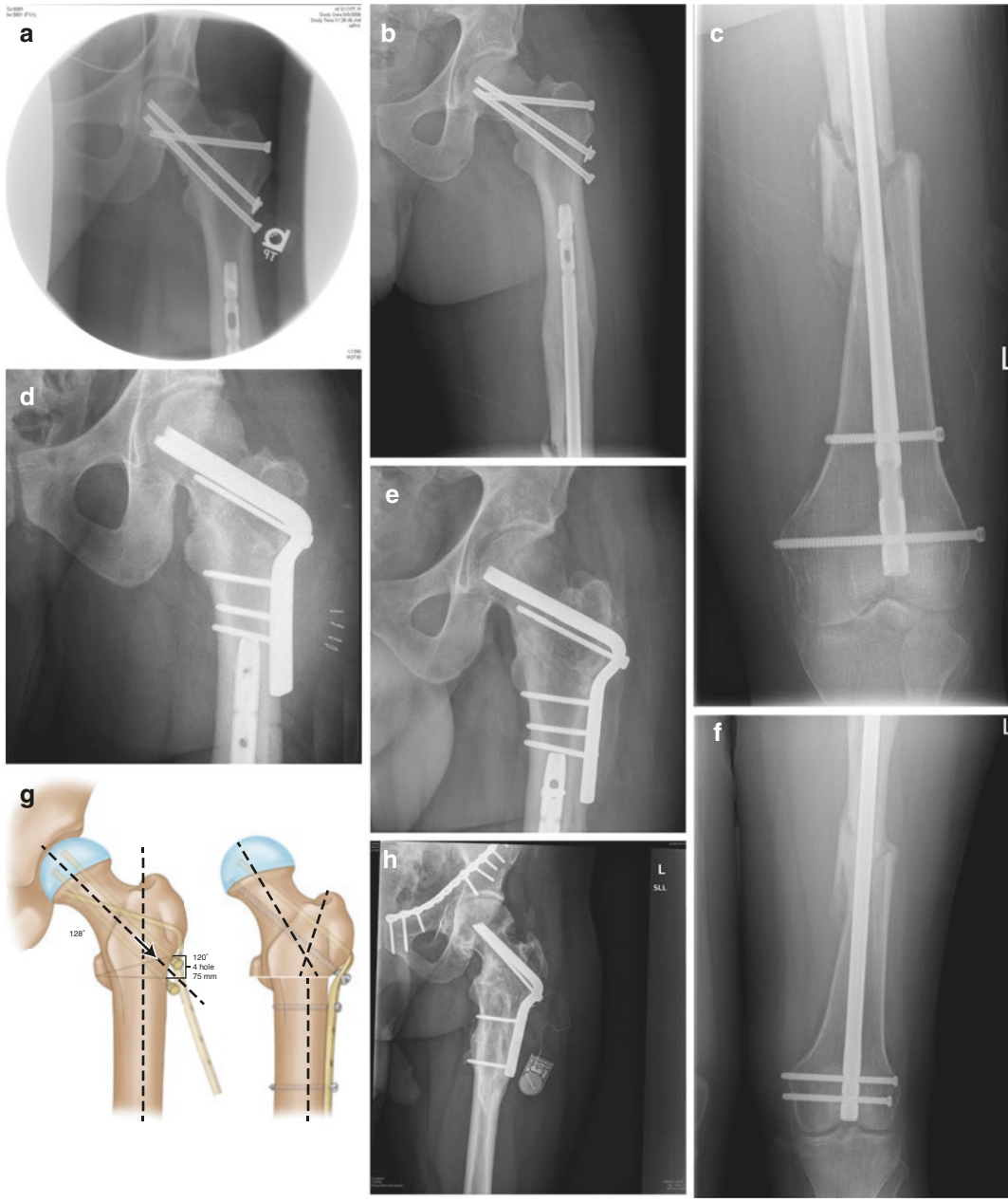


**Fig. 41.4** Nonunion of the femoral neck. A 23-year-old man suffered an ipsilateral femoral neck and shaft fracture in a motorcycle accident. The shaft fracture was treated with a retrograde nail, and the vertical neck fracture was treated with cannulated screws. (**a**) Initial C-arm view of the femoral neck fixation shows imperfect reduction. (**b**) By 4 months post-op, the neck has fallen into varus and shortened. In this situation, the femoral neck will not heal and will continue to displace. (**c**) The femoral shaft is ununited at 4 months as well. (**d**) Valgus intertrochanteric osteotomy is performed for the femoral neck nonunion, and exchange nailing for the femoral shaft nonunion. (**e**) and (**f**) Four months after surgery, both nonunions are healed. (**g**) Example of a osteotomy procedure plan for this osteotomy on a different patient. (**h**) Example of 8-year follow-up on a patient who had this same procedure

Principles of plate fixation for nonunion are like those for plate fixation of acute fractures, with the caveat that additional stability is usually required due to the longer time often required for healing. Gentle soft tissue handling is always important, but in nonunion surgery there is often scar tissue that hampers exposure. There will always be some stripping involved and the bone surface of hypertrophic nonunions may need to be contoured to allow plate fit. When possible, use submuscular placement techniques and percutaneous screw placement to get plate length proximal and distal to the NU site. Exposed bone near the NU site may be drilled, "feathered," or decorticated with an osteotome to stimulate the healing response on the periosteal surface. If the intramedullary canal can be opened during debridement of an infected, atrophic or synovial nonunion, that should be done to allow the endosteal blood supply access to the NU site. However, hypertrophic NUs should not be "taken down" for that purpose, unless it is needed for alignment correction. Correct alignment in three planes is necessary not only for function, but for stability and for healing. The use of a femoral distractor on the concave side and a lamina spreader in the defect may help with alignment correction [46]. Plates should be positioned on the tension side of the bone when anatomy allows and should be placed under tension across the nonunion, using the articulated tensioning device for larger fragment plates, or a push-pull screw with a Verbrugge or Farabeuf clamp. Dynamic compression plate holes should be utilized when available [47]. Dual plating may be necessary to enhance stability but beware the damage to the vascularity of the bone. Do not order the dead bone sandwich! When adding a second, supplemental plate to protect alignment (e.g., medial distal femur or proximal tibia), attempt to use a smaller, strategic implant placed in buttress mode through a minimally invasive approach on the opposite side from the tension plate. In the distal humerus, two plates are almost always necessary to stabilize both the medial and lateral columns. For metaphyseal nonunion, such as in the proximal tibia, locking plates may be necessary to achieve adequate grip on the peri-articular fragment, but be careful that locking on both sides of the NU does not compromise compression across it. At either end of the femur, 95° blade plates are excellent devices for fixation, compression, and alignment correction of metaphyseal nonunion.

Nonunion of the femoral neck is an example of a situation in which improved stability and correction of mechanical alignment, in combination with biological factors, can lead to reliable healing. Displaced femoral neck fractures are at high risk for nonunion due to several factors, including intra-articular environment, retrograde blood flow, lack of periosteal envelope, and prominent mechanical shear forces at the fracture site. For this reason, in younger more active patients, they require anatomic reduction and stable fixation to achieve union. When nonunion or loss of fixation occurs after treatment, the hip can sometimes be saved and union achieved with intertrochanteric valgus osteotomy as described by Pauwels. In this procedure, a laterally based wedge is removed from the intertrochanteric region of the proximal femur, which results in a valgus tilt to correct the varus deformity and shortening of the nonunion. It is most reliably fixed with a blade plate. The procedure has a high rate of success at achieving union and can successfully restore hip function even in the face of some degree of avascular necrosis of the femoral head, provided there is no collapse of that head (Fig. 41.4) [48–50].

## 41.8 Surgical Treatment of Malunion

Entire fellowships are devoted to this topic and detailed instruction is beyond the scope of this chapter. The stages of the process include analysis of the locations and degrees of deformity; planning the sites, orientations, and magnitudes of osteotomies; and fixation options. It is very important to understand the significance of the deformity to the patient's functional demands and desires and to have in-depth discussion of outcomes and risks. It is devastating to turn an annoying or cosmetic malunion into a disabling nonunion, or worse, and infected nonunion.

Perhaps the simplest situation is an angular malunion of a long bone diaphysis. Figure 41.5

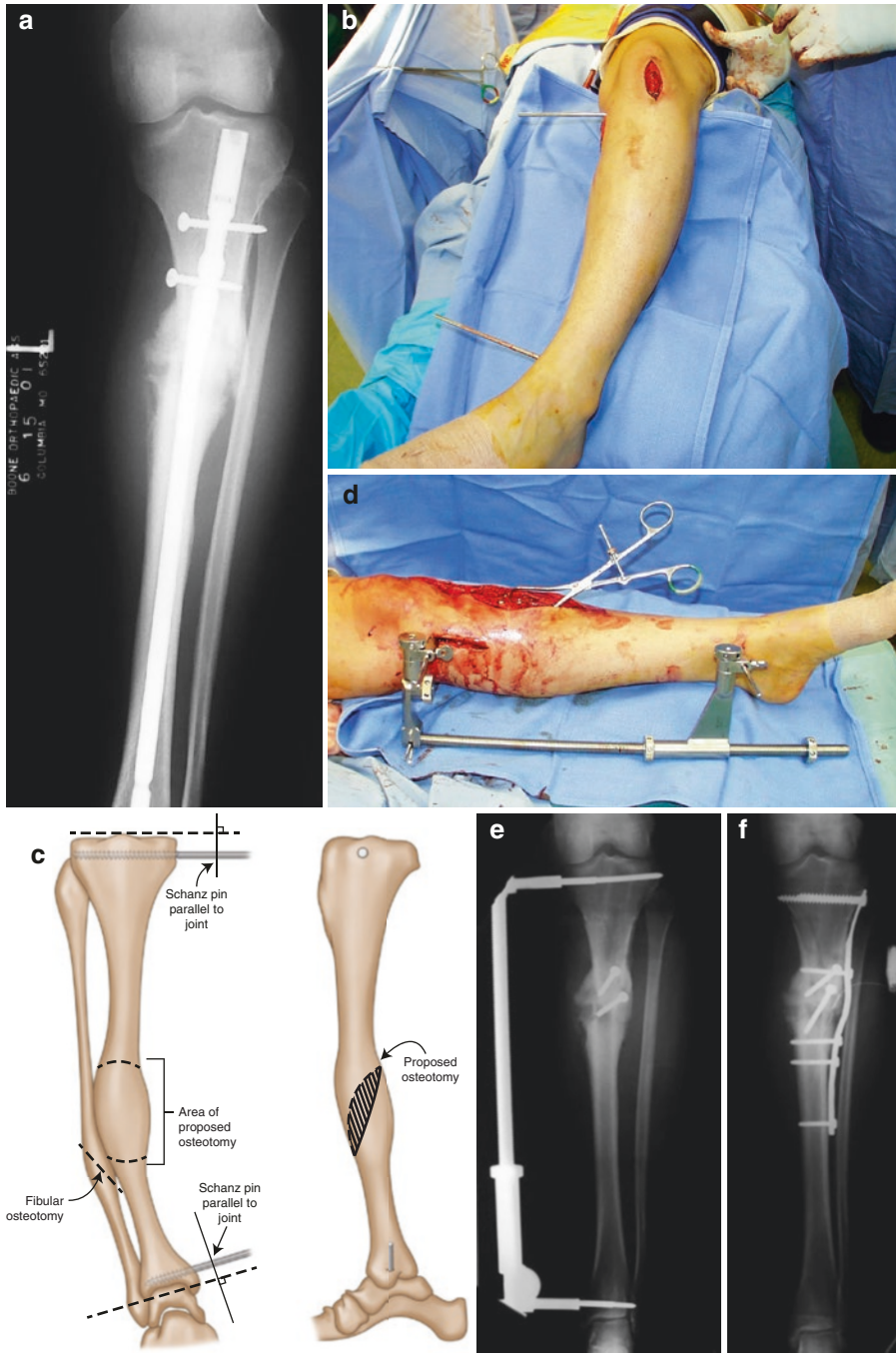


**Fig. 41.5** Oblique osteotomy of tibial malunion. (**a**) A 28-year-old man with a varus tibial malunion following intramedullary nailing of his proximal third fracture. The malunion resulted from an improper starting point for the tibial nail. (**b**) After hardware removal, Schanz pins are placed parallel to the knee and ankle joints. The osteotomy is performed, and the femoral distractor is used to bring the pins parallel to each other. (**c**) Diagram from Sanders et al. showing the location and orientation of the osteotomy (reused with permission from [52]). (**d**) After performance of the osteotomy, a clamp is placed across the bone cut. (**e**) Intraoperative radiograph showing parallel alignment of the knee and ankle, and placement of lag screws across the osteotomy. (**f**) Final fixation, with a neutralization plate placed on the tension side

represents an example of an angular malunion of the tibia (Fig. 41.5). The magnitude of tibial deformity which would require surgical correction is somewhat controversial and various criteria have been published. The patient tolerance for angular malunion of the tibia is variable based on patient's age, activity, normal alignment, and occupational or recreational requirements. In general, valgus angulations <10°, varus angulations <6°, extension/flexion angulations of <10°, and malrotations of less than 10° are well tolerated by most patients. A detailed history of the patient's complaints, and careful physical exam including measurement of length discrepancies and observation of gait or simulated sport activity is important to formulate the goals of treatment. Assessment of soft tissue envelope health and vascular status will help with defining risks of the procedure. Radiographs usually necessary include at least AP and lateral views of both tibiae including knee and ankle. Long standing films may be useful in evaluating overall alignment. Rotation can usually be evaluated from physical exam although CT scan may be helpful.

Corrective osteotomy can be done with a variety of surgical techniques, including opening wedge, closing wedge, dome, clamshell [51], or single-cut oblique [52] methods. A closing wedge provides correction of angulation and rotation, and the opportunity for compression but may lead to shortening and a limited bony surface for healing. The opening wedge requires bone grafting and may lead to healing problems, particularly in the tibial diaphysis after previous fracture. The dome osteotomy is technically difficult to perform and limits the ability to correct rotation or multiplanar deformity. The single-cut oblique osteotomy can correct multiplanar deformity including rotation and allow some lengthening, while providing large bone surfaces to compress. Planning of the osteotomy has been detailed in the literature [52, 53] and can be done using trigonometry, or with computer-assisted planning, or by utilizing the "no-angulation view" technique. It should be understood that the orientation of the osteotomy has a transverse component and thus correction through the cut will always entail some degree of rotation; it is essential that the obliquity of the cut be performed in the correct orientation to improve and not worsen any rotational component of the deformity. The femoral distractor is a useful adjunct to gaining length, and an appropriately performed lag screw at the axis or correction is a helpful component for healing. Ten of 12 patients who underwent oblique osteotomy of a tibial malunion healed at an average of 4.5 months and had resumed full weightbearing, activities of daily living, and light work. Two noncompliant patients failed the operation due to soft tissue or hardware failures; both were salvaged and returned to original employment eventually [52]. Axial lengthening in this series was modest and somewhat disappointing, averaging 1.3 cm. The maximal lengthening obtained was 2.5 cm, and the authors recommend that if more than that is required, then alternative methods such as distraction osteogenesis should be considered.

## 41.9 Bone Grafting

Bone grafting is indicated when there is a gap or defect in the bone from injury or debridement, or when there is an atrophic/oligotrophic nonunion requiring biologic stimulation. Hypertrophic nonunions and malunion osteotomies rarely need any bone graft. Bone grafts are classically considered to perform three primary functions: osteoinduction, osteoconduction, and osteogenesis—formation of bone by living cells. In addition, cortical or cortico-cancellous bone grafts can perform a structural function; and when they are transferred along with a vascular pedicle, they can bring new blood supply to a non-united area. Bone grafting is usually performed as a component of surgical treatment that may include fixation or re-fixation, debridement, re-alignment, and bone stimulation. It is rarely performed as a standalone procedure, except in the case of segmental defects, or as a prophylactic treatment in high energy open tibia fractures.

The classic nonstructural bone graft is cancellous bone harvested from the iliac crest with curettes, osteotomes, or an acetabular reamer [54]. In recent years, intramedullary bone has

been harvested from femurs or tibias using a device called a Reamer Irrigator Aspirator or RIA (DepuySynthes, West Chester, PA). The RIA has been shown to provide increased volumes of bone graft in shorter times, with less donor site pain, compared with both anterior and posterior iliac crest bone graft techniques using curettes and gouges. There was no significant difference in healing rates or time required for healing although the study was under-powered [55]. Some authors have found differences in growth factors and osteogenic elements between iliac crest graft and RIA graft [56]. Fracture of the donor femur and perforation of the anterior cortex of the donor femur are serious complications that can occur with RIA bone harvest, and the risk of such events can be lessened by certain technical factors, such as monitoring the reamer tip with fluoroscopy through the harvest.

When placing cancellous graft for stimulation of atrophic nonunion or consolidation of gaps, the graft should be placed in contact with living bleeding bone on both ends, and it should overlap the ends of the bone. When possible, the intramedullary canal should be opened on either side of the nonunion (usually done before application of fixation). The periosteal surface should be scored or feathered to open small vascular channels in the bone where you wish the graft to anchor. The graft should be held in place by a healthy soft tissue envelope. The classic example is the posterolateral bone graft of Harmon for tibial nonunion [57]. A recent report of 59 procedures revealed a success rate of 75% [58]. In this procedure, the graft is placed on the intermuscular septum between the tibia and fibula, under the posterior calf musculature. The graft is in contact with the surface of both the tibia and fibula (appropriately prepared), and the goal is to create a bridging synostosis between the two bones that spans the nonunion site. Video of this technique is available online from the OTA video library at: https://vimeopro.com/orthotraumaassn/2015-surgical-technique-videos/video/187360686 (Fig. 41.6) An alternative approach going anterior to the fibula has been called "central bone grafting" [59] and may be somewhat easier due to supine positioning.

When the patient has inadequate donor bone graft sites to provide enough autograft cancellous bone, there are some choices for expander or substitutes (Table 41.2). Some bone graft substitutes are primarily osteoconductive, that is, they provide a three dimensional scaffold that allows ingrowth or on-growth of host bone. In general, these are used to fill metaphyseal defects and support subchondral bone near a joint, or for use in non-segmental defects. Their use in nonunions is primarily as a volume expander for autogenous cancellous graft. These products include calcium phosphates and calcium sulfates (Plaster of Paris), collagen-based matrices, bioactive glass, and coralline hydroxyapetite [60, 61]. Allograft cancellous bone is available in most hospitals and can also provide a scaffold for osteoconduction. The live cells and growth factors are removed during processing for sterilization, and so there is no osteoinductive capability in this product. There is a very low possibility of disease transmission with allograft bone. It can be combined with bone morphogenic protein (BMP) to increase the efficacy as an autograft substitute [62]. Demineralized Bone Matrix (DBM) products have been available for decades. They are available in the form of a gel, paste, putty, or powder. DBMs have some degree of osteoconduction property and provide an osteoinductive stimulus function through growth factors. The efficacy of these products has been highly variable in the many studies that have been done, and their use is still controversial. Recombinant human BMP (rhBMP-2 and rhBMP-7) has been used to enhance healing in fracture and arthrodesis, particularly in the spine. It does not seem to add any additional benefit when combined with iliac crest autograft [63], but, as mentioned above, it may be a useful *alternative* to ICBG if that is unavailable, particularly when combined with allograft. Calcium phosphates and sulfates are void fillers with primarily osteoconductive properties. They can be used in cement form to increase structural integrity of osteopenic bone and improve screw purchase. In addition, because the body slowly absorbs them, they have been used for antibiotic delivery.

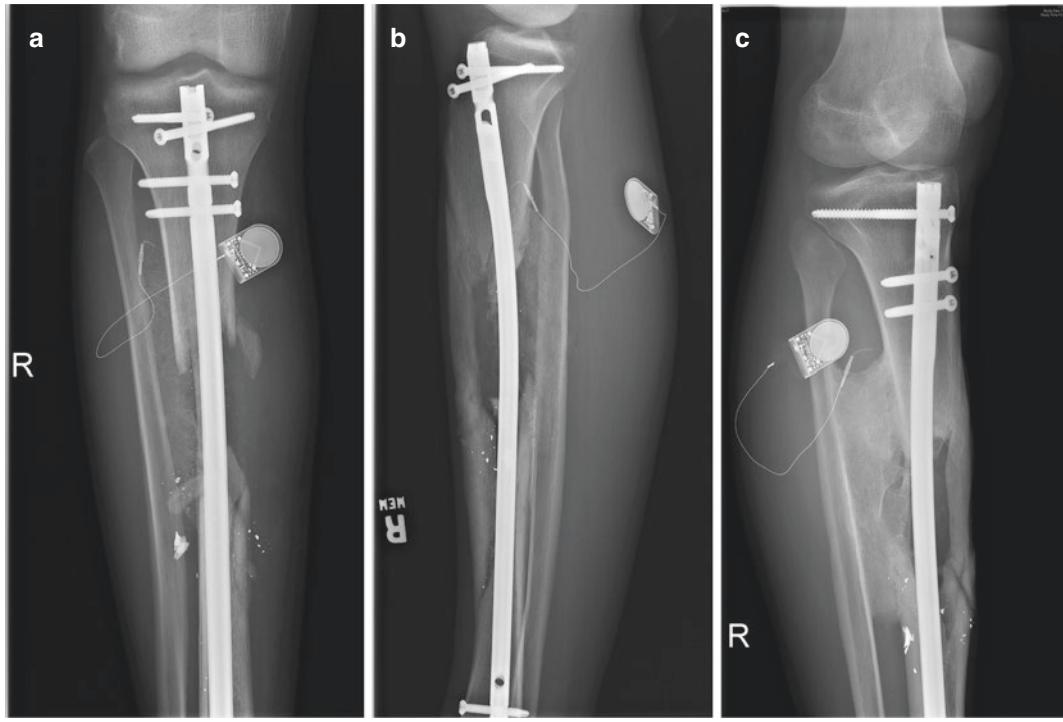


**Fig. 41.6** Posterolateral bone graft for tibial nonunion. A 23-year-old male suffered a gunshot wound resulting an open grade III-B tibia fracture with significant segmental tibial bone loss. After an initial period of external fixation and wound care, he underwent reamed intramedullary interlocked nailing. After wound healing and soft tissue recovery, he underwent a posterolateral bone graft and implantable bone stimulator to address the defect in the tibia. (**a**) Anteroposterior radiograph 1 month after bone grafting. (**b**) Lateral view after bone grafting. (**c**) Oblique view at 4 months showing a solid tibio-fibular synostosis

**Table 41.2** Bone graft substitutes, expander, and enhancers

| Material | Role | Pro | Con |
|---|---|---|---|
| Cancellous allograft | Osteoconduction, filling of metaphyseal defects, expansion of autograft volume | Three-dimensional structure of human cancellous bone | Slow and variable rate of incorporation, no osteoinduction or osteogenesis, low risk of disease transmission, requires specialized storage |
| Demineralized bone matrix (DBM) | Osteoconduction, osteoinduction | No limits to quantity, easy storage, variety of structures and forms | Variability in effectiveness due to variability in source bone and manufacturing processes, low risk of viral transmission |
| Recombinant human bone morphogenic protein (BMP) | Osteoinduction | No limit on quantity, relatively easy to store | Inflammatory response, expense, uncertain efficacy |
| Ceramics: calcium phosphate/sulfate, tricalcium phosphate, hydroxyapatite | Osteoconduction; filling of metaphyseal defects, expansion of autograft volume; limited use in nonunion | No limit of quantity, no risk of morbidity or disease transmission, easy sterilization, and storage | No osteoinduction or osteogenesis; variable resorption rate |
| Combination products | | | |

When there is segmental defect in the bone either from trauma or debridement, it can be handled by shortening the bone, transporting bone (the technique of Ilizarov), or by grafting the defect. The two grafting techniques that are most commonly used are vascularized bone transplant (e.g., free fibula transfer) or cancellous grafting using the technique of Masquelet [64, 65]. In this technique, the nonunion site is debrided and the defect is filled using polymethylmethacrylate (PMMA) cement containing antibiotics. This cement spacer is formed to fit the gap and to surround the ends of the bone, which is commonly stabilized with an external fixator, although plates and nails can be used as well. The PMMA spacer induces the formation of an investing membrane that produces various growth factors that favor bone formation. After approximately 6 weeks, the site is opened, taking great care to preserve the membrane, and the spacer is removed. The gap is then filled with bone graft, obtained from the iliac crest or by RIA, the membrane is closed around the graft, and definitive fixation is applied. The largest series of cases reported in the literature consisted of 84 patients who achieved 90% union at 1 year [66]. A systematic review of the literature regarding this technique published in 2016 revealed an 89% success rate in achieving union, and a 91% success rate in treating infection [67]. However, some smaller series have shown lesser rates of success and higher rates of complications, indicating the overall general high complexity and risk of segmental defect treatment.

## 41.10 Implantable Bone Stimulator

Implantable electrical bone stimulators have been used for treatment of nonunion and for augmentation of spinal fusion. This device (Osteogen bone growth stimulator, Zimmer Biomet, Warsaw, IN) consists of a small implantable battery ("generator") with the anode on the body of the battery and a titanium filament cathode. Once implanted in the aqueous environment of the body, the circuit is completed and a small current flows through the tissues. This is usually implanted as the last stage in the procedure, after failed hardware is removed, debridement is performed, nonunion surfaces are prepared, re-fixation is performed and bone grafting in place. The cathode wire or mesh can be folded or coiled and inserted into drill holes, troughs, or nonunion defects. Some part of the cathode should contact living bone on both sides of the nonunion, and it should not come into contact with other metallic implants. The cathode wire can be buried in bone grafts, wrapped around cortical, or matchstick grafts or inserted into drill holes in the bone. The generator is then positioned in a subcutaneous pocket that is created in a location that will not be bothersome to the patient and will not obscure radiographs of the nonunion. It is usually in a superficial enough location for palpation to facilitate removal. Removal is recommended and can usually be performed as an outpatient or office procedure with local anesthesia. This can be performed at 9–12 months as an elective procedure after healing is achieved. The battery wire will break loose at the cathode connection with gentle steady tension.

There are no prospective randomized controlled trials of implantable bone stimulator use in nonunion. An uncontrolled prospective multicenter trial and a retrospective single surgeon series both showed approximately 85% success rate in heterogenous groups of long bone nonunions [68, 69]. A retrospective study comparing NU treatment with and without implantable bone stimulator utilized the practices of two orthopedic traumatologists with similar training and experience, who were partners. There were 38 patients with a minimum of 1-year follow-up. Twenty-five did not have an implantable bone stimulator and 13 did. The use of an implantable bone stimulator was found to be significantly associated with increased rate of union (Fig. 41.7) [70].

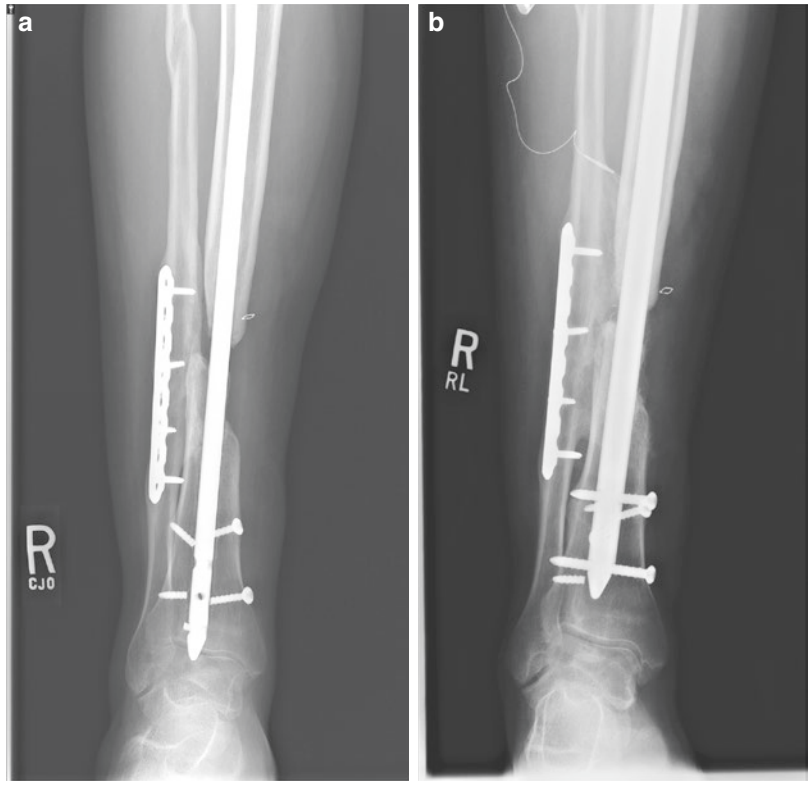


**Fig. 41.7** Implantable bone stimulator. (**a**) A 24-year-old patient suffered an open tibia fracture with bone loss that required a soft tissue free flap. He was initially treated with unreamed nailing. Five years after his injury, the fibula had healed but the tibia had not, and the interlock screws failed. (**b**) He was treated successfully with exchange nailing, posterolateral bone grafting, and implantable bone stimulator

## 41.11 Conclusion

Treatment of a nonunion or malunion is a complicated, long-term process that requires intimate knowledge of the patient's medical and surgical history, as well as personal and social history. The surgeon needs to know the patient's occupation, living situation, social and psychological support structure, hobbies, sports, expectations, hopes, and fears.

**Key Concepts**

- Medical conditions should be assessed and optimized as part of the treatment. This includes endocrine and metabolic work-up, investigation for occult infection, management of diabetes and vascular disease, nutritional assessment, addressing medications or habits (tobacco) that may inhibit healing, and evaluation of limb function and soft tis-

sue envelope. Optimization of these host factors is the first step in treatment of any patient.
- Non-operative treatments, such as bone stimulators, can work in selected patients. They are particularly suited to hypertrophic nonunions of the lower extremity with good alignment.
- When non-operative treatment of the condition is not successful or appropriate, surgical treatments can be effective and can be offered to the patient, after thorough discussion of risks and benefits. The surgeon should be experienced with a wide range of surgical treatment options and have an understanding of the outcomes. When appropriate, referral to a center with more experience in these complex treatments is advisable.

**Take Home Messages**
- Surgical treatment is based on an individualized assessment of the patient, the limb, and the bone. It may include revascularization or flap coverage in addition to orthopedic procedures such as hardware removal, debridement, correction of alignment, stable internal fixation, and bone grafting or other healing adjuncts.
- The goal of internal fixation of nonunion is to compress the fracture lines and increase the stability of the construct. This may often require longer/larger/more implants applied in a rational and biologically friendly manner. Analysis of previous fixation failure will often guide the way to surgical strategy.
- Hypertrophic nonunions usually heal well with just improved stability via internal fixation.
- Bone grafting is useful when the nonunion is atrophic, or there is a bone gap or defect. Graft can be obtained in a variety of ways from the pelvis or intramedullary canal of long bones (RIA). Bone graft substitutes or expanders can be useful, but autograft remains the gold standard for use in nonunion.
- Treatment of a functionally significant malunion requires osteotomy. This can be performed using opening or closing edge, dome, clamshell, or oblique single-cut techniques. Appropriate planning is essential.

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# 42 Strategies for Visceral Complications

Hans-Peter Simmen, Carina Eva Maria Pothmann, Florin Allemann, Hans-Christoph Pape, and Valentin Neuhaus

**Learning Objectives**

- Detect visceral complications within the limits of polytraumatized patients.
- Distinguish real complications from deviations inherent to the injury pattern and/or the operative procedure performed.
- Learn that the incidence of complications may be regarded as a surrogate marker of quality.
- Recognize that the diagnostic imaging of choice is a contrast medium enhanced CT scan.
- You are aware when an exploratory laparotomy is mandatory.
- Learn when to apply damage control principles even in clearing complications.

## 42.1 General Considerations and Definitions

*The following chapter deals with visceral complications in the context of abdominal trauma surgery.*

What is a surgical complication? The definition of surgical complications is a difficult task. Visceral complications in trauma surgery may occur due to a missed diagnosis, following an operation for an abdominal trauma, or also after non-operative treatment. The incidence of postoperative complications is a frequently used surrogate marker of quality in surgery. Complications are regarded as adverse events or any deviation from the normal and/or ideal postoperative course that is not inherent to the procedure and does not comprise a failure to cure. The term "adverse event" does not mean "malpractice" but an undesirable, unintended result during or following a treatment, usually an operative intervention [1].

It has to be taken into account that the patient's risk factors play a role in the anticipated results. Is there a way to assess for latent errors (often called "near-miss situations"). Was the patient harmed? Was only the length of hospital stay affected? Was there permanent disability? Did the patient die? These questions have to be answered to improve future performance. A safety culture has to be established, "near miss" as well as "sentinel events" have to be avoided [2–4].

One out of seven patients is suffering an adverse event. The first priorities are to recognize and adequately treat the adverse event as well as clear communication with patient and his/her family (first victim). However, the involved health care professionals can also become vic-

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tims in the sense that they are traumatized after the event (second victim). They can experience significant personal and professional distress. Second victims use different coping strategies in the aftermath of an adverse event, which can have a significant impact on clinicians, colleagues, and subsequent patients. Second victim support is needed to support health care workers and to improve quality of care. Support can be provided at the individual and organizational level. Programs, such as team debriefings, need to include support provided immediately post adverse event as well as on middle and long term basis [4, 5].

**A safe diagnostic work up helps to prevent missed diagnoses as well as to realize as soon as possible deviations from the ideal postoperative course in the follow-up period.**

Abdominal trauma, one of the leading causes of death under the age of 45, can be broadly classified into blunt and penetrating trauma, based on the mechanism of injury. Blunt abdominal trauma usually results from motor vehicle collisions, fall from heights, assaults, and sports and is more common than penetrating abdominal trauma, which is usually seen in firearm injuries and stab wounds. In both blunt and penetrating abdominal trauma, an optimized imaging approach is mandatory to diagnose life-threatening injuries. Easy availability of the portable ultrasound in the emergency department and trauma bay makes it one of the most commonly used screening imaging modalities in the abdominal trauma, especially to assess a possible hemoperitoneum. Evaluation of the visceral and vascular injuries in a hemodynamically stable patient, however, warrants intravenous contrast-enhanced multidetector computed tomography scan. Dual-energy computed tomography with its postprocessing applications such as iodine selective imaging and virtual monoenergetic imaging can reliably depict the conspicuity of traumatic solid and hollow visceral and vascular injuries. Furthermore, in polytrauma patients at risk, scores using different physiological systems proved to be more precise [6–8].

E-FAST (Extended-Focused Assessment with Sonography for Trauma) is now a widely utilized and internationally recognized standard exam in trauma care. It is highly accepted by emergency physicians and trauma surgeons alike. Thanks to the popularity of PoCUS (point-of-care ultrasound), it has continued to evolve over the last years and can now improve trauma diagnosis at all stages of the primary ABCDE [9].

However, sonography in trauma patients can be associated with obstacles as within obese patients or patients with intestinal gas. A retroperitoneal bleeding might be difficult to realize as there is no free fluid seen in the abdomen. Also, small hollow viscus organ lesions can easily be missed, since free fluid and/or free air may be overlooked in ultrasound. A delay of the diagnosis of a hollow viscus organ injury, such as a small bowel injury, has a major impact on the morbidity and mortality of trauma patients.

If there is a high grade of suspicion of a blunt hollow viscus organ injury in a polytrauma patient by the mechanism of injury and the clinical examination, we recommend an early abdominal CT or whole-body-CT scan for primary diagnostics.

If in doubt, a laparoscopy can reveal a hollow viscus problem, delayed diagnosis can be fatal [10, 11].

The current common and dogmatic opinion is that whole-body computed tomography (WBCT) should not be performed in major trauma patients in shock. Huber-Wagner et al. assessed whether WBCT during trauma-room treatment has any effect on the mortality of severely injured patients in shock. WBCT during trauma resuscitation significantly increased the survival in hemodynamically stable as well as in hemodynamically unstable major trauma patients. Thus, the application of WBCT in hemodynamically unstable severely injured patients seems to be safe, feasible, and justified if performed quickly within a well-structured environment and by a well-organized trauma team. Even in a mechanically ventilated intensive care patient requiring high doses of catecholamines to support the circula-

tion, a follow-up CT scan should be done, if a serious complication is suspected. An ultrasound is not an adequate diagnostic tool. The CT can more clearly, with a higher sensitivity as well as specificity, reveal all relevant diagnoses as well as complications [11–13].

## 42.2 Deviation from an Ideal Postoperative Course

### 42.2.1 Postoperative Bleeding

Postoperative bleeding may be seen in every patient depending on the extent of the trauma or the surgical procedures. Due to demographic consequences trauma surgeons have to treat an increasing number of older and multimorbid patients. In our own institution, a level one trauma center, more than 3000 patients are treated annually, about 400 of them are polytraumatized. A total of 30% are more than 70 years of age. Many of the multimorbid patients need to take anticoagulant agents, a condition which increases the risk of postoperative bleeding. Usually a surgical procedure is mandatory to stop the bleeding.

Following non-operative management or minimally invasive procedures, such as angioembolization for splenic trauma, patients should undergo careful surveillance to early detect failures [14, 15].

**Common complications during the postoperative course, many of them are inherent to the trauma and to the procedure, respectively.**

### 42.2.2 Wound Healing Disorders

Wound healing disorders are a common sequelae following laparotomies or penetrating wounds and may include anastomotic leakage, soft tissue infection and incisional herniae or all of them (Figs. 42.1, 42.2, and 42.3).

There are only few conservative therapeutic options. Usually a surgical revision is required which addresses the cause.

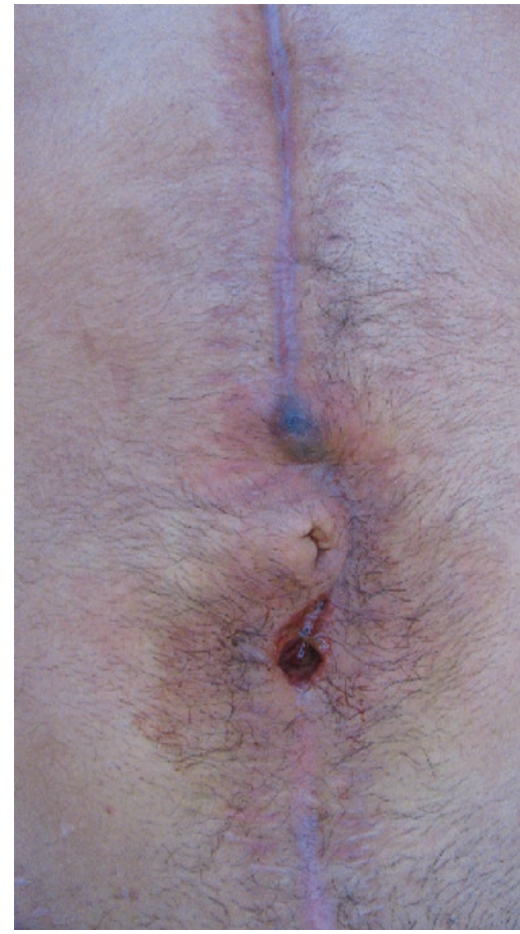

**Fig. 42.1** Wound healing disorder on postoperative day 10 following laparotomy for trauma

### 42.2.3 Small Bowel Obstruction

Small bowel obstruction due to adhesions is one of the most common complications following an emergency laparotomy. If complete (no passage of stool), a surgical procedure is mandatory.

Paralysis of the intestine is often termed paralytic ileus, prohibiting the passage of food through the intestine and leads to intestinal blockage. Sedatives used in mechanically ventilated patients, often needed in patients with severe brain injury, promote intestinal paralysis. Most of these patients can be treated without any operation. Nasogastric tubes and fluid restriction may be helpful to

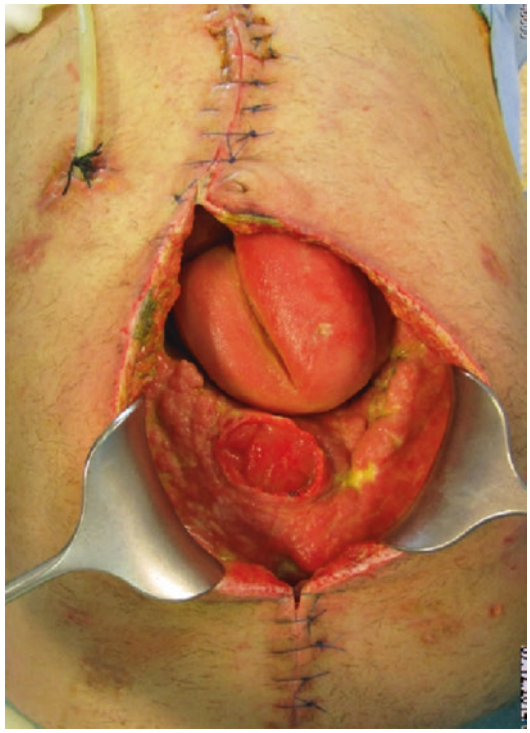

**Fig. 42.2** Burst abdomen 12 days following laparotomy for gunshot injury

decompress the stomach as well as the intestine. Also all kinds of prokinetic treatments are used. As soon as brain conditions are getting better and sedatives are reduced, the intestine will return to normal function (Fig. 42.4).

### 42.2.4 Anastomotic Leakage

Anastomotic leaks are defined as "a leak of luminal contents from a surgical join between two hollow viscus ends." They are the most important complication that needs to be recognized following gastrointestinal surgery. Early diagnosis, resuscitation, and treatment of an anastomotic leak are very important. A mild leak of the colon may be treated conservatively. However, small bowel leaks require surgery. The traditional operation with takedown of the anastomosis and construction of a new anastomosis may be appropriate, but washout with drain placement and diverting loop ileostomy may also be appropriate.

### 42.2.5 Fistula Following Small Bowel Injuries

Enterocutaneous fistulas may result from a wide variety of conditions and circumstances. Care of these patients can be quite challenging, frustrating, and, ultimately, rewarding. Fistulas are sequelae of small bowel lesions (or anastomotic breakdowns) in the presence of intestinal obstruction of the distal part and impaired blood supply, respectively. A precise diagnosis has to be established, e.g., a radiographic image of any abnormal tunnel found on the surface or inside the body, which is typical for fistulas. Images of fluids injected into the fistula reveal the dimensions of the fistula and show the organs in which it originates and ends. The water-soluble contrast media are of value at such times. To minimize mortality of patients with postoperative fistulas, nutrition, volume, and electrolyte derangements must be corrected. This must be done in addition to replacing ongoing losses in these areas. Furthermore, therapeutic options include washout, antibiotics as far as infection is present, drainage of abscesses, bowel resection and reestablish continuity of the gastrointestinal tract. If a distal obstruction is detected, it has to be cleared. Otherwise, any anastomosis, as well as fistulas, will not heal at all. Special attention should be paid to the microcirculation [16–19].

### 42.2.6 Abdominal Compartment Syndrome (ACS)

Compartment syndrome occurs when pressures increase within a fixed cavity, such as the abdomen, leading to ischemia and organ dysfunction. These "fixed" spaces are constrained by muscular and fascial boundaries, which may have limited compliance when they become swollen.

Intra-abdominal hypertension is defined as the sustained intra-abdominal pressure (IAP) above 12 mmHg.

Abdominal compartment syndrome (ACS) is a severe illness seen in critically ill patients. ACS results from the progression of steady-state pressure within the abdominal cavity to a repeated

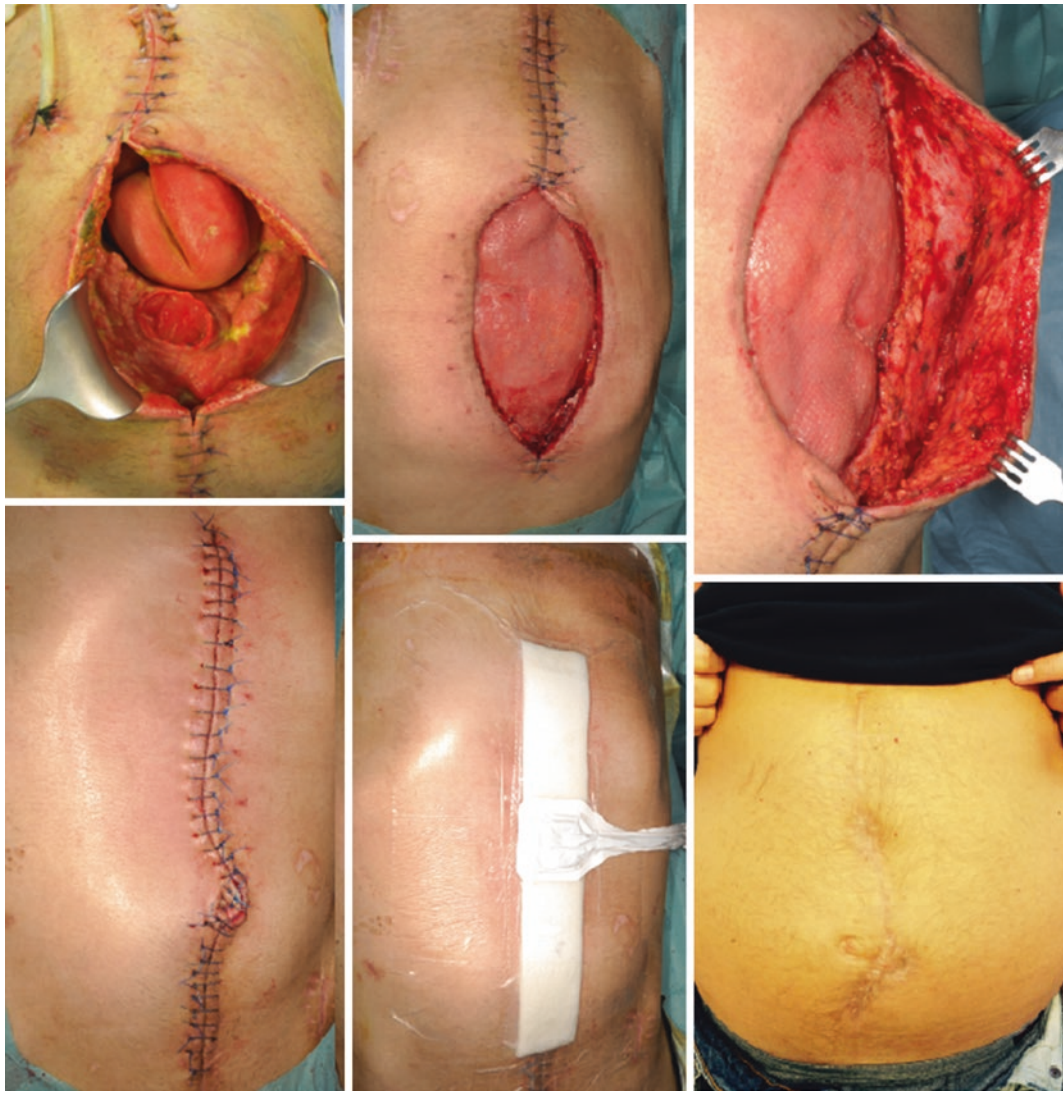

**Fig. 42.3** Burst abdomen on postoperative day 12 following laparotomy for gunshot injury (top left), stepwise repair applying a mesh graft (top middle) on day 20, freeing fascia on day 30 (top right), fasica closed using interrupted sutures on day 30 (bottom left), applying in addition negative pressure wound therapy on day 30 (bottom middle). Final result after 6 months (bottom right)

pathological elevation of pressure above >20 mmHg with associated organ dysfunction. Failure to recognize and immediately manage ACS can lend to poor prognosis as ACS is recognized as an independent predictor of mortality. High clinical suspicions with protocoled monitoring and management should be adapted when treating the critically ill, especially those with significant fluid shifts. This clinical diagnosis should be considered in patients with tense or distended abdomen with associated instability. However, it may also be seen without abdominal distention.

The exact clinical conditions that define ACS are controversial. The dysfunction may present with respiratory concerns such as high peak airway pressure and inadequate ventilation and oxygenation or decreased urine output caused by

falling renal perfusion, but these concerns are reversible with intervention. With intraperitoneal bleeding, trauma, or abscess, the physiologic response of inflammation and swelling can be held responsible for intra-abdominal hypertension.

Abdominal compartment syndrome has medical and conservative management options, and treatment is aimed at identifying and treating the cause of the compartment syndrome. Non-surgical therapeutic options for treatment of intra-abdominal hypertension involve an overall goal to improve the following: abdominal wall compliance with decreased muscle contraction, evacuation of luminal contents by decompression (nasogastric tube), evacuation of abdominal fluid by drainage, and correction of positive fluid balance through goal-directed volume resuscitation. However, patients with clinical deterioration require emergent surgical decompression and establishing "open-abdomen-treatment" using negative pressure wound therapy, meshes, and zippers. The fascia can be appropriately closed as soon as compartment pressures and swelling have decreased [20].

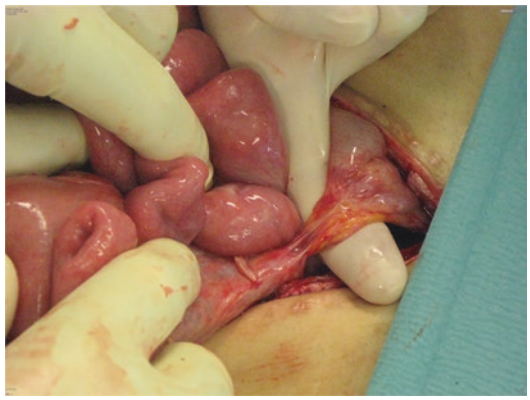

**Fig. 42.4** Intestinal obstruction due to adhesions following laparotomy for gunshot injury

### 42.2.7 Incisional Hernia (Fig. 42.5)

Incisional hernias may be the result of wound healing disorders occurring more often following emergency laparotomies than after elective interventions. Mentioned conditions such as re-laparotomies for bleeding, surgical procedures due to intestinal obstructions, fistulas, and ACS are predisposing conditions. Adipose patients are at higher risk to develop an incisional hernia. There are no conservative therapeutic options. Conventional methods are applied to repair the

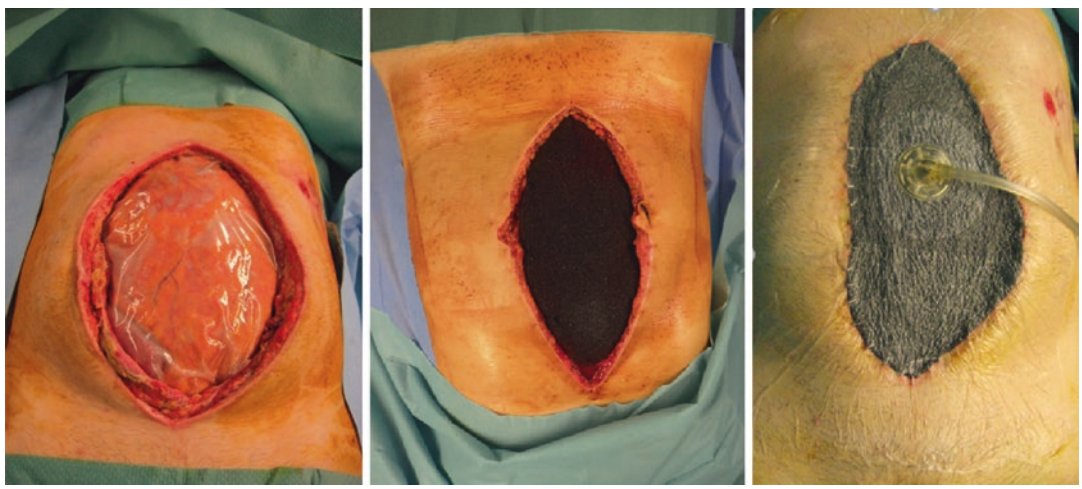

**Fig. 42.5** Laparotomy for decompression of an abdominal compartment syndrome. Temporary fascial closure using a negative wound pressure therapy. A polyurethan sheet is tucked under the fasica (left), the sponge is trimmed to match the size and contour of the wound (middle), the adhesive dressing is placed over the sponge and suction is applied (right)

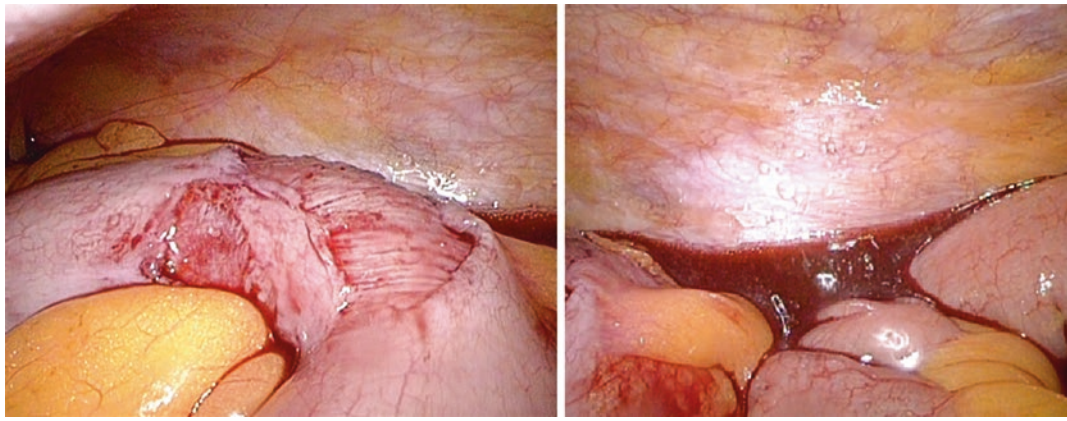

**Fig. 42.6** Laparoscopic inspection reveals serosal lesions which accounts for free fluid

hernia. The weakened tissue of the abdominal wall is re-incised and a repair is reinforced using a prosthetic mesh [21].

### 42.2.8 How to Go on with Visceral Complications in Polytraumatized Patients?

All therapeutic measures to clear complications or deviations from the ideal postoperative course following laparotomy for trauma should implement the standardized protocols of polytrauma management. In critically ill patients, damage control procedures only should be applied, even for complications [22, 23].

### 42.2.9 Role of Laparoscopy

If a patient condition deteriorates during the follow-up period, laparoscopy is an alternative procedure to look for missed or even new diagnoses inspecting the peritoneum for signs of perforation and excluding significant intra-abdominal injuries or pathologic findings. Laparoscopy can substantially reduce additional surgical intrusion. It has both diagnostic and therapeutic potential and, when negative, may reduce the number of unnecessary laparotomies. However, in polytraumatized patients with additional intracranial injuries, which are associated with blunt abdominal trauma in more than 40%, laparoscopy constitutes an additional risk especially if intracranial pressure is elevated and should therefore be avoided. The majority of access-related complications occur at the time of abdominal entry. There are varied access techniques for peritoneal entry such as the open (Hasson) method, the Veress needle technique, direct trocar insertion, and hybrid forms of entry [22, 23] (Fig. 42.6).

## 42.3 Examples

### 42.3.1 Example 1

A 28-year-old man (188 cm, 110 kg) was repairing roller blinds in level 5, lost balance, and fell down from 15 m. He arrived in the trauma bay 90 min after the accident. First exam according ATLS was okay. Blood pressure was 100 mmHg, heart rate was 140/min.

A whole-body-CT scan (including craniocerebral CT) was done 10 min after arrival (about 100 min after the accident).

Fractures of pelvis, femur, both arms, thoracic and lumbar vertebra were detected.

In addition, lung contusions on both sides and a dissection of the celiac trunk were diagnosed.

Damage control surgery was done, by stabilizing the fractures with external fixators. The celiac trunk was stented.

Step-by-step internal fixation of the fractures was done during the following days. Two weeks after the accident, the patient was still on the intensive care unit and mechanically ventilated, he was complaining of troublesome pain despite painkillers. A septic shock was diagnosed: low blood pressure, tachycardiac, need for high doses of catecholamines (noradrenaline 55 µg/min, vasopressin 0.04 mdc/min), no spontaneous renal function, and no bowel function. Still on mechanical ventilation and sedation with midazolam, ketamine, fentanyl.

#### 42.3.1.1 What Happened, What Was Going Wrong?

Despite serious conditions, needing high doses of catecholamines, the patient was transferred to the CT scan which revealed free intra-abdominal opaque fluid, as well as much free air, which is a clear indication for an exploratory laparotomy.

On the basis of the intraoperative findings, a team timeout was held. Despite the serious condition, it was decided to go on instead to stop vasoactive support (at this time over 70 µg noradrenaline). A resection of 1 m distal small bowel, the ascending and transverse colon was performed, and an end ileostomy established. Open abdomen treatment was started and continued for several weeks.

The 15 m fall may have caused more damage to the bowel as suspected despite no findings in the early CT scan 90 min after trauma (except the lesion on the celiac trunk). Injuries of the abdominal visceral vessels are uncommon but devastating entities resulting in extremely high rates of mortality. The most common cause of abdominal vascular injuries is penetrating trauma, accounting for 90–95% of these injuries. In contrast, blunt trauma accounts for 5–10% of all abdominal vascular lesions. Although traumatic injury to the celiac artery is among the rarest of all vascular injuries, mortality can be as high as 75% [24].

A vessel injury in association with high doses of vasoactive drugs to support circulation in the follow-up period impaired the microcirculation, which had a negative impact on blood supply to the bowel causing ischemia and perforation.

Infectious complications due to multi-resistant germs can develop everywhere, on every wound. It was extremely challenging to treat these infections, which are 3 years after the accident still not completely eradicated. Step-by-step, all wounds could be closed and internal fixation of fractures completed. Despite every effort (enteral as well as parenteral), malnutrition is still a problem, the patient is more or less plegic due to critical illness neurologic disorder, has a diverting stoma, chronic renal failure, a urinary catheter is also still needed, causing recurrent uroseptic episodes.

Three years after the accident the costs exceed 2 million EUR. The quality of life is very low. One may ask whether it was the best choice to continue treatment after team time out in the operating theater? (Figs. 42.7, 42.8, and 42.9).

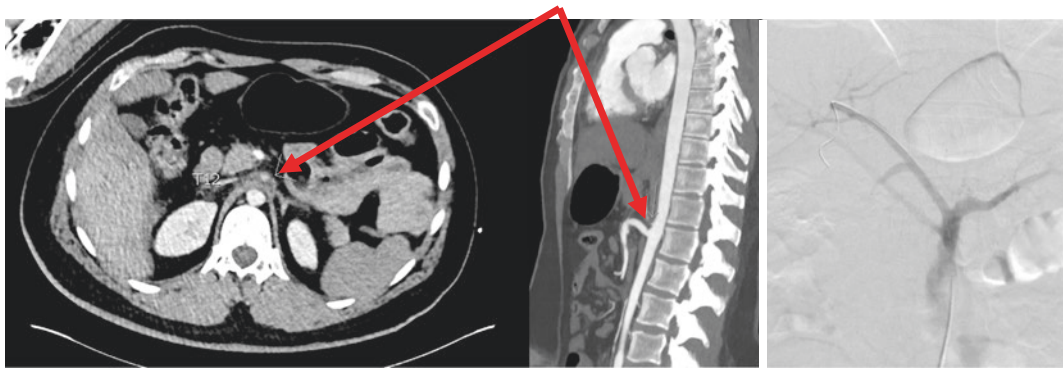

**Fig. 42.7** Contrast-CT at admission showing dissection at celiac trunc (red arrows, left and middle), and after stenting (right)

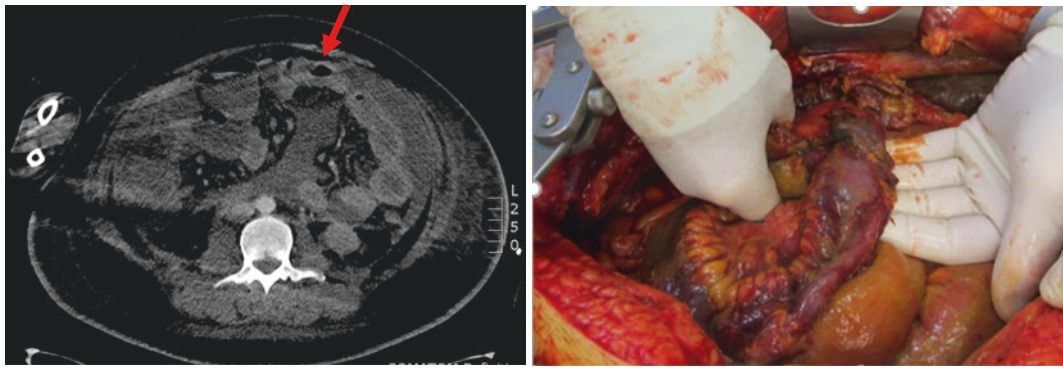

**Fig. 42.8** Findings in CT: free fluid and free air (red arrow, left), intraoperative findings: necrotic small bowel (right)

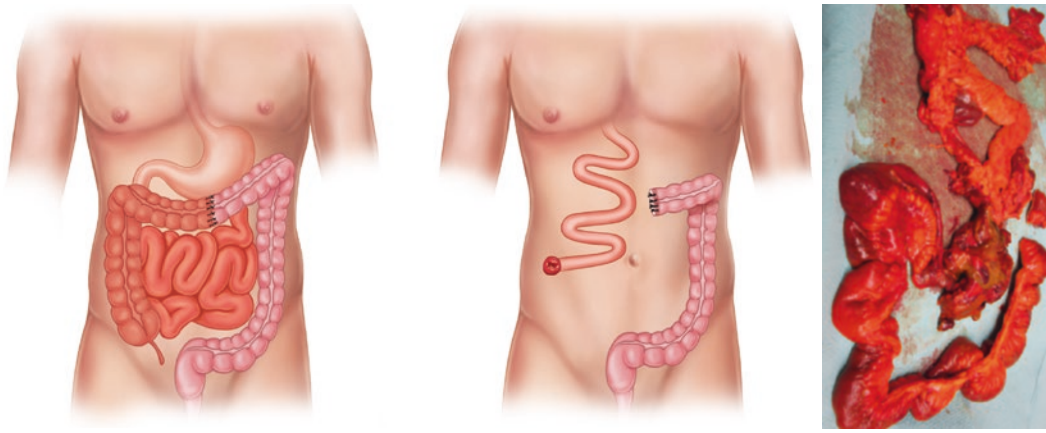

**Fig. 42.9** Operative procedure: resection of ascending colon and transverse colon, and 1 m of small bowel. Creation of an end ileostomy, left and descending colon switched off

### 42.3.2 Example 2

A 59-year-old man was shot once suffering a penetrating gunshot wound. The examination revealed shock, hypotension, narrow pulse pressure, tachypnea, oliguria, an apparent trajectory, and an evisceration. He required immediate exploration: stomach, pancreas, and liver were injured besides an open fracture of the left upper arm. A partial gastrectomy was performed. In addition, a graze wound of the pancreas adjacent to the stomach was identified. The pancreas and liver injuries were just washed out.

The patient recovered well. However, a localized collection of purulent fluid was found in the follow-up imaging, since the patient complaints about abdominal pain. The fluid collection was drained by an image guided procedure.

The interventional radiologist is an important key player in clearing complications minimally invasive (Fig. 42.10).

## 42.4 Conclusions

The most frequent visceral complications in polytraumatized patients include postoperative bleeding, especially in patients receiving direct oral anticoagulants, intestinal obstruction, abdominal compartment syndrome, anastomotic leakage, incisional hernia, especially following emergency laparotomies, wound healing disorders, and fistula following small bowel injuries.

Many visceral complications are inherent to injury patterns as well as to surgical procedures

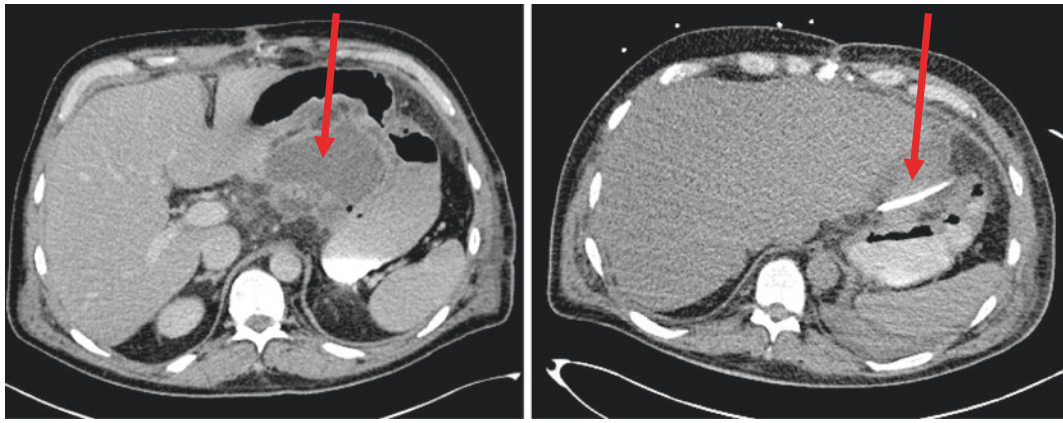

**Fig. 42.10** Gunshot injury to stomach, pancreas, and liver. Accumulation of fluid on day 10 adjacent to the stomach before (red arrow, left) and after percutaneous pigtail insertion (red arrow, right)

**Table 42.1** Common visceral complications in polytraumatized patients

| |
|---|
| • Postoperative bleeding, especially in patients receiving direct oral anticoagulants |
| • Wound healing disorders |
| • Intestinal obstruction |
| • Abdominal compartment syndrome |
| • Anastomotic leakage |
| • Intra-abdominal fluid collections (abscesses, pancreatic pseudocysts, bilioma) |
| • Incisional hernia, especially following emergency laparotomies |
| • Fistula following bowel injuries |

performed. The more severe the injuries suffered, the higher is the risk of any complications (Table 42.1).

Some authors still advocate "diagnostic peritoneal lavage" (DPL) to investigate unclear accumulations of fluid following blunt abdominal trauma. However, in the past decades, laparoscopic techniques gained enormous acceptance. Therefore, the times of less conclusive DPL are definitely over because laparoscopic techniques are superior and much more informative.

The term "adverse event" does not mean "malpractice" but an undesirable, unintended result during or following a treatment. The first priority after such an event is the patient and his family (first victim). However, the involved health care professionals can also become victims in the sense that they are traumatized after the event (second victim).

The diagnostic imaging of choice is a contrast medium enhanced CT scan. If you are in doubt, perform an exploratory laparotomy. Use damage control principles even in clearing complications [7, 22–27].

An excellent team-work to clear complications is mandatory.

**Take Home Messages**

- One out of seven patients is involved in an adverse event. The first priority after such an event is the patient. A complication does not mean malpractice.
- A comprehensive diagnostic work up helps to prevent missed diagnoses as well as realize as soon as possible deviations from the ideal postoperative course in the follow-up period.
- The diagnostic imaging of choice is a contrast medium enhanced CT scan.
- In unclear situations, keep laparoscopy in mind.
- For patients whose examinations are unreliable, laparotomy is a reasonable method of management.

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# Rehabilitation: Soft Tissue Coverage

# 43

Inga S. Besmens and Maurizio Calcagni

**Core Messages**

- The reconstruction of complex soft tissue losses associated with underlying fractures remains a clinical challenge.
- The current literature offers no evidence to support superior outcomes of either limb salvage or primary amputation for type IIIB and IIIC tibial fractures.
- The rule "life before limb" remains valid for lower extremity reconstruction.
- Aggressive debridement, a targeted antibiotic therapy and negative pressure wound therapy bridge the time until the optimal setup for definite defect coverage is available.
- Regional flaps in the lower extremity tend to be close to the defect itself. It is of vital importance to ensure they are not part of the trauma zone.
- Both muscle and fascio-cutaneous free flaps can be used, as long the wound is well debrided and all dead spaces are obliterated.

The reconstruction of complex soft tissue losses associated with underlying fractures remains a clinical challenge. Many different factors have to be considered and weighted in the treatment algorithm to functional recovery of the limb.

The treatment of complex lower extremity injuries made relevant progress over the past decades [1]. The widespread use of microsurgical techniques in general and of free tissue transfer at the end of the 1980s probably represents the biggest breakthrough to making the salvage of extremities with open fractures and soft tissue defects possible [2]. Moreover, available microsurgical techniques allow for a perfect tailoring of the reconstruction to the defect thereby achieving optimal functional and aesthetic outcomes [3]. Despite the improvements in the treatment and the experience gained, some topics are controversial and remain debated: the best timing, the role of negative pressure therapy, and the best indication for different reconstructive techniques.

## 43.1 Timing of Soft Tissue Reconstruction and Patient Selection

As in any trauma scenario the rule "life before limb" remains valid also for lower extremity reconstruction. Surgical focus can only shift to the extremity injuries once all life-threatening

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injuries have been addressed. A thorough wound debridement is then the first step and prerequisite prior to any further procedure. All non-viable tissue must be removed including soft tissues as well as devascularized bone fragments to reduce the risk of infection and consecutive nonunion [4]. Taking into consideration, patients' age and comorbidities as well as the expected remaining function of the limb trauma surgeons and reconstructive surgeons should decide on the surgical strategy (limb salvage versus revision amputation) as early as possible. Recent publications have also suggested that other non-medical patient characteristics should be considered in this decision-making process as they appear to have a significant influence on the outcome. Factors that are significantly associated with poorer outcomes include older age, female sex, lower level of education, living in a poor household, or being a current or past smoker [5].

Severely contaminated wounds in a polytraumatized patient should undergo serial debridement every 2–3 days to prepare for limb salvaging surgery. A clean wound bed is the starting point of any soft tissue and bone reconstruction [6] as studies have shown that infection is among the strongest predictors of a long-term nonunion rate [4].

Historically, based on a study by Godina et al. who reviewed 532 patients with extremity trauma undergoing free flap reconstruction, early free flap coverage within 72 h of injury was favored. However, more recent studies demonstrated that the window for early reconstruction is significantly longer than the 72 h suggested by Godina. Heller and Levin demonstrated that soft tissue reconstruction within 7 days after the injury allows for good results [7]. Francel et al. also found significantly fewer complications when patients with open tibia fractures underwent early soft tissue reconstruction, that is, according to their definition, within 2 weeks after trauma [8]. If it is clear that early reconstruction yields favorable results, the definition of "early" however is very variable. Kumar et al. report on their experience with the treatment of lower extremity injuries suffered through modern warfare. Their patients with open tibial fractures received flap reconstruction between 7 and 82 days after the initial injury due to long transport from the battlefield or because of concomitant life-threatening injuries. Most wounds had positive bacterial cultures on admission. Patients then underwent serial debridement and lavages, combined with VAC therapy which led to a non-infected wound in over 80% of the cases and a 98% flap success rate [9].

Similarly, Karanas et al. report on a series of patients with open fractures of which 85% were managed with a VAC dressing following debridement. Definite soft tissue reconstruction was delayed by an average of 22 days. There were no flap losses and only one case of late osteomyelitis, suggesting lower extremity reconstruction can be performed safely and effectively in the subacute period following adequate debridement and wound management [10].

As illustrated by these studies timing between injury and the definitive reconstruction has become less important, probably because of the significant improvements in local wound care. Aggressive debridement combined with a targeted antibiotic therapy and negative pressure wound therapy has indeed become the mainstay of treatment to bridge the time until the optimal setup both on patient and clinician site is available [11].

## 43.2 The Trauma Zone

The evaluation of the extent of the zone of injury is often difficult especially in high energy traumas where tissue viability and healing potential can be affected wide outside the macroscopic necrotic zone.

Two different debridement techniques are available: serial and radical. When the serial approach is chosen, the surgery is repeated several times over the first 2–3 days and the extent of the necrosis is revaluated. Coverage is accomplished only at the end of this process. This approach (also called "wait and see") is problematic when vital structures that might dry out (e.g., nerves, tendons, periosteum, etc.) are exposed and it is incompatible with emergency free tissue coverage.

The principle of radical debridement is to extend the incision through normal, healthy tissue to eliminate all non-viable components, all longitudinal vital structures (vessels, nerves, bones, and tendons) if not completely devitalized are preserved. This technique requires excision not only of all macroscopic non-viable tissue, but also of all tissue that is at all questionable. This approach may lead to the removal of some normal tissue but allow for a safer and immediate closure of the wound.

A second look operation (24–48 h from injury) with definitive coverage can be useful in overcoming the risk of misjudgments about tissue viability.

## 43.3 The Role of Negative Pressure Therapy

Negative pressure wound therapy (NPWT) helps to minimize desiccation, lowers bacterial count, and removes fluids from the wound [12]. As stated above it should be employed in any case where definitive wound closure within 72 h post-trauma cannot be performed. Rinker et al. showed that NPWT used as a "bridge" to free flap reconstruction in patients with open tibia fractures was associated with reduced complication rates in up to 42 days [13]. This time period should give the clinician to the chance to optimize the set up for free flap surgery.

There are other indications for NPWT. Patients with a preexisting traumatic or degenerative vascular damage are poor candidates for flap surgery. Blood supply to the wound and to the surviving healthy structures is further impaired by the injury and the healing potential is dramatically reduced. Moreover, the peripheral vascular disease can also compromise the blood supply to local and regional flaps and even restrict the availability of recipient vessels for microsurgical free flaps. Studies have shown that in these patients the treatment with NPWT could decrease the need for free flaps without any increase of complications at a cost of a much longer hospital stay [14, 15].

In these cases, a healthy granulating wound bed is achieved through cycles of negative pressure therapy. This wound can then be closed with a direct STSG or staged grafting after initial application of an artificial dermis equivalent. Molnar et al. demonstrated that application of negative pressure dressings improved their take rate and time to vascularization [16]. Lastly negative pressure dressings can also be applied over closed wounds in high risk patients such as morbidly obese patients to reduce wound complications as seromas and dehiscence. The simple placement of a negative pressure dressing over a closed wound could reduce the complication rate in a study including morbidly obese patients undergoing acetabular fracture surgery [17].

## 43.4 Definite Soft Tissue Reconstruction of the Lower Extremity

Wound closure is a controversial topic and there are some aspects that are still debated, in particular the best tissue to use (muscle vs. (fascio-)cutaneous flaps) and the type of flap (local, regional, or free microsurgical). Nevertheless, some principles are accepted and should be accounted for in the decision making. Figure 43.1 illustrates the treatment algorithm used at our Institution for soft tissue defect coverage.

There are other factors like surgeon experience or the availability of the infrastructure that can influence the decision. However it is widely accepted that a sufficient, well vascularized, and stable soft tissue coverage is an absolute prerequisite for infection prevention and for fracture union [18]. Moreover, it has been demonstrated that a multidisciplinary approach and the experience of the surgeons in the initial evaluation and planning are key factors for the successful treatment of complex injuries of the extremities [19]. In the modern treatment of complex lower extremity trauma, the recovery of both function and aesthetics is important. We present here the different surgical options with their most common indications.

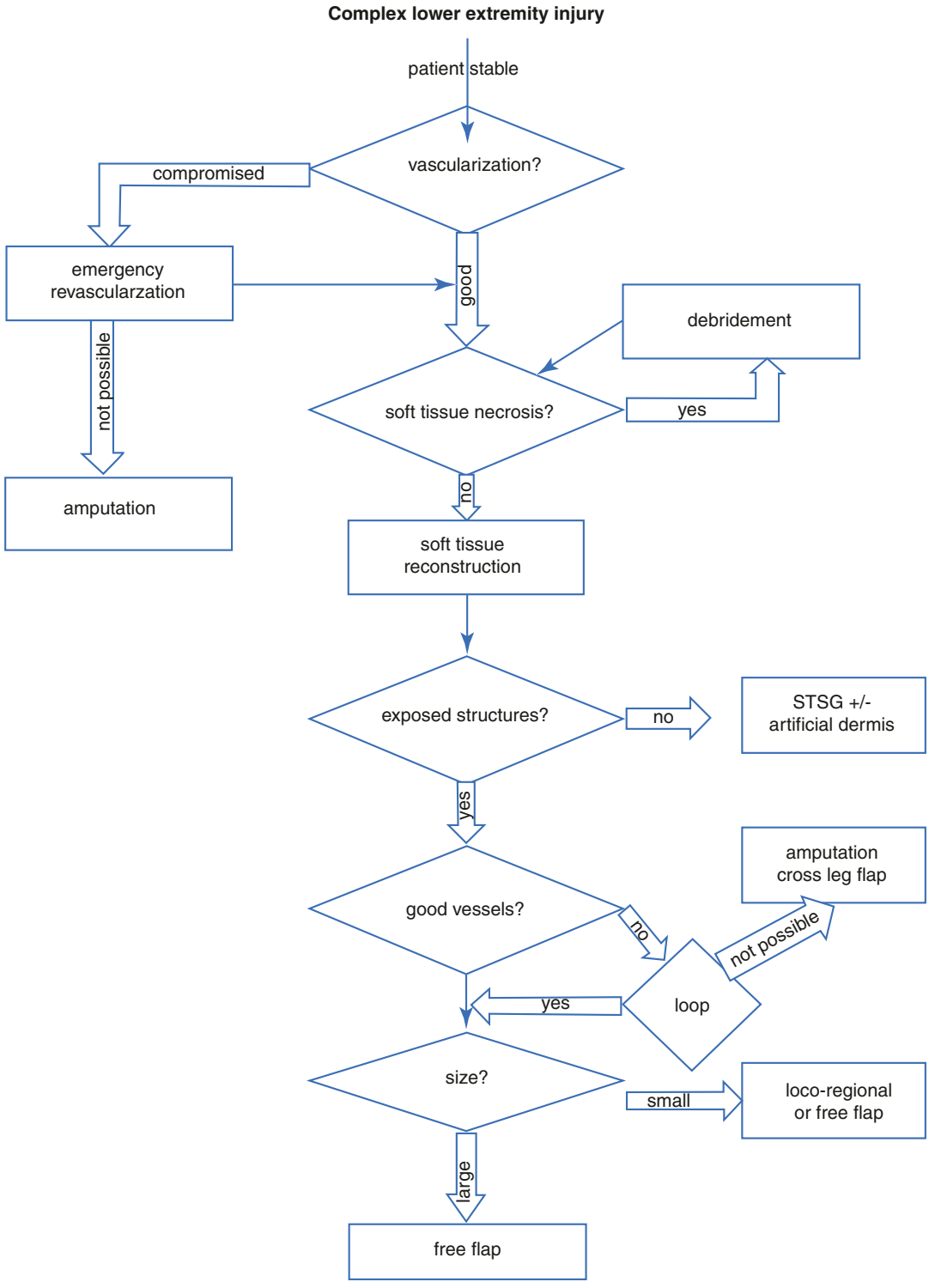



**Fig. 43.1** Treatment algorithm for soft tissue defect coverage

### 43.4.1 Skin Grafts

A split thickness skin graft (STSG) with or without a dermis equivalent remains one of the simplest options for coverage of well vascularized wounds. STSG are typically harvested from the upper thigh (although they can be harvested from most other regions of the body) and can be meshed and expanded to cover a much larger surface area. In uneven wounds or where movement and local shearing forces could affect the grafts take, a negative pressure dressing should be applied over the graft.

As already mentioned before, a healthy and clean wound bed is an absolute prerequisite before graft transplantation [20]. Moreover, grafts cannot take on poorly vascularized wound beds like bone without periosteum or tendons without peritendineum. If these areas need to be skin grafted, the prior use of a dermis equivalent can help to improve the chance of success. However, STSGs with or without dermis equivalents should not be used routinely since they rely on the local blood support and do not enhance it, interfering with the bone healing. Their main indications are in superficial wounds with healthy and well vascularized fascia or in patients where poor general conditions or the absence of an adequate blood supply that cannot be improved prevent the use of a free tissue transfer or regional flap. Such a case is depicted in Fig. 43.2.

### 43.4.2 Local or Distant (Regional) Flaps

In many cases, soft tissues contiguous to the defect can be used as local flap. The classification of local flaps is extensive in regard to the flap composition and pattern of vascularization, but this is beyond the scope of this chapter and we refer to the existing literature [21].

In the lower limb, random pattern flap cannot not be used regularly because of the limited laxity of the skin. Pedicelled fascio-cutaneous flaps can be used in the proximal third of the leg but are of limited use because the fascia is very stiff and difficult to rotate. Muscle and musculocutaneous flaps are also available. An adjacent muscle can be mobilized to cover a defect thereby making it suitable for skin grafting or it can be completely prepared maintaining only the vascular pedicle and rotated into the defect. Generally speaking, these regional flaps are mostly indicated for the coverage of small to medium defects. As these flaps are rather close to the defect area, it is of vital importance to ensure they are not part of the trauma zone. If there is

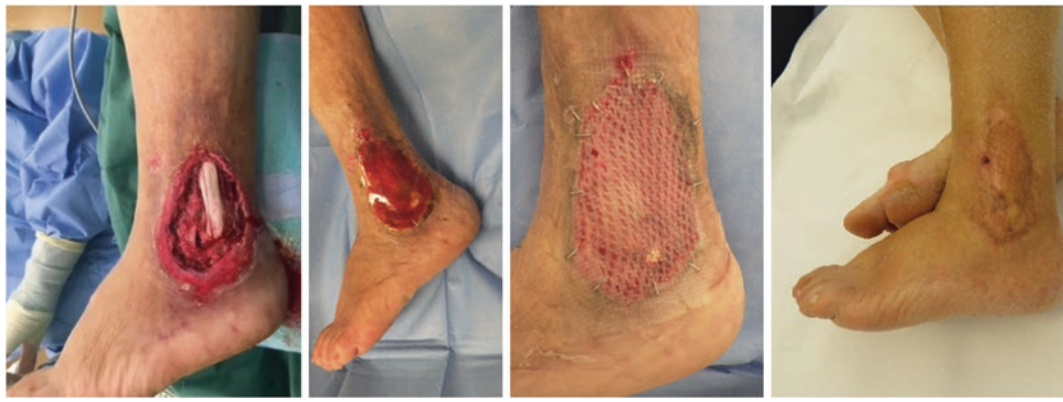


**Fig. 43.2** This 70-year-old female had originally suffered a minor skin abrasion over her lateral malleolus. Improper local treatment combined with marginal peripheral vascularization had led to a local skin necrosis. After debridement, the peroneal tendons were exposed. The defect was covered with Integra™. After sufficient revascularization time (in this case 4 weeks), the Integra was delaminated and covered with a split thickness skin graft from the upper thigh. Healing was uneventful

any doubt about the quality of the blood supply of the surrounding soft tissue, a free tissue transfer should be preferred.

Table 43.1 gives an overview of potential regional flaps in the leg.

The choice between a loco-regional flap and a free one is dictated by many different factors. On the one side, the distal third of the leg and the foot have a terminal type of vascularization with less compensatory options and no redundant soft tissue which reduces the availability of loco-regional flaps. On the other side, the size and depth of the defect are often the main reason for a free microsurgical flap. Moreover, local flaps are completely dependent on the local blood supply and in some cases the harvest of a loco-regional flap might further impair circulation and even result in a steal phenomenon.

In these instances, or when the attempt to close a defect with a regional flap has failed, a free tissue transfer is indicated.

Figure 43.3 demonstrates the use of a gastrocnemius flap.

**Table 43.1** Flap options for different defect locations in the lower leg

| Location | Type of flap | Flap options |
|---|---|---|
| Knee/ upper third | Fascio-cutaneous | Distally based anterolateral thigh (ALT) flap [46] |
| | | Medial sural artery perforator flap [47] |
| | Muscle | Medial (larger) or lateral head of gastrocnemius [48] |
| | | Proximally based soleus [49] |
| | | Bipedicled tibialis anterior [50] |
| Middle third | Muscle | Proximally based soleus [49] |
| | | Medial (larger) or lateral head of gastrocnemius [48] |
| | | Flexor digitorum longus (FDL) [51] |
| | | Extensor digitorum longus (EDL) [52] |
| | | Extensor hallucis longus (EHL) [53] |
| | | Flexor hallucis (FHL) [54] |
| | | Tibialis anterior |
| Lower third | Fascio-cutaneous | Distally based sural artery flap [55] |
| | | Distally based lesser saphenous flap [56] |
| | | Propeller flap [57] |
| | | Cross-leg flap |
| | Muscle | For medial defects: FHL, FDL, tibialis anterior, extensor digitorum brevis |
| | | For lateral defects: peroneus brevis or tertius |
| Foot | Fascio-cutaneous | Distally based sural artery flap |
| | | Medial plantar artery flap |
| | | Dorsalis pedis flap |
| | Muscle | Flexor digitorum brevis |

### 43.4.3 Free Tissue Transfer

The evolvement of microsurgical techniques in the last decades makes salvaging of traumatized limbs, that would have been amputated in the past, possible. The free flap is an effective method of lower extremity reconstruction [22].

When considering defect coverage with a free microvascular tissue transfer, the location of the injury and the general vascular status are among the most important factors [7].

The choice of recipient vessel and anastomosis technique are still a matter of debate, but some general rules are widely accepted [23]. The first one is to always choose a healthy vessel with a good flow. Therefore the vascular anastomosis should always be placed well outside of the zone of injury. The main reason for this is the inflammatory response that usually extends beyond the obvious wound and leads to changes to the blood vessels that lead to an increased fragility and increased perivascular scar tissue and eventually to a higher failure rate [24].

The arterial anastomosis is usually done in an end-to-side fashion to reduce the risk of further devascularizing the limb. The use of a previously ligated vessel is not recommended for the risk of a reduced flow and scarring of the intima. End-to-end anastomoses should be limited to the situations where the vascularization of the foot is redundant (e.g., in a 3-vessel run-off). Venous anastomoses are usually performed in an end-to-end fashion. The use of venous couplers can speed up the procedure and guarantees high patency rates also in cases of major caliber mismatch between the vessels [25]. At our institution the deep venous system is the first choice for a

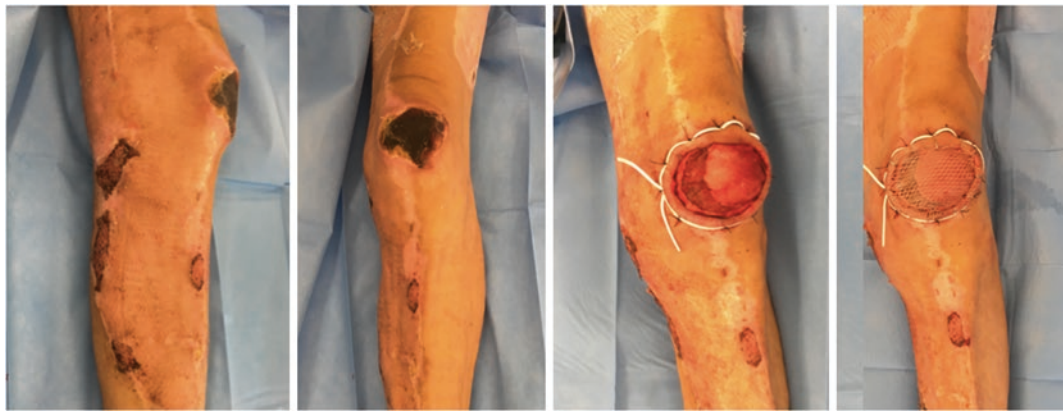


**Fig. 43.3** This 66-year-old male sustained (among other injuries) a full thickness burn ventral to the patella from a gasoline deflagration. After debridement of the burn area, the patella was exposed and defect coverage was achieved with the medial head of the gastrocnemius and a split thickness skin graft. Healing was uneventful

recipient vessel because of the proximity to the artery and the reduced risk of postoperative compression through swelling. However, there is evidence that the success rate of a venous anastomosis is not affected by the location of the recipient vein [26]. An accurate microsurgical technique is of paramount importance and is the single most relevant factor for a high patency rate and eventually successful free tissue transfer. Careful dissection, atraumatic handling of the vessels, precise placing of stitches, and avoidance of tension at the anastomosis site are some of the most important factors [27].

Free tissue transfers are long and complex operations and careful planning and an adequate team are pivotal. Well trained and experienced surgeons, a consequent two-team approach, as well as minimizing repositioning of the patient are some of the key points to reduce the anesthesia time that eventually decrease the risk of postoperative complications as wound infection, dehiscence, hematoma, and seroma [28].

### 43.4.4 Free Flap Choices

The choice of flap for the individual defect coverage depends on the size of the defect, the pedicle length required for microvascular anastomosis, the amount and the type of tissue needed for the reconstruction. When patients with lower extremity trauma require both osseous and soft tissue reconstruction, the team treating the patient should join the expertise of both trauma and plastic surgery. This combined approach is often referred to as the orthoplastic approach [29].

Vascularized bone grafting in the lower extremity can be done by means of a free (or sometimes pedicled) fibula transfer with or without a skin island, a free iliac osteocutaneous flap or in select indications, normally smaller defects, a free medial femur condyle with or without a skin island. As a general rule for any gap greater than 6–7 cm, a vascularized bone transfer should be considered. The contralateral fibula is the donor site of choice [30].

If no bone grafting is required muscle flaps like the free latissimus dorsi flap or fascio-cutaneous flaps like the free anterolateral thigh (ALT) flap can be used for reconstruction.

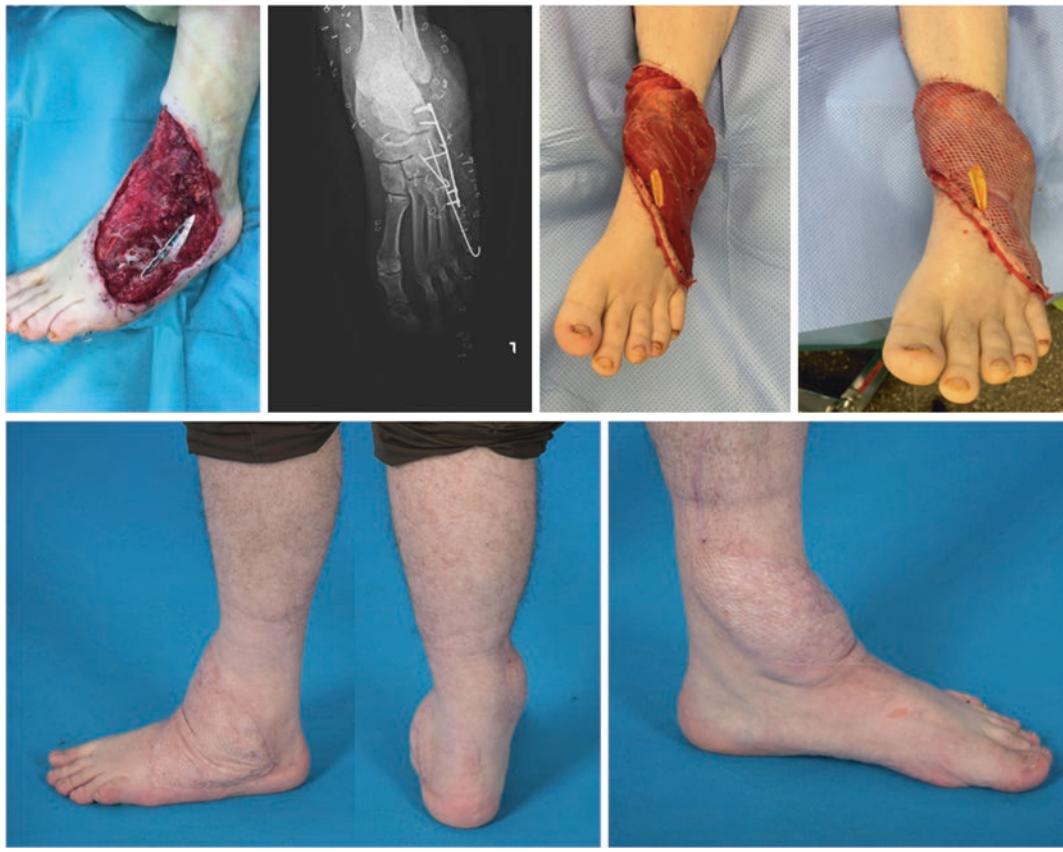
The discussion about the relative advantages and disadvantages of each flap type is still open and often is a matter of personal preference since superiority of one flap type for all indications could not be demonstrated. In our department free muscle flaps are the first choice for reconstruction of complex lower extremity injuries. These flaps have several advantages in our opinion that make them preferable. They can adapt nicely to any defect form and depth providing a better local blood supply which is considered an advantage especially in irregular and contaminated wounds [31].

Moreover, the denervated muscle shrinks over time ultimately providing a better contour [32] which is of course of significant functional relevance especially in the foot and ankle region. Additionally the plasticity of muscle can help to obliterate dead space, thereby reducing potential complications associated with hematoma or seroma formation [33]. However, recent studies challenge these assumptions [34]. Hong et al. reported on the successful use of anterolateral thigh perforator flaps to combat infection and bring stability to wounds with chronic osteomyelitis in the lower extremity [35].

In conclusion it is evident that the type of flap used does not really make a difference, as long the wound is well debrided and all dead spaces are obliterated. Additionally, there are some patient-related factors which will influence the choice. In an obese patient, for example, a fascio-cutaneous flap will be very thick and will result in a less aesthetic outcome, on the contrary, the harvest of the latissimus dorsi might be less favorable, on the long term, for the shoulder function in patients that might need crutches for their whole life. It is thus of utmost importance that surgeons weigh risks and benefits of options for each patient individually.

Figures 43.4 and 43.5 illustrate the use of a free muscle flap, in this case a latissimus dorsi flap, and the Fig. 43.6 the use of a fascio-cutaneous flap (an ALT flap) in lower extremity reconstruction.

A list of commonly used free flaps in lower extremity reconstruction is provided in Table 43.2.



**Figs. 43.4 and 43.5** This 55-year-old male patient had a motor cycle accident and sustained (among other injuries) complex third degree open fractures of the left midfoot with comminuted fractures of the fifth metatarsal base, the MT V head, and the cuboid bone. After the patient had been stabilized, the soft tissue defect over the midfoot fractures was covered with a vacuum dressing and once a clean wound bed was achieved, the fractures were addressed by the department of traumatology. The soft tissue defect was then covered with a latissimus dorsi flap end-to-ide to the posterior tibial artery as a preoperative angiography that demonstrated a chronic occlusion of the anterior tibial artery. One year postoperative, the flap has healed nicely and atrophied significantly

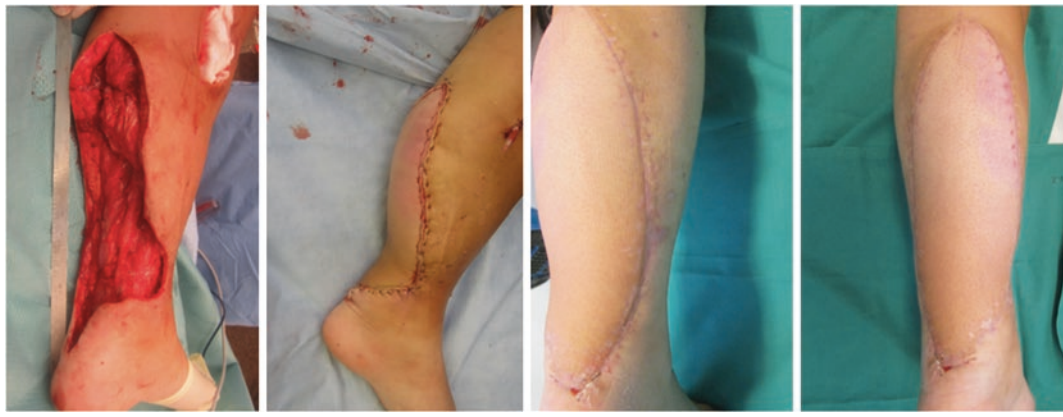


**Fig. 43.6** Initially this 40-year-old female had suffered a soft tissue laceration from a glass bottle on her dorsal lower thigh. The large defect was reconstructed with a free ALT flap to the posterior tibial artery. The Achilles tendon was reconstructed with a fascia lata slip that was included in the ALT flap

**Table 43.2** Common free flap options in lower extremity reconstruction

| Free flap | Features |
|---|---|
| Latissimus dorsi (LD) | Workhorse for lower extremity reconstruction |
| | Mathes and Nahai Type V muscle |
| | Large flap with large caliber pedicle |
| Serratus anterior | Mathes and Nahai Type III muscle |
| | Ideal where thin coverage is needed |
| | Can be raised with LD and bone in chimeric fashion |
| (Para)scapular | Can be designed cutaneous, fascio-cutaneous, fascial, osteo-cutaneous, or as a chimeric flap |
| | Relies on branches of the circumflex scapular artery that passes through triangular space |
| Gracilis | Mathes and Nahai Type II muscle |
| | Minimal donor site morbidity |
| | Relatively small pedicle diameter |
| Radial forearm | Very long vascular pedicle, thin and pliable |
| | Type B fascio-cutaneous flap with multiple septo-cutaneous perforators |
| | Ulnar circulation to the hand must be evaluated before the flap is harvested |
| | Radial bone can be taken with the flap |
| ALT | Perforators can be identified with a Doppler just lateral to the intermuscular septum |
| | If the flap is bulky, secondary revision can be performed 3 months postop |

## 43.5 Postoperative Regime

When it comes to postoperative regimes after free microvascular tissue transfers, true evidences are scarce but microsurgeons focus on similar aspects for the treatment after surgery.

### 43.5.1 Anticoagulation

Traditionally intravenous heparin is widely used to avoid thrombosis at the anastomotic site, but there are no evidences supporting this [36].

Most institutions follow standardized deep venous thrombosis prophylaxis and in addition some microsurgeons prescribe acetyl-salicylate acid. However, the type and dosage of drugs used does not seem to have a statistically significant effect on the incidence of free flap complications, including bleeding, thromboembolism, and flap loss.

### 43.5.2 Temperature

Postoperatively microsurgeons tend to make sure that the transferred flap is not exposed to lower temperatures for fear of vasospasms. Experimental

studies suggest that the blood flow is improved at higher temperatures [37].

### 43.5.3 Nutritional Factors

Many surgeons restrict caffeine consumption in free flap patients for fear of its vasoconstrictive action. There is however no clear evidence to support this. A study by Lunt et al. showed that caffeine intake reduced the middle cerebral artery diameter thus functioning as a vasoconstrictor [38].

### 43.5.4 Monitoring

Even though there is no evidence on superiority of different monitoring techniques, studies show a general agreement regarding the optimal way to monitor free flaps in the early postoperative phase. Frequent clinical evaluation seems to be the standard in most centers, with echo Doppler as an additional tool, for an average of 4.8 days. Many surgeons check their flaps personally in addition to the residents and nursing staff [39].

### 43.5.5 Immobilization and Elevation

Immobilization of the affected extremity is typically dictated by the underlying bone injury. If split thickness skin grafts have been applied over muscle flaps, immobilization is also used to prevent shearing forces on the graft. Postoperative swelling and edema that is to be expected pose a special challenge in microsurgery as these factors could lead to flap failure by means of progressive venous congestion or even compressions on the anastomosis. This is why we favor immobilization and light elevation of the limb in the early postoperative phase. Afterwards progressive dangling of the extremity needs to be executed [40] to acclimatize the flap to the effects of gravity and dependency on the microvascular tissue transfer to the lower limb [41].

## 43.6 Outcome

Lower extremity trauma with open fractures is rather common.

Surgeons and patients generally favor reconstruction over amputation. Soft tissue injury severity has the greatest impact on decision making regarding limb salvage versus amputation [5].

Lower limb reconstruction is more acceptable psychologically to patients with severe lower limb trauma compared with amputation, even though the physical outcome for both management pathways is more or less the same [42]. While length of hospital stay is similar for limb salvage and primary amputation, length of rehabilitation is longer for limb salvage patients. Salvage patients require additional surgery more often and are significantly more likely to undergo re-hospitalization. Long-term functional outcomes (up to 7 years post-injury) are equivalent between limb salvage and primary amputation, both forms of management are associated with high rates of self-reported disability (40–50%), and functional status continues to worsen over time. Report of pain following limb salvage or primary amputation is similar [43].

The current literature offers no evidence to support superior outcomes of either limb salvage or primary amputation for type IIIB and IIIC tibial fractures. When outcomes are similar between two treatment strategies, economic analysis that incorporates cost and preference (utility) may define an optimal treatment strategy to guide physicians and patients [44].

Unless the injury is so severe that salvage is not a possibility, based on economic models, surgeons should consider limb salvage, which will yield lower costs and higher utility when compared with amputation [45].

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# 44 Principles of Surgical Patient Safety

Philip F. Stahel and Vincent P. Stahel

**Learning Objectives**

- Identify the current challenges to surgical patient safety and the lessons learned from other high reliability industries.
- Explain the impact of effective communication on improving patient outcomes.
- Recognize the role of patient safety checklists in preventing adverse surgical outcomes.
- Establish the need for surgeon leadership and individual accountability for building a sustained culture of patient safety.

## 44.1 Introduction

No surgeon in the world would get up in the morning with the intent of creating a surgical complication. Beyond a doubt, surgeons and patients are intrinsically aligned in their intent of avoiding complications and adverse events. In spite of this natural bond, surgeons have historically fallen short of rising up as unwavering stewards for patient safety. Unquestionably, surgeons do *not* appreciate when their hospital administrators dictate how patients should be treated, and they are intrinsically averse to filling out forms and adhering to regulatory compliance-mandated paperwork and protocols. Yet, the unintentional void created by the absence of surgeon leadership in the field of patient safety has been filled by other stakeholders, including patient advocacy groups, malpractice lawyers, and legislators [1, 2]. The antiquated paradigm of patient safety standards being driven by a fear of medicolegal repercussion has escalated to an unjustified and fiscally irresponsible practice of "defensive medicine." The unintentional fallout from practicing defensive medicine is a drastic exacerbation of health care costs, with little or no benefit to the patient, in conjunction with an increased risk for collateral damage by the overuse of diagnostic testing [3]. This notion reflects directly on the paradigm shift in the initial assessment of the polytrauma patient, where the historic standard of care per the ATLS® guidelines consisted of a physical head-to-toe exam with limited use of conventional imaging [4]. In contrast, the diagnostic trauma work-up in the twenty-first century is almost invariably based on multi-slice CT scanning, which puts patients at an incremental long-term risk of radiation-induced cancer, and deprives the next generation

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of surgeons of the skill set of performing a thorough clinical exam [5].

Further challenges for patient safety include the wide variation of surgical indications worldwide, the inequity of access to surgery for disparities, and a questionable long-term sustainability of surgical quality at the current rate of progress associated with increasing costs for modern and innovative procedures [6]. Considering that around 200 million surgical procedures are performed worldwide every year, even a conservative low estimate of 1–2% average complication rates implies at least 2–4 million patients annually suffer harm from their surgical care. Strikingly, in the twenty-first century, we still have to come to terms with the absurd reality that it is significantly safer to board a commercial airplane, a spacecraft, or a nuclear submarine, than to be admitted to a U.S. hospital for surgical care [7]. What can surgeons do to protect their patients from the hidden dangers of an imperfect health care system? The most intuitive solution is to avoid complications from surgical treatment that is either not indicated or not beneficial for patients. In other words, avoiding unnecessary surgery could be considered the most pragmatic approach towards reducing preventable surgical complication rates [8]. Ironically, surgeons appear to have a lower threshold for recommending surgery to their patients, with a higher level of confidence, than they would recommend for themselves under the exact same case scenario [9]. The evident variation in non-surgical treatment recommendations indicates a substantial influence of surgeon bias in surgical decision-making [10]. These provocative insights unveil that surgeons are potentially biased towards recommending unnecessary surgery. Unequivocally, any postoperative complication that originates from a procedure that was not stringently indicated in the first place is by definition 100% preventable.

Dr. Arnold S. Relman (June 17, 1923 to June 17, 2014), the late editor of the *New England Journal of Medicine*, stated the following insightful quote: "*Of all the forces coming together to harm or even kill the patient, their physician should not be one of them!*" This notion provides an irrefutable imperative for surgeons to embrace the concept of "shared decision-making" as a core pillar in the partnership with their patients and thereby improving patient safety and reducing the rate of preventable complications resulting from variability in non-surgical care [11].

## 44.2 From "Blame and Shame" to High Reliability

The historic approach to medical errors and surgical complications has consisted of blaming the surgeon who delivers direct patient care under the "blame and shame" paradigm. This antiquated culture of patient safety is based on the erroneous assumption that surgical errors may be prevented in the future by admonishing, blaming, suing, or firing surgeons. In contrast to "blame and shame," accountability entails that surgeons are in charge of their patient's safety *independent of the outcome* [6]. The modern paradigm of patient safety revolves around "systems thinking" and "high reliability" in order to account for the notion that humans are prone to committing errors [12]. The hallmark of a "high reliability organization" (HRO) is not that it is error-free, but that errors do not disable it [7]. High reliability science represents the study of organizations in high-risk industries, such as commercial aviation and nuclear power technology, that maintain safety through redundant back-up options in case of failure under hazardous conditions [7]. Unfortunately, errors in the surgical care of our patients frequently lead to unintentional harm on first occurrence in absence of a "fail-safe" back-up option, and our health care industry still shows significant gaps in achieving high reliability in a sustainable fashion. This notion is exemplified by current statistics which reveal that medical errors represent the third leading cause of death in the United States, after cardiovascular disease and cancer [13]. When comparing the evidence-based estimate of more than 400,000 preventable annual deaths occurring in US hospitals every year to professional aviation, this statistic is analogous to three Jumbo jets crashing each day, all year long, in perpetuity [14]. In this hypothetical

scenario, the Federal Aviation Administration (FAA) would likely ground all commercial airplanes until the underlying error is recognized and irrevocably fixed. In contrast, the medical profession continues to accept errors that lead to preventable patient harm as an unfortunate and inevitable "side effect" of modern health care [7].

Intriguingly, as it relates to the field of surgery, adverse events and complications are more frequently related to errors occurring *before* or *after* the procedure than by technical mistakes by a surgical blade "gone wrong." These include (1) a breakdown in communication; (2) a delay in diagnosis or failure to diagnose; or (3) a delay in treatment or failure to treat [15]. Surgeons are presented with challenges that reach far beyond pure technical aspects—the decision of initiating appropriate and timely surgical care, weighed against the risk of providing delayed or negligent care by choosing observation and/or non-operative treatment ("*to cut or not to cut*"). Many of the current limitations to the creation of a globally recognized and consistently practiced culture of patient safety stem from the lack of surgeon-driven leadership [3, 16]. Transparent leadership and credible role modelling are the prerequisites to ensure the unreserved buy-in by all members of the health care team for adoption of safety practices, including strict adherence to patient safety checklists and core measures [17, 18]. From a pragmatic standpoint, surgeons can drive their own "high reliability practice" by adopting two fundamental standards that have proven to decrease variability in surgical care and improving patient safety: Effective communication and surgical safety checklists [15].

## 44.3 Effective Communication

Patient harm resulting from surgical complications is frequently derived from a communication breakdown within the care team rather than from a technical complication in the operating room [19]. Published studies on closed claims by the American College of Surgeons revealed about 25% of all claims related to patients who sustained surgical harm were attributed to a breakdown in communication [20]. Of these, 85% of adverse events related to communication breakdown occurred by verbal communication. While most surgeons perceive themselves as "good communicators," in reality, less than 20% of all physicians have been formally trained on how to communicate with patients [21]. Ironically, the main predictor of patients' perceptions of whether quality care was provided has no correlation with objective metrics of clinical care, but rather with the patients' subjective perceptions of the *quality of communication* with their surgeon. Evidence-based approaches for improved communication are widely published and available as resources for physicians [19]. Multiple studies have shown that effective communication with patients is associated with a decreased incidence of claims and lawsuits, better clinical outcomes, improved patient compliance with recommended treatment regimens, and decreased unplanned readmission rates [19].

### 44.3.1 Readbacks

The first fatal airplane crash in history occurred on September 17, 1908, when the aviation pioneer Orville Wright's co-pilot died in a failed flight attempt. Since that time, aviation safety standards have significantly improved. The current risk for an American dying in an airplane crash is about 1:500,000, compared to the 1:20,000 chance of dying in a car accident [22]. The standardized use of "readbacks" represents a fundamental pillar of commercial aviation safety [23]. In essence, a formal readback by the recipient of verbally communicated information ensures a standardized two-way communication [24]. In the health care setting, readbacks represent a proven standard of structured language used to provide clarity and accuracy of verbal orders and critical test results, as mandated in the National Patient Safety Goals (NPSG's) by the Joint Commission [6]. While the current debate in the field is related to optimizing the modality of readbacks, this crucial form of communication is still virtually non-existent among surgeons. The renowned surgeon Dr. Eddie Hoover

characterized the problem with the following quote: "*Getting surgeons to readback orders and instructions will age you 10 years, yet the Navies of the world have demonstrated for eons that it improves efficiency, promotes safety, and saves lives*" [25]. This notion provides the basis for a call for formal verbal "readback orders" among surgeons and other healthcare professionals in the perioperative setting with the goal of avoiding or reducing the high incidence of adverse surgical events related to a breakdown in communication.

### 44.3.2 SBAR

Verbal communication must be timely, precise, directed, and understood. The "SBAR" framework (Table 44.1) represents another best practice standard of effective communication derived from a high reliability industry, such as naval nuclear submarine technology [7, 26]. The SBAR mnemonic is simple, streamlined, and highly effective in avoiding miscommunication in the perioperative setting [21].

### 44.3.3 AIDET

The AIDET mnemonic represents an established and widely disseminated proven framework for successful communication between surgeons, their patients, and patients' families (Table 44.2). Similar to other checklists, the AIDET mnemonic ensures not to skip any piece of information that may be important from the patients' perspective [21].

In summary, effective communication in health care can be dramatically improved by the use of standardized communication frameworks [19]. Furthermore, the quality of communication has been shown to correlate with the patients' perception of the quality of care provided. In the current age of patient-centered care, surgeons have an obligation to move on from being technically excellent, to mastering non-technical skills. Effective communication will improve the surgeon–patient relationship and overall patient outcomes.

**Table 44.1** The "SBAR" mnemonic for improved effective communication

| |
|---|
| **S—Situation** |
| "*The situation is…*" (What is going on with the patient?) |
| **B—Background** |
| "*The background to the situation is…*" (What is the clinical background or context?) |
| **A—Assessment** |
| "*My assessment of the situation is…*" (How do I interpret the problem?) |
| **R—Recommendation** |
| "*My recommendation is…*" (What do I recommend to resolve the problem?) |

## 44.4 Surgical Safety Checklists

Most surgeons are intrinsically opposed to the use of checklists, as those appear to be imposed and mandated by third party entities and appear to question the surgeons' clinical and technical expertise for safely managing the surgical care of their patients [27]. Clearly, checklists do not make a surgeon any "smarter," more knowledgeable, better trained, or more technically skilled [28]. However, checklists provide a safeguard and protection from the human error of forgetting or skipping important steps in a process, particularly when considering the high-stress and high-acuity environment, such as the trauma bay or the operating room [28]. Atul Gawande, the world-renowned patient safety "guru" and one of the innovative founders of the "Safe Surgery Saves Lives" campaign and WHO surgical safety checklist [29, 30], provided a compelling argument for the use of checklists in his bestselling book "The Checklist Manifesto" [31].

> *In a complex environment, experts are up against two main difficulties. The first is the fallibility of human memory and attention, especially when it comes to mundane, routine matters that are easily overlooked under the strain of more pressing events. A further difficulty, just as insidious, is that people can lull themselves into skipping steps even when they remember them. Checklists seem to provide protection against such failures.*

**Table 44.2** The "AIDET" mnemonic: A standardized framework for effective communication with patients and patient families

| |
|---|
| **A—"Acknowledge"** |
| Greet people with a proactive and friendly approach. Look them in the eyes and smile. Use their names if you know them. The first delivered impression is the most important and lasting impression. Establish a preferred rapport with the patient and patient family. |
| *Example:* "*Good morning Mr. Smith. Welcome to the Medical Center XYZ. We have been expecting you and we are glad that you are here. Would you please take a moment to confirm that we have your most current information?*" |
| **I—"Introduce"** |
| Introduce yourself politely. Tell the patient who you are and how you are going to help. Explain your role, function, experience, and skill set. Escort people where they want to go, instead of pointing or giving directions. |
| *Example*: "*Mr. Smith, my name is Anne. I will be performing your sonography today. I am a certified ultrasonographer and I perform about 20 such procedures each day. The doctors say that my skills are among the best. Do you have any questions for me?*" |
| **D—"Duration"** |
| Outline the expected duration and wait time. Keep in touch regularly to ease the perception of prolonged wait times. Let people know if there is a delay and provide realistic expectations of expected times. Fix unnecessary wait times where necessary. |
| *Example*: "*Dr. Stahel had to take care of an emergency. He was concerned about you waiting to be seen, and he wanted to let you know that it may be about 30 min before he can see you. Are you able to wait, or would you prefer to run some errands and come back later?*" |
| **E—"Explain"** |
| Tell the patient what to expect. Communicate all steps in the process and address any questions that the patient may have. Make time to help by recognizing and diminishing the patient's anxieties and uncertainties. |
| *Example*: "*The test will take about 30 min. The first step is for you to drink this solution, and then we'll have to wait 20 min before drawing a blood sample. Would you like to read while you wait?*" |
| **T—"Thank"** |
| End the conversation with the patient by a standardized "*Thank you!*" Foster an attitude of gratitude. Use reward and recognition tools, as appropriate. |
| *Examples:* "*Thank you for choosing our hospital.*"—"*Thank you for your trust.*"—"*Thank you for taking the time for this visit—it has been a privilege to care for you.*" |
| Finalize the communication and interaction with the patient by the standard question: "*Is there anything else I can do for you today?*" |

The "Universal Protocol" by the Joint Commission represents the paradigm of a standardized, simple, and pragmatic surgical safety checklist. This is designed to avoid the "worst case scenario" complications in surgery, including operating on the wrong site or on the wrong patient [32–34]. The Universal Protocol was introduced in 2004 to United States hospitals participating in the Medicare/Medicaid program (CMS) as a mandatory quality assurance checklist [35], consisting of the following three components:

1. A pre-procedure verification process.
2. Preoperative surgical site marking.
3. A surgical "time-out" immediately prior to starting the procedure.

### 44.4.1 Pre-procedure Verification

About one-third of all wrong-site and wrong-patient procedures have their genesis before patient admission to the hospital [32]. Potential scenarios include inaccurate clinic note dictations related to a wrong side, the mislabelling of radiographs or other diagnostic tests, or a mix-up of patients with similar or identical names. The rationale for conducting a pre-procedure verification process is to confirm (1) patient identity, (2)

the nature of the planned procedure, and (3) the correct surgical site [35]. Each patient is unequivocally identified by an identification bracelet which includes the patient's name, birth date, and a medical record number. The pre-verification process further ensures presence and adequacy of all relevant documents, including written informed consent and a current history and physical exam. The surgeon's surgical plan and the team's understanding of the planned procedure must be confirmed to be consistent with the patient's expectations. A checklist is used to review and verify that all documents and pertinent information are available, accurate, and completed, prior to moving the patient to the operating room [35].

### 44.4.2 Surgical Site Marking

Surgical site marking is performed as part of the pre-procedure verification process in the preoperative holding area [36]. The following best practice standards should be taken into consideration for a safe and accurate surgical site marking [35]:

- Site marking must be performed by a licensed practitioner who is a member of the surgical team and will be present during the surgical "time-out" and during the procedure. Under ideal circumstances, site marking should be performed by the surgeon.
- The surgical site is marked in the preoperative holding area, before moving the patient to the operating room or to an interventional procedure room.
- The patient should be actively involved in confirming the correct surgical site marking, whenever possible.
- The site marking must be unambiguous by the use of unequivocally defined terminology, such as "YES," "GO," "CORRECT," or "CORRECT SITE." Surgical site marking with an "X" should be avoided as this may be misunderstood as "not this side." The specific modality of marking must be defined in the respective facility's policies and procedures.
- Additional marking of the contralateral side (e.g., "no" or "not this side") is contraindicated, as this creates confusion and increases the risk of wrong-site surgery.
- The surgeon's responsibility of correct site marking should be confirmed by adding the surgeon's initials. The only exception is a surgeon with the initials "N.O." since this may be confused with a "no" and imply that the marked site should not be operated on.
- Surgical site marking must be applied with indelible ink on skin, using permanent markers. The markers must be resistant to the surgical preparation process and remain visible at the time of skin incision. It should be noted that sterile markers are not required, since the published literature demonstrates that the use of non-sterile markers does *not* increase the risk of postoperative infections (Fig. 44.1).
- The marking should be applied at or near the incision site. The side, level, and location of the procedure must be unequivocally defined by the marking, whenever possible (left vs. right; medial vs. lateral; flexor vs. extensor surface, etc.)
- Knowledge of contraindications for surgical site marking, including premature infants (risk of permanent tattoo), mucosal surfaces, teeth, and patients refusing a surgical site marking for personal reasons.
- Increased awareness in all cases where precise site marking is not possible (see below).
- Defined alternative processes should be implemented for any circumstance where surgical site marking is not feasible, to include pre- and intraoperative radiological diagnostics (e.g., spinal level marking with a needle, intraoperative arteriogram or cholangiogram, etc.)

There are specific instances in which surgical site marking may not be feasible, for technical or anatomic reasons. For example, site marking is impracticable on mucosal surfaces and on the teeth. Site marking is furthermore contraindicated in premature infants due to the risk of inducing a permanent tattoo on the skin. In addition, some surgical sites are inaccessible to accurate external marking, including internal organs (general surgery), brain and spine (neurosurgery), vessels (interventional vascular procedures), and the pelvis (orthopedic sur-

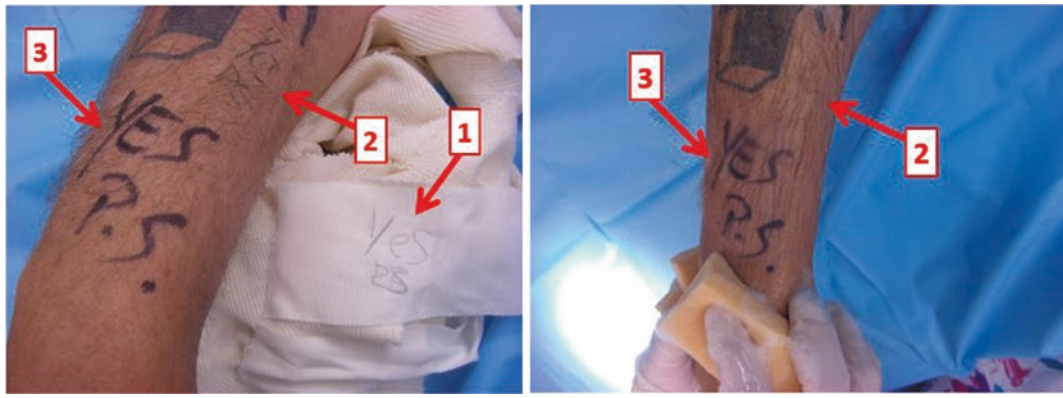


**Fig. 44.1** Clinical example of correct vs. incorrect modalities of surgical site marking. (Adopted with permission from: Stahel PF et al., *Patient Saf. Surg.* 2009, 3:14. Creative Commons 4.0 International License). Upper panel: This patient was scheduled for a surgical procedure on the right forearm. The surgical intern marked and initialed the site on the dressing, which came off prior to surgery (1). The resident then corrected the mistake by marking the surgical site on the skin using a regular pen. Neither the marking, nor the initials, are unequivocally legible (2). Finally, the attending surgeon marked the site again with a permanent marker and included his initials (3). Lower panel: During the surgical preparation, the site marking with the regular pen was washed off (2), whereas the permanent marker remained visible throughout the surgical preparation (3). This example emphasizes the crucial importance of using a permanent marker, large and well legible letters, and to sign the marking with the surgeon's initials. "YES" is the designated, standardized identifier for the correct surgical site at this surgeon's facility

gery). Rarely, patients may refuse surgical site marking for cosmetic or other personal reasons [35].

An alternative process to site marking must be in place for all these circumstances. Radiological diagnostics may need to be consulted pre- and intraoperatively to determine the surgical site with accuracy. Unlike symmetric external body parts (extremities, eyes, ears), any *occult* surgical site cannot be easily confirmed and marked prior to surgery. Thus, these particular circumstances mandate the intraoperative localization and confirmation of the correct site (e.g., correct spine level by intraoperative fluoroscopy), in conjunction with a careful evaluation of preoperative imaging studies, such as CT, MR, angiography, or cholangiography.

### 44.4.3 The Surgical "Time-Out"

The time-out represents the last part of the Universal Protocol "checklist" and is performed immediately before the initiation of the planned procedure in the operating room [35]. The time-out represents the final recapitulation and reassurance of accurate patient identity, surgical site, and planned procedure. In addition, the following items are confirmed during the time-out: correct patient positioning, known allergies, the need for perioperative antibiotics, the availability of relevant documents and diagnostic tests, instruments, and implants [37]. The following aspects should be taken into consideration for a "best practice" time-out:

- The time-out process must be standardized and defined in the policies and procedures of each respective facility.
- The time-out is called by a designated member of the surgical team, e.g., the circulating nurse or the surgeon.
- A "two-stage" time-out process allows for the patient to be awake and participate in the verification process of patient identity, surgical site, and planned procedure (so-called awake time-out) prior to induction of anesthesia. This is followed by a second final time-out

after surgical prepping and draping, and immediately before skin incision.
- All members of the surgical team (i.e., surgeon, anesthesiologist, CRNA, circulating nurse, operating room technician, radiology technician, etc.) must be present in the operating room and actively participate in the time-out prior to skin incision.
- During the time-out, all non-essential activities are suspended to an extent which does not compromise patient safety.
- The time-out must be repeated intraoperatively for every additional procedure performed on the same patient.

In essence, the three individual steps of the Universal Protocol checklist are intended to ensure correct patient identity, correct procedure, and correct surgical site. More importantly, this checklist empowers *any* member of the team to speak up and stop the procedure whenever there is an apparent inconsistency or risk to patient safety, independent of the hierarchy and culture in the operating room. Pitfalls and limitations which may render the checklist less effective are hidden in each component of the protocol [38]. The degradation of surgical safety checklists to a "robotic-hackneyed ritual" can be mitigated by the surgeon's personal ownership and leadership with an unwavering and credible commitment to the checklist [27, 39, 40].

## 44.5 The Next Frontier of Patient Safety: Individual Accountability

Surgeons are under an increasing amount of pressure and expectation to perform at the highest level. They must deliver absolute diagnostic accuracy and infallible surgical quality under the conflicting paradigm of patient safety and maximal cost efficiency. In addition, surgeons are expected to have the highest standards of ethical values and professionalism, to be respected role models, dedicated teachers, academic researchers, successful administrators, and entrepreneurs. These expectations are analogous to the task of squaring the circle. As the historic paradigm has shifted in the past two decades from a "*culture of blame and shame*" to a "*culture of systems safety,*" we have now reached a tipping point in which the expectations of "the system" are at their limit. A physician-driven approach is therefore needed to build and sustain a "*culture of individual accountability*" beyond systems safety. A classic example is represented by hand hygiene—a simple core measure with immense impact on patient safety as it relates to preventing hospital-acquired infections. International estimates show that overall compliance with hand hygiene among health care personnel is as low as 10–30%. A "perfect system" may provide staff training programs and logistic support, including door signs and hand sanitizer dispensers in- and outside of patient rooms. However, in absence of individual accountability and physician leadership, the expected goal of 100% hand hygiene compliance remains utopic. How is it possible that low-wage workers in the meatpacking industry are able to sustain 100% compliance with hand hygiene protocols? Intriguing insights from our own experience reveal that hand hygiene compliance rates drop from more than 90% when staff feel observed and monitored, to less than 40% when unobserved. This phenomenon likely relates to the "Hawthorne effect" by which a subject's behavior changes as a result of being observed and reflects poorly on the individual accountability of "*doing the right thing*" for our patients at all times. Senior surgeons therefore have the obligation to step up and to be respected role models to their junior colleagues in training by teaching non-technical virtues, including the unwavering advocacy for patient safety, strict professionalism, effective communication, and individual accountability [41, 42]. The ultimate benchmark for the success of surgeon mentors is to produce trainees who will be better surgeons and stronger patient advocates than their predecessors, by embracing patient safety as a core surgical responsibility.

## 44.6 Conclusion

The last frontier in surgical patient safety is for surgeons to step up and embrace patient safety as a core surgical responsibility. Adherence to best practice safety protocols, including surgical safety checklists, in conjunction with mastering non-technical skills, such as effective communication and individual accountability, will likely promote the field of surgery to the next high reliability industry with sustained excellent patient outcomes.

**Key Concepts**

- Medical errors currently represent the third leading cause of death in the United States.
- Most adverse events in surgery originate from a breakdown in communication, rather than from technical surgical errors.
- Established scripted mnemonics for effective communication improve the surgeon-patient partnership and reduce the risk of preventable complications due to communication breakdown.
- Surgical safety checklists prevent the accidental omission of critical steps in the perioperative process and improve patient safety assurance, in analogy to other high-risk industries, such as professional aviation.

**Take Home Messages**

- The legendary Flight Director of the lunar Apollo missions, Gene Kranz, stated in the wake of the Apollo 1 disaster in 1967: "*From this day forward, Flight Control will be known by two words: 'Tough and competent'. Tough means that we are forever accountable for what we do or what we fail to do. We will never again compromise our responsibilities. Competent means we will never take anything for granted. We will never be found short in our knowledge and in our skills.*"
- It is time for surgeons to become "*tough and competent*" for patient safety!

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# Psychiatric Issues in the Treatment of Severe Trauma

45

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**Learning Objectives**

After completing this chapter, readers will be able to:

- State estimated prevalence rates of psychiatric illness and specify the most common disorders among both adult and child patient populations treated for major traumatic injuries.
- Differentiate and recognize the role of pre-existing psychiatric illness in the development of incident (new) psychiatric illness following major traumatic injury.
- Describe established methods for identification of psychiatric illness in patients with major traumatic injuries.
- Discuss the main types of treatments available for the treatment of psychiatric illness following major traumatic injury.

## 45.1 Introduction

Although it is undisputed that the treatment of patients with severe traumatic injuries requires expertise in orthopedics and trauma care, it is not as well appreciated that it also requires broader expertise in other medical disciplines including psychiatry. It is well recognized that traumatic injuries may be followed by an array of health problems, impaired physical functioning, reduced ability to work, employment difficulties, and permanent disability [1]. Additionally, in many patients, recovery from traumatic injuries may be complicated by psychiatric illness, which is further associated with impaired physical healing, general health, functioning, employment, and quality of life [1–3].

Despite this knowledge, systematic identification of psychiatric illness in patients with traumatic injuries is generally lacking in usual care and thus most psychiatric illness in these patients is not recognized or addressed [1, 4]. This chapter will review available literature on psychopathology in trauma patient populations, summarizing the types and prevalence of psychiatric illnesses, describing methods to help identify these vulnerable patients in clinical care, and providing an overview of interventions for psychiatric difficulties in patients receiving treatment for major traumatic injuries.

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## 45.2 Research Approaches to Psychiatric Disorders in Patients Receiving Treatment for Traumatic Injuries

Although psychiatric illness well documented to represent an important complication of major trauma, the proportions of patients reported to develop psychiatric complications have varied widely across research studies [1, 4]. The main psychiatric disorders of relevance to patient populations treated for major trauma are posttraumatic stress disorder (PTSD), major depressive disorder (MDD), and substance use disorders (SUD) including alcohol and drug use disorders; anxiety disorders including generalized anxiety disorder and panic disorder in adults and behavioral disorders in children may also complicate trauma recovery for some. A review of the scientific literature has yielded a representative collection of articles reporting rates of psychiatric illness among samples of patients in trauma care settings, summarized in separate tables for adults and children in this chapter, and the clinical implications are discussed. The findings of this research should inform clinicians on the prevalence of psychiatric illness they may anticipate in the patients in their practices.

This literature is not easy to assimilate. Methodological issues in the research are pivotal to the interpretation of the reported statistics. Perhaps most importantly, different types of mental health assessment tools may yield vastly different findings. Symptom screening self-assessment tools are often used in studies that apply a threshold cutoff to the resulting symptom score to identify positive cases. The conditions identified by these scales do not represent validated psychiatric disorders but rather are arbitrary constructs that may greatly overestimate psychopathology in populations studied [5–7]. Structured diagnostic interviews uniquely assess psychiatric disorders that determine need for psychiatric treatment and choice of treatment, but they are far more burdensome in terms of both patient and assessor time and effort than brief self-report symptom scales. Self-report screening tools and clinical interviews or observation may identify psychological distress, however, which may also benefit from mental health interventions.

Other methodological issues in this literature are also relevant to interpretation of the reported findings. Many studies assess and report rates of illness only as post-injury *prevalence* of psychiatric disorders. Some studies, however, also provide pre-injury lifetime and/or recency such as in the year or month before the injury or current prevalence at the time of the injury. Current or recent prevalence rates are generally less than lifetime prevalence rates, because of the much longer time inherent in a lifetime for accumulation of psychiatric illness than in any given shorter time period. Few studies provide post-injury *incidence* (new disorders first occurring after the injury in people who did not previously have the disorder). Post-injury *incidence* of psychiatric illness is the statistic that is most likely to capture psychopathology limited to disorders specifically arising from the trauma exposure and/or injury [8]. In contrast, post-injury prevalence may include many cases that are simply the continuation of chronic pre-existing psychiatric illness. Thus, assessment of pre-injury psychiatric disorders is needed for the differentiation of post-injury incidence from prevalence. Pre-existing disorders are likely to represent an association with risk for trauma exposure and for psychiatric illness following traumatic injury.

Sampling issues in both the adult and pediatric trauma injury literature may also affect the findings. Patients with different types of injuries (e.g., orthopedic trauma, burns, minor injuries) may differ in their psychiatric morbidities. Further, many study samples have low participation of eligible patients, including volunteer or convenience samples. Such samples may not be representative of the patient populations from which they are selected, potentially introducing sampling bias and underestimating psychopathology, given that the prevalence of psychiatric illness in research nonparticipants is known to be elevated [8].

## 45.3 Psychiatric Illness in Patients with Traumatic Injuries

The published literature contains number of published research studies examining psychopathology in patients receiving medical care for major traumatic injuries. More studies have been conducted on adult than pediatric populations. Identification of the prevalence of psychiatric illness in patients treated for major traumatic injuries can help establish the importance of psychiatry in trauma care and inform trauma care teams of anticipated needs for psychiatric expertise in their patients.

### 45.3.1 Psychiatric Illness in Adult Patients with Traumatic Injuries

Table 45.1 presents findings from 17 published research studies (described in 19 articles, because 1 study yielded 3 articles) [9–11] providing full diagnostic assessment of psychiatric disorders in samples of adult patients with traumatic injuries. There exists an even larger number of studies using non-diagnostic instruments such as self-report symptom questionnaires and screeners, but these studies do not further improve estimates of psychopathology provided by diagnostic studies and will thus not be summarized in this chapter. The types of injuries represented in these studies included general trauma as well as specific types of injuries such as motor vehicle accidents (MVAs), burns, closed head injuries, and spinal injuries. The patient samples were recruited from hospital trauma centers (8 studies), burn units (7 studies), trauma rehabilitation programs (1 study), and primary care practice (1 study).

Diagnostic interviews used in these studies included most commonly the Structured Clinical Interview for DSM (SCID), and also the Composite International Diagnostic Interview (CIDI), the Diagnostic Interview Schedule (DIS), and, for PTSD, the CAPS (Clinician-Administered PTSD Scale). All of these interviews provide valid and reliable diagnostic assessments. One study [12] administered a diagnostic instrument by self-report survey rather than an interviewer-administered assessment, but it followed the complete diagnostic criteria closely. Two diagnostic interview studies [12, 13] reported prevalence data only for PTSD.

Post-injury psychiatric disorders were assessed by 13 studies, pre-injury disorders by 11, and both by 7. The studies had important methodological differences based on variable timeframes of pre- and post-injury disorders examined and reported, including current prevalence at the time of the study, cumulative post-injury prevalence, and variable pre-injury prevalence in lifetime, recency, or current point prevalence. The representation of studies became narrow within these various temporal categories of timeframes, limiting comparisons of findings across studies. In one study [14] reporting both current and post-injury prevalence of psychiatric disorders 1 year after injury, more than two-thirds of those with a post-injury disorder had a current disorder. In one study [15] reporting both post-injury prevalence and incidence, in nearly three-fourths of all the post-injury disorders the new disorders represented new disorders arising for the first time after the injury.

About half the patients in these samples were found to have post-injury psychiatric disorders [11, 15, 16]. There was an apparent dose–response relationship of trauma with psychopathology: in patients with minor injuries, only about one-fourth had post-injury psychiatric disorders [14]. Post-injury psychiatric comorbidity was typical [5], especially between mood and anxiety disorders and PTSD [15, 17].

PTSD was one of the most prevalent post-injury psychiatric disorders in several studies, occurring in as many as one-third [11–13, 18], or even more than one-half [19] of patients. PTSD was diagnosed in about 1 out of 10 (as current prevalence) patients in 2 studies of burn injuries [8, 20] and in 2% (as post-injury prevalence) of patients with minor injuries [14] and 1% (as current prevalence) of patients in a rehabilitation program for spinal injuries [16].

Nearly one-half of the adult studies assessed the post-injury prevalence of depressive disor-

**Table 45.1** Adult trauma patient studies using psychiatric diagnostic instruments

| Study (first author/yr) | Sample | Assessment time | Assessment tool(s) | Pre-injury disorders | Post-injury disorders |
|---|---|---|---|---|---|
| Ahmadi 2006 [23] | 324 acute physical trauma pts randomly sampled from hospitals | Baseline in hospital | Structured DSM-IV interview for diagnosis and substance use | Lifetime SUD 40% (alcohol 30%, tobacco 15%). Lifetime substance use 69% (alcohol 47%, tobacco 66%). | Current substance use 35% (alcohol 3%, tobacco 14%). |
| Blanchard 1996 [13] | 158 MVA pts referred from primary care (convenience sample) | 1–4 mos post- injury | SCID I, II (DSM-III-R), CAPS | | Current PTSD 39%. |
| Bryant 1996 [12] | 35 burn unit pts (convenience sample, 61% participation) | 12 mos post-injury | PTSD-I (DSM-III-R) via self-report survey | | Post-injury PTSD 31%. |
| Dersh 2007 [16] | 1323 consecutive pts with chronic disabling occupational spinal injury in rehab program | ≥4 mos post-injury | SCID I (DSM-IV) | Any lifetime dx 39%: any SUD 27% (alcohol 14%, drug 8%), MDD 10%. | Any current dx 58% (excl. pain dx, present in 96%): MDD 50%, SUD 17% (alcohol 17%, drug 16%, opioid 15%), PTSD 1%. |
| Dyster-Aas 2008 [8] | 73 severe burn injury pts in burn unit (85% participation) | Baseline (during acute care), 12 mos post-injury | SCID I (DSM-IV) | Any lifetime dx 66% (MDE 41%, AUD 32%, PTSD 10%). Any 12-mo pre-injury dx 52% (MDE 30%, AUD 18%, PTSD 7%). | Baseline: any current dx 45%: MDE 16%, AUD 16%, PTSD 10% (4% burn-related). At 12 mos: current MDE 16%, PTSD 9% (8% burn-related); incident MDD 6%. |
| Epstein 1993 [18] | 15 (of 118) pts at trauma center with severe accidental injury (convenience sample) | 9 mos post-injury | Structured interviews for DSM-III-R dx | | Post-injury PTSD 40%. |
| Fauerbach 1996, 1997, 2000 [9–11] | 98 burn center pts (25% participation) | d/c, 4 mos and 8–12 mos post d/c | SCID (DSM-III-R) | Any lifetime dx 64% (mood dx 31%, AUD 41%, DUD 14%, anxiety dx 10%). | At d/c: current PTSD 8%, MDD 4%, AUD 11%. At 4 mos: current PTSD 28%, MDD 10%, AUD 12%. At 12 mos: any current dx 51%: MDD 11%, AUD 11%. |
| Jorge 2004 [17] | 118 pts with closed head injuries from hospital trauma centers (convenience sample) | Baseline; 3, 6, 12 mos post-injury | SCID (DSM-IV) | Lifetime SUD 24%, depressive dx 19%, anxiety dx 9%. | At 1 yr: any post-injury mood dx 45%, MDD 27%. |

**Table 45.1** (continued)

| Study (first author/yr) | Sample | Assessment time | Assessment tool(s) | Pre-injury disorders | Post-injury disorders |
|---|---|---|---|---|---|
| Öster 2014 [20] | 107 consecutive burn center pts | Admission, 12 mos, 2–7 yrs | SCID I, II (DSM-IV) | Any lifetime Axis I dx 57% (MDE 36%, SUD 29%, any anxiety dx 27%). Personality dx: 21%. | At 12 mos: current MDE 13%, PTSD 11%. At 2–7 years: any current dx 31%: MDE 3%, PTSD 0%, simple phobia 19%. |
| Palmu 2010 [5] | 107 consecutive pts from 2 burn centers (69% participation) | ≥2 wks post-injury | SCID I, II (DSM-IV-TR) (lifetime, 1 mo pre-injury, current) | Any lifetime Axis I dx 61%: MDD 15%, PTSD 8%, SUD 47% (alcohol 36%, drug 8%). Any 1-mo pre-burn dx 41%: MDD 5%, PTSD 3%, SUD 33% (alcohol 28%, drug 5%). Personality dx 23% (incl. cluster B 19%). | Any current Axis I dx 48%: MDD 4%, PTSD 3%, SUD 33% (alcohol 28%, drug 5%). |
| Poole 1997 [21] | Consecutively hospitalized trauma pts: 46 intentional (not suicide) and 74 nonintentional trauma (80% participation) | Before hospital d/c | PDI for DSM-III-R | Any lifetime dx 55% (intentional trauma pts 63%, incl. ASP 28%, MR 24% and nonintentional trauma pts 53%, incl. ASP 10%, MR 11%). | |
| Ramchand 2009 [24] | 677 physical injury pts from 4 trauma centers (80% participation) | Baseline, 6 mos, 12 mos | CIDI (DSM-IV alcohol abuse); individual binge drinking and drug use questions | 12-mo pre-injury alcohol abuse 24%. 12-mo pre-injury drug use 42% (marijuana 37%, cocaine 12%). 1-mo pre-injury binge drinking 37%. 2-h pre-injury alcohol/drug use 30%. | |
| Richmond 2009 [14] | 275 minor injury pts (randomly selected from 2 trauma centers; 27 lost to F/U) | 3, 6, 12 mos post-injury | SCID (DSM-IV) | Any lifetime dx 29%, any current dx 16%. | At 1 yr: any post-injury dx 23%: MDD 5%, PTSD 2%, SUD 4%; any current dx 16% (excluding pts with pre-injury dx). |
| Shalev 1996 [77] | 51 consecutive trauma pt hospital admissions (85% participation) | 1 wk, 6 mos post-injury (prospective) | PTSD section of SCID (DSM-III-R) | | At 6 mos: PTSD 26% (unclear if post-injury or current prevalence). |

(continued)

**Table 45.1** (continued)

| Study (first author/yr) | Sample | Assessment time | Assessment tool(s) | Pre-injury disorders | Post-injury disorders |
|---|---|---|---|---|---|
| ter Smitten 2011 [15] | 90 consecutive burn center admissions (45% participation) | 1–4 yrs post-injury | CIDI (DSM-IV) | | Any 12-mo dx 39%. Incident dx 28%: MDD 10%, GAD 10%, injury-related PTSD 7%; SUD 10% (alcohol 8%, drug 2%). |
| Whitman 2013 [19] | 42 consecutive trauma pt hospital admissions (100% participation; 11% lost to F/U) | Daily ×7 d Weekly ×3 (final interview at 1 mo) | DIS (DSM-IV) | | Injury-related PSTD 59%. |
| Wisely 2010 [22] | 58 consecutive burn center admissions (58% participation) | | Semi-structured diagnostic interviews | Any lifetime dx 50% (depression 17%). | |

*pt* patient; *F/U* follow up; *d* day; *wk* week; *mo* month; *yr* year; *d/c* discharge; *rehab* rehabilitation; *MVA* motor vehicle accident; *incl*. including; *excl*. excluding; *DSM-III-R* Diagnostic and Statistical Manual of Mental Disorders, 3rd Ed. Revised; *DSM-IV* Diagnostic and Statistical Manual of Mental Disorders, 4th Ed.; *DSM-IV-TR* Diagnostic and Statistical Manual of Mental Disorders, 4th Ed.-Text Revision; *SCID* Structured Clinical Interview for DSM Disorders; *PTSD-I* PTSD Interview; *CAPS* Clinician-Administered PTSD Scale; *PDI* Psychiatric Diagnostic Interview; *CIDI* Composite International Diagnostic Interview; *DIS* Diagnostic Interview Schedule; *dx* diagnosis; *SUD* substance use disorder; *AUD* alcohol use disorder; *DUD* drug use disorder; *MDD* major depressive disorder; *MDE* major depressive episode; *PTSD* posttraumatic stress disorder; *ASP* antisocial personality disorder; *MR* mental retardation; *GAD* generalized anxiety disorder

ders. The reported rates varied widely, ranging from <5% [5, 11, 14] to 50% [16]. In some studies, MDD was more prevalent than PTSD after the injury, but in other studies, PTSD was more prevalent. Considerably higher rates of post-injury MDD were found in studies sampling from rehabilitation units, reported in one-fourth to one-half of patients [16, 17]. In these studies, the post-injury MMD prevalence was considerably higher than its lifetime prevalence before these patients' traumatic incidents, suggesting that MDD may tend to complicate the post-injury course particularly among patients undergoing rehabilitation rather than predisposing to their risk of exposure to trauma.

The post-injury prevalence of SUDs in studies examining these disorders generally ranged between about one-tenth and one-third of patients [5, 11, 15, 16] although the post-injury prevalence of these disorders was found to be very low in a study of patients with only minor injuries [14]. In a study of burn patients, the post-injury SUD prevalence specific to alcohol was more prevalent than SUD related to other drugs [5], but in a study of spinal injury patients in a rehabilitation program, the post-injury prevalence of SUDs related to drugs was as prevalent as for alcohol [16]. It is unclear to what extent these differences in post-injury alcohol and other drug problems represent differential contributions to risk for trauma exposure in disorders that may have already been present before the injury, or to what extent these disorders may differentially arise as complications of the injuries in distinct patterns for burn injury versus spinal injury patient populations.

The pre-injury prevalence of psychiatric disorders in general was at least as high as the post-injury prevalence in the studies reviewed. Pre-existing psychiatric disorders were identified in about one-half to two-thirds of traumatic injury patients [5, 8, 9, 16, 20–22]. SUDs and personality disorders were identified as types of disorders with relatively high pre-injury prevalence in trauma injury patient populations.

Pre-injury SUDs were identified in about one-fourth to one-half of the trauma injury patients in

studies examining SUDs [5, 8, 9, 16, 17, 20, 23]. Importantly, in recent timeframes right before the traumatic injury, about one-fourth of patients were identified to have a SUD involving alcohol [5, 8, 24], and in one study, nearly one-half of patients in the sample were determined to be using illicit drugs [24]. In one study, one-third of the patients had used alcohol or drugs within 2 h of their injuries [5]. Collectively, these studies suggest not only that SUDs likely represent important risk factors for trauma exposure and injury, but also that these disorders, representing chronic illnesses, can be expected to continue in the post-injury period and present complications for medical and psychiatric recovery, in up to one-third of patients. The study of patients with chronically disabling spinal injury by Dersh and colleagues [16] noted that the patients with post-injury opioid dependence had twice the pre-injury prevalence of SUDs of the patients without opioid dependence. This finding prompted a recommendation for physicians to be careful to obtain a history of pre-existing SUD before prescribing opiates for chronic post-injury pain.

A few studies have examined personality disorders, which are generally lifelong conditions, reporting them to be present in one-fifth to one-fourth of trauma injury patients before the injury [5, 20]. Most of the personality disorders were Cluster B personality disorders including antisocial and borderline personality [5, 20, 21]. One study [10] found that burn survivors scored especially high on neuroticism and low on extraversion. The patients in that study who developed PTSD had higher neuroticism and lower extraversion scores than those who did not. These findings suggest distinct roles for these two personality features in both risk for traumatic injury and risk for development of PTSD among injured patients. The evidence suggests that personality disorders and personality features such as novelty seeking and risk taking [25–28] likely represent risk factors for exposure to trauma as well as persisting afterward to complicate post-injury recovery.

Comparing the prevalence of psychiatric disorders prior to and subsequent to the injury reported in research studies may help inform contemplation of the roles of psychiatric disorders in risk for trauma and as a consequence of trauma although caution is warranted because the timeframes compared are usually not equal. The post-injury prevalence of MDD was considerably higher than its pre-injury prevalence in two studies [16, 17], suggesting that this disorder may be more of an outcome of traumatic injury than a risk factor for trauma exposure. In four studies, substance use or SUDs were found to have a higher prevalence before than after traumatic injury [5, 11, 16, 23], suggesting a role of substance abuse and problems related to it in creating risk for traumatic injury more than being a result of the injury. One of these studies [16], however, found the post-injury prevalence (16%) of drug use disorders to be higher than the lifetime pre-injury prevalence (8%) in a sample of spinal injury patients in a rehabilitation program. Additionally, the post-injury prevalence of opioid use disorder (15%) in this sample accounted for almost all of the post-injury drug use disorders, suggesting that seeking pain relief may have played a role in the development of the addictions in these patients.

It has been suggested that different types of traumatic injuries may be associated with different patterns of pre-existing psychiatric disorder prevalence. One study found pre-existing SUDs, psychotic disorders, and personality disorders to be especially common in burn patients, possibly implying that these disorders in particular may predispose to burn injuries [5]. Four studies of burn patients [5, 8, 9, 11, 20] found that the lifetime prevalence rates of pre-existing SUDs and mood disorders were quite high, also possibly implying that these disorders may represent risk factors for burn injuries. Potential mechanisms conferring risk might be diminished cognitive processing, inadequate awareness, and impaired impulse control that may occur as part of these psychiatric illnesses [9–11, 17, 20]. SUDs and mood disorders have further been found to be specifically predictive of post-injury psychiatric illness in burn patients [11]. In a study of chronically disabling spinal injuries, PTSD developed for the first time seven times more often before

than after the injury, illustrating the recurring nature of trauma that can serve as a risk factor for subsequent spinal injury [16].

Only one adult study reviewed here [15] reported post-injury incidence of psychiatric disorders, which was identified in more than one-fourth, and no single incident disorder was identified in more than one-tenth of the sample. Of note, PTSD related to the specified traumatic injury represents an incident disorder because by definition it could not have occurred prior to the injury.

Yet other pre-existing characteristics of patients treated for traumatic injuries differentiate them from other patient populations [21]. The traumatic injury itself inserts a certain amount of selection bias into injured populations, because of the associated risk factors for trauma exposure. Social disadvantages including poverty, lack of education, and unemployment may place individuals at risk for trauma [27–29]. Specific contributors to this risk in disadvantaged populations include exposure to crime, danger, and victimization by firearms and other weapons in low-income neighborhoods, as well as employment in lower-income jobs that may involve greater physical hazards. Behavioral factors may also predispose individuals to trauma, including recreational substance use, non-use of safety devices such as automobile seat belts and motorcycle helmets, and hazardous behaviors such as climbing to unprotected heights or onto unsafe structures. Because of these pre-existing characteristics, exposure trauma is not a random occurrence in life, contrary to common assumptions [21, 28], and not all people are at equal risk for exposure to trauma [30]. As briefly mentioned earlier, people with a history of trauma are more likely to experience future traumatic events, and thus trauma exposure can be a repetitive phenomenon for some individuals who seem to be injury prone, termed "trauma recidivism" (p. e1) [31] (p. 685) [32] (p. 847) [33]. For example, a study of victims of violent injury found that 44% would have another violent injury within 5 years, and that 20% would die of trauma or substance abuse in that period [34].

### 45.3.2 Psychiatric Illness in Pediatric Patients with Traumatic Injuries

Table 45.2 presents findings from seven published studies (described in eight articles, because one study yielded two articles) [35, 36] providing full diagnostic assessment of psychiatric disorders in samples of child and adolescent patients with traumatic injuries. Similar to the literature on adult trauma, the child trauma literature also contains myriad studies using non-diagnostic instruments such as self-report symptom questionnaires and screeners that do not further improve estimates of psychopathology provided by diagnostic studies and will thus not be summarized in this chapter. The types of injuries represented in these study samples included general trauma, MVAs, and burns. The samples were recruited from hospitals and burn units. Of these seven studies, only post-injury disorders were assessed by six, and both pre- and post-injury prevalence were assessed by one; incidence was reported by two studies. The Diagnostic Interview for Children and Adolescents (DICA) was used in three of the studies, and five other structured diagnostic interviews were used each by a single study.

About one-third to one-half or more of the pediatric patients in these studies had a post-injury psychiatric disorder [37, 38], and one study found nearly one-third to have an incident disorder [39]. As in adults, psychiatric illness in children tended to be comorbid [38, 39], and acute post-injury onset of PTSD appeared to be a gateway for the development of other psychiatric disorders within the next 6 months [38].

As in studies of adults, pediatric injury-related PTSD was one of the main psychiatric disorders to be found in the context of the traumatic injury. Injury-related PTSD was identified in variable rates across these studies, commonly (18–35%) after MVA [40, 41] and in few (5–13%) after burns and other injuries [35, 37, 38, 42]. Psychiatric disorders other than PTSD were examined by only three studies [37–39]. Post-injury depressive disorders were observed in as few as no patients with burn injuries [38] and in

**Table 45.2** Studies of children/adolescents using psychiatric diagnostic instruments

| Study (first author/yr) | Sample | Assessment time | Assessment tool(s) | Pre-injury disorders | Post-injury disorders |
|---|---|---|---|---|---|
| Bloom 2001 [37] | 46 hospitalized child/adolescent pts with TBI and no known prior psychiatric illness | ≥1 yr post TBI | DICA-R (DSM-IV) | Any dx 35%: ADHD 22%, anxiety dx 13% | Any post-injury dx 59%: ADHD 35%, MDD 26%, PTSD 13%, anxiety dx 7%; any current dx 50%: ADHD 35%, MDD 11%, PTSD 7%, anxiety dx 2%. |
| De Young 2012 [38] | 130 pts aged 1–6 yrs at burn center for accidental burns (40% participation) | 1 and 6 mos post hospital d/c or outpatient visit | DIPA (DSM-IV-TR) parent interview | | At 1 mo: any post-injury dx 35%: ODD 16%, SAD 16%, PTSD 5%, ADHD 5%, MDD 3%; any incident dx 32%. At 6 mos: any current dx 27%: ODD 14%, SAD 8%, PTSD 1%, ADHD 6%, MDD 0%; any incident dx 14%. |
| Max 2012 [39] | 141 pts aged 5–14 yrs in consecutive hospital admissions for TBI (80% participation) | 6 months post-injury | K-SADS-PL | | Current depressive dx 13%; incident depressive dx 2%. |
| Stallard 1998 [41] | 119 consecutive pts aged 5–18 yrs with MVA from hospital ED (43% participation) | 22–79 d post-injury | CAPS-C | | Post-injury PTSD 35%. |
| Stottard 2017 [42] | 42 consecutive pts aged 1–4 yrs hospitalized for burns (51% participation) | 1 mo post hospital d/c | DICA-P; PTSDSSI | | Post-injury PTSD 10% (DICA-P) vs. 3% (PTSDSSI). |
| van Meijel 2015, 2019 [35, 36] | 147 consecutive pts aged 8–18 yrs hospitalized for accidental injury (39% lost to F/U) | 3 mos and 2–4 yrs post-injury | ADIS-IVC/P | | At 3 mos: current PTSD 6%. At 2–4 yrs: current PTSD 6%. |
| Zink 2003 [40] | 143 hospitalized pts aged 7–15 yrs with MVA | 2 and 6 mos post-injury | PTSD section of DICA-R | | At 2 mos: any current PTSD 18%. At 6 mos: post-injury PTSD 22%; current PTSD 10%. |

*pt* patient; *F/U* follow up; *d* day; *mo* month; *yr* year; *d/c* discharge; *MVA* motor vehicle accident; *TBI* traumatic brain injury; *ED* emergency department; *DSM-IV* Diagnostic and Statistical Manual of Mental Disorders, 4th Ed.; *DSM-IV-TR* Diagnostic and Statistical Manual of Mental Disorders, 4th Ed.-Text Revision; *CAPS-C* Clinician-Administered Posttraumatic Stress Disorder Scale for Children; *DICA-R* Diagnostic Interview for Children and Adolescents-Revised; *DICA-P* Diagnostic Interview for Children and Adolescents-Parent version; *K-SADS-PL* Schedule for Affective Disorders and Schizophrenia for School-Age Children, Present and Lifetime Version; *DIPA* Diagnostic Infant Preschool Assessment; *ADIS-IVC/P* Anxiety Disorders Interview Schedule for DSM-IV—Child and Parent Version; *PTSDSSI* PTSD Semi-Structured Interview and Observational Report; *dx* diagnosis; *ADHD* attention deficit hyperactivity disorder; *ODD* oppositional defiant disorder; *CD* conduct disorder; *MDD* major depressive disorder; *PTSD* posttraumatic stress disorder; *SAD* separation anxiety disorder

up to about one-fourth of patients with traumatic brain injury (TBI) [37], and very few incident depressive disorders were found [39]. In a study of children with TBI [37], post-injury externalizing disorders including the hyperactive type of attention deficit hyperactivity disorder (ADHD), oppositional defiant disorder (ODD), and conduct disorder (CD) tended to be persistent post-injury disorders, but internalizing disorders (mood, anxiety, and eating disorders) were likely

to resolve over time. Of note, children are well known to report more internalizing disorder symptoms for themselves than their parents do for them, and parents report more externalizing disorder symptoms for their children than their children report for themselves [37, 43–47], which could have played a role in the apparent more rapid recovery of the internalizing symptoms.

Pre-existing psychiatric disorders were identified in only one pediatric study [37], in which about one-third of children with burn injuries who were selected for having no known pre-existing psychiatric illness were found to actually have a pre-existing psychiatric disorder as determined by structured diagnostic interviews. In that study, ADHD represented most of the identified pre-existing psychopathology, with a lifetime prevalence several times higher than the 5% ADHD prevalence reported for the general child population [48]. This high pre-existing ADHD prevalence suggests that this disorder may be a risk factor for accidental injuries in children, a hypothesis that has been tested and found to be the case by other studies [49].

### 45.3.3 Clinical Implications of Psychiatric Illness in Patients Receiving Treatment for Traumatic Injuries

The main clinical implication of the studies of adult and pediatric trauma injury patients reviewed here is that post-injury psychiatric illness and distress are highly prevalent in these patients. Not only does the accompanying psychopathology result in mental suffering in its own right for these patients and their loved ones, but it appears to have important negative consequences for their short-term and long-term medical recovery, functional outcomes, and restoration of psychosocial status and quality of life.

Acutely, the occurrence of post-injury psychiatric illness or psychological distress in adult traumatic injury patients was found in these studies to be associated with longer hospitalization and greater treatment costs, higher levels of distress, and more functional impairment [9, 11, 22]. However, by the time 4 and even 12 months have elapsed, patients with and without psychiatric disorders appeared to converge in their functionally capacities, at least in one study described in two articles [9, 11]. Post-injury MDD in particular, however, has been found to be associated with poorer social functioning, more impaired daily functioning abilities, more sick days in bed, and non-return to employment at 12 months post-injury [14, 17]. These findings demonstrate the importance of identifying patients with post-injury mental health problems and providing psychiatric care not only to reduce psychiatric morbidity but also with the aim to improve their ultimate medical, psychosocial, and functional outcomes.

## 45.4 Identification of Psychiatric Illness in Patients with Traumatic Injuries

To be cared for appropriately, psychiatric illness must first be identified. A starting point for clinician awareness of the possibility of post-injury psychiatric illness is to consider their patients' individual histories and clinical characteristics known to be associated with, or specific risk factors for, psychopathology provided by research studies. Careful research methods are required to untangle the separate yet sometimes overlapping risk factors for psychopathology after trauma from risk for the trauma itself because risk for development of psychopathology after trauma exposure may differ from, yet be confounded with, risk for exposure to trauma [7, 50]. The risk factor most consistently and robustly found to predict post-injury psychiatric illness in both adult and pediatric studies is the presence of pre-existing psychiatric disorders [8, 11, 13, 16]. Additionally, pre-existing psychopathology has been found to predict less satisfactory recoveries even adjusting for post-injury psychiatric illness [9]. The specific pre-existing disorders found to confer greatest risk for post-injury disorders are detailed in the section above, largely consisting of depressive and anxiety disorders, PTSD, and

substance use disorders. For PTSD, in addition to pre-existing psychopathology, female sex, severity of the traumatic incident and of resulting injuries and initiation of litigation were found by one study in this review to be modest predictors of the development of PTSD, and loss of consciousness in the incident was found to be possibly protective [13].

The studies using full diagnostic assessment of patients with traumatic injuries described in this chapter described few consistent predictors of post-injury psychiatric illness beyond pre-existing psychopathology. Therefore, other findings from the broader trauma literature may be applicable in the absence of information gleaned specifically from traumatic injury populations. In general, research on samples of survivors of a variety of types of trauma broadly including non-patient epidemiological samples and disaster survivors has identified female sex and pre-existing psychopathology as the two most robust predictors of PTSD [51]. Other risk factors have been inconsistently or weakly reported in association with PTSD, including age, education, race/ethnicity, marital status, litigation, and financial compensation for injury [51–53]. The prevalence of depressive and anxiety disorders is well described as higher in women than men by a factor of about 2, and to be associated with early life adversity in general populations [54, 55]. Substance use disorders are well known to be at least twice as prevalent as men than women in the general population, associated with nonminority race for alcohol and minority race for drugs, younger individuals, and economically disadvantaged groups, especially the homeless population [56, 57]. In sum, clinicians may want to be most vigilant for post-injury psychiatric illness in their patients with traumatic injuries with past histories of psychiatric illness, paying attention especially to depressive, anxious, and posttraumatic stress disorders in female patients and substance use disorders in male patients.

One additional post-injury clinical characteristic may be a possible clinical flag representing potential for development of PTSD. A prospective study of 42 hospitalized trauma patients queried PTSD symptoms daily for the first post-injury week and then weekly through the first month, and 59% were diagnosed with PTSD [19]. By 1 week, 100% of patients meeting avoidance/numbing symptom group criteria (≥3 of 7 possible symptoms) met PTSD criteria at the end of the month, and 94% of patients not meeting criteria for this symptom group by 2 weeks post-injury did not develop PTSD. Thus, by 1 week, prominent avoidance and numbing identified all of those who would develop PTSD, and absence of avoidance and numbing identified almost all of those who not develop PTSD. Consistent with the apparent early importance of avoidance and numbing symptoms found in this study, a diagnostic study of patients with burn injuries reported that avoidant coping predicted development of PTSD during the first post-injury year [12]. It may be that patients with prominent avoidance and numbing responses early in their post-injury course are so emotionally overwhelmed by their traumatic experience that they cannot bear to think or talk about it or to feel emotions related to it, and patients who show these behavior patterns may be ones who warrant the most careful observation for the development of PTSD.

In the studies of children with traumatic injuries reviewed in this chapter, some individual characteristics were found to be associated with post-injury psychopathology, although there were few consistent predictors of post-injury psychopathology in children. A few lone studies found that girls had significantly more post-injury PTSD than boys [41], that older children were more likely to experience post-injury depression [39], and that prior trauma history was associated with development of PTSD [41] and with permanent physical impairment [36]. Numerous other studies, however, did not find these associations [36, 38–41, 58] or any association of post-injury psychopathology with race or socioeconomic status [39, 40] or type of trauma or injury [40, 41] in children.

Compared to patients briefly treated in the emergency department or outpatient care, patients hospitalized for injuries generally have more extensive contact with hospital personnel provid-

ing more opportunities for observation of emotional distress or psychiatric impairment [14, 15, 59]. However, members of trauma treatment teams may not only lack specific expertise in identification and management of psychiatric illness but also work under well-recognized time pressures of current medical environments, all conspiring against recognition and adequate management of these important problems. Additionally, systematic screening of all traumatic injury patients for psychological issues is not routine in most practices, but this practice could greatly improve recognition of need for mental health care [41] and has thus been recommended by various authors [36, 38].

Self-report symptom screening tools can be implemented systematically in clinical practice to help identify patients at risk for post-injury psychopathology. There are a number of simple, brief screening instruments that are easy for patients to complete and clinicians to score that have been determined to be valid for this purpose. Published articles provide detailed reviews of adult [6, 60] and child [61] screening of post-traumatic, depressive, and anxiety symptoms and alcohol and other drug abuse in the context of traumatic injury or general medical care. It should be emphasized that symptom screening tools are not diagnostic instruments, as they designed for maximal sensitivity and low specificity, making them overly inclusive in case-finding [61]. Thus, brief screening tools should be used only to identify patients needing further evaluation and not to infer psychiatric diagnosis or direct treatment decisions [50, 62]. Psychiatric diagnosis is time-consuming and requires specialized skills, and neither sufficient time to fully assess psychiatric disorders nor specialized training in psychiatric diagnosis are likely to be part of the repertoire of physicians specializing in traumatic injury medicine. Similar issues also apply to provision of psychiatric treatment, and thus both diagnosis and treatment of major psychiatric illness in patients with traumatic injuries will likely require the skills of a dedicated mental health professional.

Some examples of brief self-report screening instruments that have acceptable psychometric properties are freely available, and can be readily applied in clinical practice for detection of psychopathology in adult patients with traumatic injuries are the PTSD Checklist (PCL), a 17-item PTSD symptom scale [63, 64]; the Quick Inventory of Depressive Symptomatology–Self-Report (QIDS-SR), a 16-item scale for MDD symptoms [64]; the 3-item Alcohol Use Disorders Identification Test Consumption (AUDIT-C) [60, 65]; and the Two-Item Conjoint Screen (TICS) questions [60, 66]. Most simply, a single-item question can be asked of the patient about binge use of alcohol (defined as having ≥5 alcoholic drinks for men and ≥4 for women on a single occasion) or about use of illicit drugs in the last year. In a diagnostic study of adult patients with traumatic injuries, these questions identified the presence or absence of substance use disorders in these patients with a respective accuracy of about three-fourths for alcohol use disorder and of about one-half to three-fourths for drug use disorder, respectively [24]. In inpatient and emergency care settings, blood alcohol levels and urine drug screening may be useful for detecting very recent substance use.

Examples of freely available, readily applied screening tools for psychopathology with acceptable psychometric properties for children and adolescents in the context of trauma [47, 67] include the UCLA PTSD reaction index for DSM-5 (PTSD-RI-5), a 27-item scale for PTSD symptoms for children ages 6–17 years [68], and the Depression Self-Rating Scale (DSRS), an 18-item inventory of depressive symptoms for children ages 6–13 years [69].

## 45.5 Mental Health Care for Patients with Traumatic Injuries

Despite the frequency of psychiatric illness and its known complication of recovery from traumatic injuries [9, 11, 20], some studies in this chapter's review reported that only about half or fewer of injured patients with PTSD or other post-injury psychiatric illness received psychiat-

ric treatment for it [5, 8, 12]. In one pediatric study, no patients received treatment [41].

In many patients with traumatic injury and psychiatric illness, the psychiatric illness may have been present prior to the trauma and may have contributed to the patient's likelihood of encountering trauma; others may develop new or incident disorders only after the injury, and these disorders may well have been precipitated by the trauma. Regardless of whether the disorder is pre-existing or new after the injury, it is important to recognize and provide treatment for it, for the sake of not just the patient's psychological welfare but also to maximize chances of the most satisfactory medical outcomes as well. Available treatments for psychiatric disorders are effective and can dramatically improve or even resolve the symptoms altogether, and thus appropriate linkage to mental health care is an important intervention for patients with these disorders [59]. Psychological distress not meeting criteria for a diagnosis occurs even more often than diagnosable psychiatric disorders, representing a normative and nonpathological response, which may warrant intervention as well. Although the above review of traumatic injury patient populations identified many psychiatric disorders that deserve recognition and treatment, three of the major and commonly encountered psychiatric syndromes will be summarized below: PTSD, MDD, and substance (alcohol and drug) use disorders. There is little information on the treatment of these psychiatric disorders specific to patients hospitalized for traumatic injuries, but a great deal of information is applicable from the many studies of treatment for these disorders among psychiatric patient populations [59].

PTSD is considered the "signature" psychiatric disorder of traumatic injury [7, 50]. Among established psychiatric diagnoses, PTSD is unusual in that it is conditional on exposure to trauma. Trauma is defined by current American diagnostic criteria for PTSD [70] as a sudden threat or injury to life or limb through incidents such as accidents, disasters and war, and intentional human acts of violence [52]. The diagnosis of PTSD requires sufficient symptoms classified as intrusion (e.g., nightmares, flashbacks), avoidance (e.g., can't go back to the site of the trauma), negative cognitions and emotions (e.g., loss of interest, emotional numbing), and hyperarousal (e.g., hypervigilance, sleep disturbance), beginning after the trauma and lasting for >1 month, causing distress or impaired functioning, and not arising from another medical condition. PTSD symptoms usually begin quickly after a traumatic event, but full development of the disorder may unfold slowly over time. Although many patients will recover spontaneously from PTSD, the symptoms can persist for years or even decades. PTSD can be a serious disorder in terms of the emotional suffering and severe disability that can result from it.

Two psychotropic medications, paroxetine and sertraline—both antidepressant agents of the selective serotonin reuptake inhibitor (SSRI) mechanism—have been demonstrated to significantly reduce PTSD symptoms [51, 52, 71]. Unfortunately, for many patients, paroxetine may not be a suitable candidate because of its interaction with anticoagulant medications often administered after traumatic injuries. There have been many studies of other types of antidepressant agents and other psychotropic medications for the treatment of PTSD with favorable results, but only these two medications have received FDA approval for pharmacotherapy of PTSD. Benzodiazepines and antipsychotic medications have immediate sedative effects in contrast to SSRIs that typically require many weeks for effectiveness, but benzodiazepine and antipsychotic medications are not considered to be effective primary or adjunctive pharmacotherapy for PTSD.

Psychotherapy has also been shown to be effective for treatment of PTSD, especially exposure therapies that involve processing memories of the traumatic event and also PTSD-oriented cognitive-behavioral therapy that helps patients develop more adaptive cognitive and emotional responses to their traumatic experience. Although both pharmacotherapy and psychotherapy are effective treatments for PTSD, the decision of which or both types of treatments to use will be based on patient preference and ability to devote time, effort, and resources to therapy as well as

availability of therapists skilled in these methods.

MDD is the "bread and butter" of psychiatric care, being one of the most common disorders presenting to psychiatric treatment settings as well as one of the most prevalent disorders in general populations. Therefore, it is not unexpected that MDD is also one of the main psychiatric disorders presenting in patients being treated for traumatic injuries. MDD may occur as a single episode in a person's life, but episodes of the illness tend to recur, and sometimes MDD may become a chronic or even lifelong condition. To be diagnosed by current American diagnostic criteria, a major depressive episode (MDE) must last ≥2 weeks with depressive symptoms occurring most of the day for most days and representing a change from the person's usual self [70]. The main symptoms defining a MDE are depressed or irritable mood and loss of interest or pleasure in usual activities. Other symptoms, including appetite and sleep disturbance and fatigue are physical, suggesting or sometimes even being confused with medical illness. Yet other symptoms are cognitive, including feelings of guilt and worthlessness, inability to concentrate, and slowed thinking. The episode must cause distress or impaired functioning and not be explained by another medical condition to qualify as MDE, and for a diagnosis of MDD, the episode cannot be part of a bipolar (manic/depressive) disorder. MDD not only causes substantial psychological suffering, but it can also cause profound functional disability. A severe complication can be death by suicide, which has been documented to occur in as many as 15% of patients with severe MDD [54].

Because MDD is often comorbid with PTSD in patients unfortunate enough to develop both disorders, it is fortuitous that the two FDA-approved medications for PTSD are also effective for the treatment of MDD. There are many different types of antidepressant medications demonstrated effective and FDA-approved for the treatment of MDD, and many effective types of psychotherapy [54]. Because none of these medications has been found to be more effective than the others, and all require weeks of adequate dosing for full beneficial effects, the choice of the particular agent is largely determined by the suitability of the side-effect profile given the patient's preferences and other medical and psychosocial issues [72]. Psychotherapy may also be effective in conjunction with antidepressant medication, or by itself especially for less severe depression. The main types of psychotherapy used for depression are cognitive and behavioral therapy, interpersonal therapy, psychodynamic or psychoanalytic therapy, and supportive therapy [73].

Substance (alcohol and drug) use disorders arise from behaviors related to repetitive consumption of large amounts of these substances over time [56, 57]. These disorders involve cognitive, behavioral, and physiological symptoms related to continued use of these substances in spite of serious physical, psychological, and social complications of their use. As time progresses, continued use of these substances can generate considerable medical and psychiatric morbidity and sometimes even leads to death. Clinical characteristics of SUDs include craving of the substance, tolerance, and withdrawal syndromes. In patients hospitalized for major trauma, serious withdrawal syndromes may emerge and medical detoxification may be needed. Alcohol withdrawal peaks on about the third day of abstinence, and withdrawal from very heavy and prolonged use can lead to delirious states, withdrawal seizures, and even delirium tremens. Heavy substance use can impede the assessment of other psychiatric disorders, for which diagnosis may not be possible until some time has elapsed after cessation of use.

A common feature of substance use disorders is rationalization of the use of alcohol and/or drugs as "self-medication" of unpleasant physical or emotional states. Many patients attribute their substance use to external sources of psychosocial difficulties such as interpersonal conflicts or financial difficulties. Rationalization of substance use is a well-recognized and very common part of the illness. For individuals facing significant medical challenges such as patients recovering from major traumatic injuries, their challenging situation may be a ready target for

attribution or rationalization of substance use. Physical pain from injuries may further motivate these patients to "self-medicate" with alcohol and/or drugs. Regardless of the source of these behaviors, treatment is appropriate. Patients may be more able to surmount stigma surrounding their substance abuse if they can frame it within the challenges of their situation and may be more willing to consider and accept treatment. Effective treatment, however, helps patients move from self-blame and from blaming external sources for their difficulties to acceptance of the substance use problem as a medical illness and assuming responsibility for establishing a course toward recovery.

As for PTSD and MDD, the mainstay of treatment for SUDs also includes both pharmacological and therapeutic approaches. SUDs are generally chronic, frequently relapsing disorders, although most relapses occur in the first year after initiation of treatment. Available treatments effective and a substantial proportion of patients have good long-term courses. Two FDA-approved pharmacologic agents with demonstrated treatment effectiveness for alcohol use disorder (AUD) are naltrexone and acamprosate. Psychosocial treatments include cognitive-behavioral therapies, 12-step group peer programs such as Alcoholic Anonymous that emphasize achievement of sobriety, family and social therapies, and a brief counseling technique known as motivational interviewing that addresses patient ambivalence toward change using principles of harm reduction rather than emphasizing total abstinence [74].

Some special aspects of psychiatric treatment in children deserve mention. An important principle of pediatric psychiatry is that how parents conduct themselves in challenging situations may substantially influence the child's emotional response to the situation, and conversely that the child's distress may also affect the parents' ability to function and effectively parent their child through difficult circumstances [61, 75]. Thus, family members such as parents or other caregivers are routinely included in psychiatric treatment of children. Most children are resilient even in the face of major difficulties such as traumatic injuries. Provision of emotional support is appropriate for all children, however, as almost all children can be expected to experience psychological distress after trauma. A useful intervention is the "normalization" of discussion and feelings about the traumatic incident [40, 61]. Children with intense emotional distress and/or psychiatric disorders may need formal treatment, including individual and family therapy and even pharmacotherapy for severe or disruptive symptoms. Pre-existing psychopathology such as ADHD may obscure diagnosis of other disorders and complicate post-injury psychiatric treatment. Importantly, not all psychopathology in children with traumatic injuries should be assumed to be caused by the trauma [62].

A few additional special psychiatric considerations that may emerge in the acute treatment of traumatic injuries. Psychotic disorders, substance use disorders, and personality disorders that may predispose to traumatic injury, especially burns, may complicate the treatment of the injuries, requiring specialized psychiatric care in coordination with the trauma treatment team [5]. Chronic pain is well known to be associated with psychiatric disorders, but certain disorders (SUDs, anxiety disorders, and MDD) frequently precede the development of the pain disorder; additionally, MDD also has a propensity to develop anew after the onset of pain [5, 76]. Regardless of the causal directions in these associations, pain management may be complicated by these psychiatric disorders. Brain matter lesions in patients with TBI may impair executive functioning and directly induce depressive and anxiety disorders and personality changes that may hinder functional recovery from injuries in both adults and children [16, 39]. Delirium may arise as a function of severe medical compromise following injury, creating difficult and hazardous behavioral aberrations requiring acute medical intervention.

Although research has demonstrated that psychiatric treatments are effective and that psychiatric illness is associated with less favorable medical and functional outcomes of traumatic injuries, studies with designs such as randomized controlled trials are needed to experimentally test

the effects of treatment of psychiatric disorders on these outcomes. At present, it can only be inferred that psychiatric treatment can potentially improve medical and functional outcomes based on non-experimental studies that are available, but there is every reason to believe that future research will demonstrate this benefit.

## 45.6 Conclusions

Mental health issues constitute a substantial source of interventions needed for patients receiving care for acute traumatic injuries, as most patients experience emotional distress, and substantial proportions have diagnosable psychiatric disorders. Patients with traumatic injuries have elevated risk for psychiatric illness, including disorders that newly develop during their post-injury course and pre-existing disorders that persist in the post-injury period and contribute risk for the injury that led the patient to treatment for it. Untreated psychiatric illness in these patients is associated with less satisfactory medical and functional outcomes, yet most patients with psychiatric illness go unrecognized and/or their illness is untreated. To address these problems that are inherent in the current fragmented systems of care, integrated multidisciplinary teams with dedicated psychiatric expertise are needed to ensure that psychiatric issues in these patients are properly recognized and addressed [40]. Well-designed studies are needed to demonstrate that appropriate psychiatric treatment can improve not only psychiatric outcomes, but also medical and functional outcomes with reduced length of recovery and cost of treatment—which may in turn encourage new initiatives to include specialty care within trauma treatment environments.

**Key Concepts**

- Psychiatric illness in patients receiving treatment for major traumatic injuries is greatly under-recognized and largely untreated.
- Psychiatric illness complicating treatment of major traumatic injuries must first be identified, and then linkage to appropriate psychiatric care is an important aspect of care for major traumatic injuries.
- Pre-existing, post-injury, and incident (new) psychiatric illness after major trauma are all important to the treatment of traumatic injuries, and each has a distinct role for contribution to exposure to trauma and recovery from traumatic injuries.
- Integrated multidisciplinary teams with dedicated psychiatric expertise are needed to ensure that psychiatric issues in patients with major traumatic injuries are properly recognized and addressed.

**Take Home Messages**

- Recovery from traumatic injuries may be complicated by psychiatric illness, which is further associated with impaired physical healing, general health, functioning, employment, and quality of life.
- About half of patients receiving care for major traumatic injuries will experience psychiatric illness during their recovery.
- Few patients with psychiatric illness present during treatment for major traumatic injuries are identified, and most do not receive psychiatric treatment.
- Brief self-report psychiatric symptom tools are available for identification of patients with increased risk for psychiatric illness complicating treatment of major traumatic injuries, and systematic application of these tools will identify patients needing diagnostic evaluation and possibly treatment for psychiatric illness.
- Psychiatric treatment is effective and may not only reduce psychiatric suffering but also improve medical and functional outcomes of treatment for major traumatic injuries.

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# Rehabilitation: Long-Term Outcome and Quality of Life

# 46

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**Learning Objectives**

After reading this chapter, the reader should be familiar with:

- Levels of evidence and how they are structured.
- Outcome measures and how they can be reported.
- Significance of patients lost to follow-up.
- Role of validity and statistical significance in clinical practice.
- Factors contributing to quality of life in a patient with upper and/or lower extremity injury.

## 46.1 Introduction

Well-designed clinical research remains necessary in order to critically evaluate the quality of orthopedic trauma care and to advance the field of orthopedic trauma surgery. Recently, evidence-based medicine has provided valuable insights into clinical research and has emphasized the significance of thoughtful study designs and the importance of a critical appraisal of the orthopedic literature. In particular, with the growing body of the orthopedic trauma literature, it is becoming increasingly important for clinicians and researchers to critically evaluate the available literature, to recognize strengths and weaknesses of study designs, and to interpret study results within the clinical context. When assessing orthopedic trauma outcome studies, important questions to ask include:

1. What is the validity of the presented outcome data?
2. What are the numerical results of the outcomes reported?
3. What are the implications for the clinical practice?

In this chapter, these fundamental questions will be discussed in the context of the orthopedic trauma outcome literature. Furthermore, this chapter will summarize the results of the most pertinent outcome studies in the field of orthope-

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dic trauma and emphasize the lessons learned from these studies.

## 46.2 Validity of Outcome Data

When assessing the validity of an orthopedic outcome study, the most pertinent question is whether the study represents an unbiased estimation of treatment outcomes. Bias (or systematic error) is typically linked to the study design and execution of a study. Important variables when assessing the validity of orthopedic trauma outcome data include the following:

1. Level of evidence
2. Outcome measures used
3. Patient follow-up

## 46.3 Level of Evidence

Evidence-based medicine has recently gained significant prominence in the field of orthopedic surgery as well as in other areas of medicine. Numerous manuscripts and textbooks in this field have been published and a detailed review of all evidence-based medicine principles is beyond the scope of this book chapter. One of the key aspects of evidence-based medicine is the introduction of a hierarchical rating system for the level of evidence whereby the level of evidence is grading the quality of the overall study design. In this context, a higher level of evidence suggests a lower risk of bias. Most rating systems for the level of evidence of therapeutic studies (i.e., the majority of orthopedic trauma outcome studies) use a five-level scale including level 1 (randomized clinical trial), level 2 (prospective cohort study or poor quality randomized clinical trial), level 3 (case control study), level 4 (case series), level 5 (expert opinion) [1, 2] (Fig. 46.1). For instance, the Journal of Bone and Joint Surgery uses a five-level scale for prognostic, diagnostic, therapeutic, and economic studies (Table 46.1). Most major orthopedic journals have adapted this five-level hierarchical rating system and grade the published articles accordingly [3].

When assessing the clinical impact of outcome studies, the hierarchical grading system for the level of evidence plays an important role. While this rating system provides the reader with important information on potential bias, the level of evidence should also be used cautiously. First, the level of evidence only provides an overall assessment of the study design and further critical assessment of the study methods and study results is necessary. Second, randomized clinical trials (RCTs) are not always possible for each clinical scenario in particular in the orthopedic trauma population. For instance, the Lower Extremity Assessment Project (LEAP) was designed to evaluate the outcomes of mangled lower extremity injuries to assess lower limb amputation versus salvage [4, 5].This well-designed study was performed in a non-randomized fashion as randomizing patients with mangled lower extremities into limb salvage versus amputation would not appear feasible [4, 5]. Although RCTs are powerful studies, they are expensive, time consuming, and often face difficulty in adequate enrollment. Thus, large non-randomized observational studies have been promoted as an alternative to RCTs. However, even in high powered observational studies, residual confounding variables cannot be eliminated and effects from treatment may be misleading and incorrect [6]. Therefore, it is imperative that randomization is implemented when feasible and quality RCTs are not replaced. Finally, it must be emphasized that no single study can provide a definitive answer to a study question. Clinical treatment algorithms in orthopedic trauma should be based on a composite assessment of the entire literature and should consider all levels of evidence from level 1 (RCT) to level 5 (expert opinion). According to Scheschuk et al. [7] level 4 studies, which are in the lower end of the hierarchy of evidence, have remained the most prevalent level of evidence used in orthopedic trauma literature up to 2013.

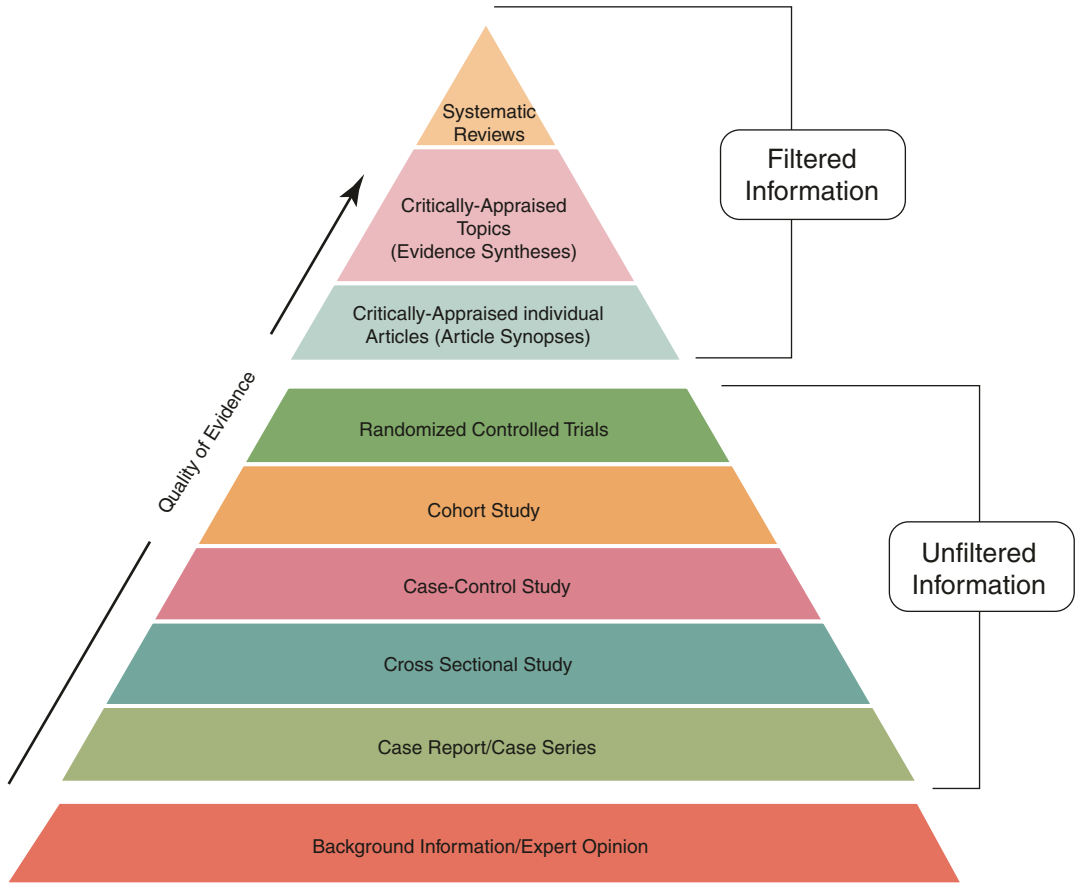


**Fig. 46.1** Hierarchy of evidence. (Reprinted with permission from: Desai, V. S., Camp, C. L., & Krych, A. J. (2019). What Is the Hierarchy of Clinical Evidence? Basic Methods Handbook for Clinical Orthopaedic Research, 11–22. doi:10.1007/978-3-662-58254-1_2)

## 46.4 Outcome Measures

The type of outcome measure is another important variable when assessing the validity of an orthopedic trauma outcome study. In the orthopedic trauma literature, numerous outcomes scoring systems have been used [8]. In general, outcome measures can be divided into clinician-based, performance-based, and patient-reported outcome measures. Standardized outcome measures may focus on general health, body region-specific function, or disease-specific function. As of today, no general recommendations exist as to which outcome measures should be used in orthopedic trauma outcome studies. Well-designed outcome studies provide outcome data on the patient's general health in addition to a body region- or disease-specific questionnaire. When using more than one outcome measure, it is crucial to identify the main outcome measure of the study. The main outcome measure should be according to the main hypothesis that is being tested in the study. Another important consideration is whether the used outcome measure has been validated in prior investigations. An outcome instrument is considered valid if it truly measures what it is supposed to measure. In this context, it is important to emphasize that validation of an outcome measure is not an "all or nothing" concept and validity has several components (e.g., face validity, criterion validity, construct validity, content validity, etc.). A detailed discussion of outcome measure validation procedures is beyond the scope of this chapter. In general, the

**Table 46.1** Level of evidence

| Study type | Diagnostic—investigating a diagnostic test | Prognostic—investigating the effect of a patient characteristic on the outcome of the disease | Therapeutic—investigating the results of a treatment | Economic |
|---|---|---|---|---|
| Question | Is this (early detection) worthwhile? Is this diagnostic or monitoring test accurate? | What is the natural history of the condition? | Does this treatment help? What are the harms? | Does the intervention offer good value for dollars spent? |
| Level I | • Randomized controlled trial | • Inception cohort study | • Randomized controlled trial | Computer simulation model (Monte Carlo simulation, Markov model) with inputs derived from Level-I studies, lifetime time duration, outcomes expressed in dollars, per quality-adjusted life years (QALYs) and uncertainty examined using probabilistic sensitivity analyses |
| | • Testing of previously developed diagnostic criteria (consecutive patients with consistently applied reference standard and blinding) | | | |
| Level II | • Development of diagnostic criteria (consecutive patients with consistently applied reference standard and blinding) | • Prospective cohort study | • Prospective cohort study | Computer simulation, model (Monte Carlo simulation, Markov model) with inputs derived from Level-II studies, lifetime time duration, outcomes expressed in dollars, per (QALYs) and uncertainty examined using probabilistic sensitivity analyses |
| | • Prospective cohort study | • Control arm of randomized trial | • Observational study with dramatic effect | |
| Level III | • Retrospective cohort study | • Retrospective cohort study | • Retrospective cohort study | Computer simulation model (Monte Carlo simulation. Markov model) with inputs derived from Level-III studies, lifetime time duration, outcomes expressed in dollars, per (QALYs) and uncertainty examined using probabilistic sensitivity analyses |
| | • Case-control study | • Case-control study | • Case-control study | |
| | • Nonconsecutive patients | | | |
| | • No consistently applied reference standard | | | |
| Level IV | • Case series | • Case series | • Case series | Decision tree over the short time horizon with input data from original Level-II and -III studies and uncertainty by examined univariate sensitivity analyses |
| | • Poor or nonindependent reference standard | • Historically controlled study | | |
| Level V | • Mechanism-based reasoning | • Mechanism-based reasoning | • Mechanism-based reasoning | Decision tree over the short time horizon with input data informed by prior economic evaluation and uncertainty is examined by univariate sensitivity analyses |

*Reprinted from Marx RG, Wilson SM, Swiontkowski MF. Updating the assignment of levels of evidence. J Bone Joint Surg Am. 2015;97(1):1–2*

Studies may be downgraded on the basis of study quality, imprecision, indirectness, or inconsistency between studies or because the effect size is very small (i.e., a high-quality randomized controlled trial (RCT) should have ‡80% follow-up, blinding, and proper randomization). A systematic review is ranked based on the level of evidence of studies included in the review

validity of an outcome measure is typically established by comparison between the tested outcome measure and an established outcome instrument (i.e., reference standard). For instance, validation studies used the Medical Outcomes Study 36-Item Short Form (SF-36), a well-established and validated measure of health status, as a reference to test the validity of the Short musculoskeletal function assessment (SMFA) questionnaire, which has shown to be a valid tool to assess functioning in trauma patients [9].

It is suggested that patient-reported outcomes in orthopedic trauma should use at least two standardized instruments: One to assess health-related quality of life and the other to assess disabilities specifically related to their condition [10]. As of today, the SF-36 is one of the most commonly employed outcome instruments in orthopedic trauma surgery as well as in orthopedic surgery in general [11]. The SF-36 is a patient-reported measure of the overall patient's quality of life. It consists of 36 items and the questionnaire can be completed within 5–10 min. It has been validated and used in numerous studies within the field of orthopedic surgery as well as in other fields of medicine [12–19]. The SF-36 also allows the comparison of outcomes with normative population data from age- and sex-matched controls. Moreover, the SF-36 has been translated and validated in multiple languages and international normative data have been recorded. Despite these favorable characteristics, the SF-36 also has some limitations that can affect the interpretation of outcome data. First, the items of the SF-36 tend to focus more on lower extremity function than on upper extremity function [20]. This emphasizes the importance of including a body region-specific questionnaire along with a general health questionnaire when performing clinical outcome research in orthopedic trauma. Yet, the SF-36 does not incorporate certain basic quality of life domains, such as sexual function or sleep. In some instances, this may lead to the scenario that improvements as well as diminishments in these areas may go undetected. For example, patients undergoing treatment of pelvic fractures may frequently be impaired by sexual dysfunction and recording of SF-36 data may be limited by "ceiling effects" as well as "floor effects."

Patient-reported outcomes have become increasingly popular and continue to be a critical element in the orthopedic literature. Within orthopedics, various patient-reported outcomes have been validated and collectively referred to as legacy measures. However, a majority of these legacy measures are specific to certain conditions, with multiple being used for the same anatomic locations limiting the comparison of results in different studies. In 2004, the NIH established the Roadmap for Medical Research in order to develop a reliable clinical research infrastructure with the aim of translational benefits for patients [21]. Within this program, the Patient-Reported Outcomes Measurement Information System (PROMIS) was born in an effort to provide reliable, valid, standardized measures of key symptoms and health domains applicable to a range of chronic conditions and has been used extensively in many fields of healthcare [21]. A major limiting factor in these outcome measures is the length of test and number of questions causing user fatigue [22]. PROMIS may be administered as a computer adaptive test which selects subsequent questions based on the examinee's answers allowing for a more refined, quicker test [23]. Morgan et al. [24] in a study of 47 patients with proximal humerus fractures demonstrated moderate to high correlation of PROMIS with legacy measures (DASH, sMFA, Constant Shoulder score). Furthermore, they found reduced administrative burden of the PROMIS as compared with all legacy measures and a reduced ceiling effect compared with sMFA and the DASH scores.

Multiple studies have suggested that PROMIS is a reliable measure, however there is a paucity of its utilization in the current literature. In 2016, the Quality Outcomes Data Work Group from the American Academy of Orthopaedic Surgeons Board of Directors recommended the use of PROMIS Global Health as a measure of general quality of life in orthopedic patients [25]. As this instrument is incorporated in more orthopedic populations, there will likely be a greater emphasis on this particular outcome measure.

Besides the assessment of clinical limitations, healthcare utilization and treatment costs represent important outcome measures when evaluating the efficiency of orthopedic trauma care. In this context it is important to emphasize that most importantly treatment should be rendered according to what is best for the patient. However, in the treatment of patients with musculoskeletal injuries, the orthopedic trauma surgeon is also mandated to make fiscally sound decisions since cost-efficient treatment is above all in the best interest of the injured patient. The question of cost effectiveness becomes specifically important in areas of complex surgeries and when the effectiveness of treatment remains uncertain. In the orthopedic trauma literature, a frequently discussed topic is the cost effectiveness of limb salvage versus amputation in patients with mangled lower extremities. A more detailed discussion on the clinical aspects of this topic will be provided later in the chapter "Outcome after Lower Extremity Injuries." As of today, the question of limb salvage versus amputation remains controversial and the multiple medical, social, and economical aspects need to be considered when discussing treatment plans with the injured patient. In brief, patients with mangled lower extremities face the situation that attempted limb salvage may offer them the undoubted benefits of keeping their lower limb. In order to achieve this favorable result, these patients may undergo several reconstructive surgical procedures and repeat hospitalizations with the remaining risk of requiring amputation at a later time point. In contrast, primary amputation may offer the potential benefits of quicker discharge from the hospital, earlier ambulation after prosthesis fitting is completed, and earlier return to work. For these reasons, the medical outcomes of limb salvage versus amputation need to be assessed carefully and this sensitive issue needs to be discussed thoroughly with the patients and their families. Importantly, the financial aspects of treatment have to be included in this discussion as it is clearly in the patient's best interest to be educated about the costs that will incur from medical treatment, hospitalizations, time away from work, as well as lifetime costs from ongoing prostheses needs. Recent investigations have focused on cost utility analyses of amputation versus limb salvage in patients with mangled lower extremities emphasizing the importance of costs as a critical outcome measure [26]. Finally, the use of uniform measurement tools would help improve the quality and comparability of research on patient-reported outcomes, and measures of trauma-specific outcomes would improve the study of long-term injury outcomes.

## 46.5 Patient Follow-Up

A critical assessment of study data also requires a careful evaluation of the clinical follow-up that was obtained in the study presented. In an outcome study reporting on patients' recoveries after treatment of extremity injuries, the presented study data may be flawed if subjects who received treatment are not included in the data analysis due to lack of follow-up data. This lack of outcome data may both overestimate and underestimate the benefit of treatment effects depending on the outcome of patients not returning for follow-up. Hypothetically, "best case scenarios" and "worst case scenarios" could occur. Thus, patients who did not recover well from their injuries may be upset about their outcome and chose to receive follow-up treatment at a different institution ("I am upset. I am not going back"). If a large number of these patients do not get enrolled in the outcome analysis, the recorded outcomes may be better than the actual real outcomes that have been achieved with the treatment rendered. Vice versa, patients who achieved an excellent recovery potentially may decide to skip their follow-up since they may not feel the necessity to seek any further evaluations ("I feel fine, why bother?"). If a large number of these patients do not get enrolled in the outcome analysis, the recorded outcomes may be worse than the actual real outcomes of the treatment rendered. For these reasons, any remarkable loss of follow-up carries the risk of skewing the study data and a critical assessment of the study data needs to include the assessment of the loss of follow-up.

Current guidelines of major orthopedic journals request that any randomized controlled trial with more than 20% loss of follow-up should be downgraded from an evidence level 1 to an evidence level 2 study [3]. However, these recommendations are based on traditional postulations and it remains unclear how much loss of follow-up can be considered as acceptable. Recent statistical models using trauma databases have pointed out that even less than 20% loss of follow-up may frequently yield in a significant change of study results [27]. In addition, different risk factors such as male gender, smoking status, illicit drug abuse, and lack of health insurance have been associated with noncompliance and loss of follow-up [28]. For these reasons, authors of orthopedic trauma outcome studies should not only report their loss of follow-up but should also report which specific attempts were made to minimize loss of follow-up. Also, an attempt should be made to record the data available on those patients who did not comply with their final follow-up examinations.

Besides the loss of follow-up, orthopedic trauma outcome studies need to be assessed for their length of follow-up. Patients with extremity injuries go through different phases in their rehabilitation process. Along the different phases of the recovery process, different outcome variables can be recorded. In the preoperative period, measuring serum lactic acid can be useful in identifying patients who may require early monitoring and treatment, even if they do not present any clinical symptom, improving in-hospital morbidity and mortality [29]. The immediate postoperative period provides information on early complications, such as surgical site infections, mortality rates, thromboembolic events, and length of hospital stay. Within the first few months after surgery further information, such as fracture healing, return to activities of daily living and return to work, can be recorded. Furthermore, long-term outcome studies provide valuable information on the functional recovery, health-related quality of life, as well as the incidence of posttraumatic arthritis and the need for late reconstructive procedures. Many guidelines have recommended 2-year outcome evaluations for patients with extremity injuries. However, these postulations have recently been challenged.

In patients with mangled lower extremities, comparisons between 1-year follow-up data and 2-year follow-up data have shown that 1-year follow-up data provide sufficient information to test the pertinent study hypotheses while creating significantly less costs than 2-year follow-up evaluations [30]. Current recommendations from the major orthopedic trauma journal request 6 months of follow-up for pure soft tissue injuries, 1-year patients follow-up for fracture care, and 2-year follow-up data for treatment of arthritic conditions (http://journals.lww.com/jorthotrauma). These issues emphasize the significant implications of the length of follow-up as an important variable for assessing the validity of outcome data. The length of follow-up provides valuable information as to which specific outcome measures can be addressed in outcome studies on patients with extremity injuries.

## 46.6 Numerical Results

The numerical results of clinical studies should be scrutinized carefully in order to make appropriate conclusions for the clinical practice. When reviewing the results of orthopedic trauma outcome studies, pertinent questions include the following:

1. How large was the treatment effect?
2. How precise was the estimate of the treatment effect?
3. What is the statistical significance?
4. Is the decline or improvement clinically relevant?

## 46.7 Size of Treatment Effect

With regard to the size of the treatment effect, it is important to distinguish if the main outcome measure was a continuous variable (e.g., SF-36 scores ranging from 0 to 100) or a dichotomous variable (fracture union versus fracture non-union). For dichotomous variables, several

measures of treatment effect size exist. These include odds ratios, relative risk, relative risk reduction, absolute risk reduction, and numbers needed to treat.

In the orthopedic trauma literature, odds ratios are frequently used to measure treatment effects. The odds ratio is a measure of the association between a factor and an outcome. The odds ratio calculates the odds that a particular outcome will occur in association with a particular factor as compared to the odds of the outcome occurring in the absence of this particular factor. An odds ratio of 1.0 means that the evaluated risk factor does not increase the risk of the recorded outcome. Odds ratio >1.0 indicates that the analyzed factor is a risk factor, and odds ratio <1.0 indicates a protective factor. For example, an odds ratio of 1.5 means that the evaluated factor increases the odds of the outcome to occur by 50%, which is a risk factor. Odds ratios are typically used in case control studies and in logistic regression models.

Another frequently used measure for the size of the treatment effect in the orthopedic trauma literature is the relative risk reduction. The relative risk reduction plays an important role in the reporting of treatment effects that are observed in prospective controlled trials. The relative risk reduction is expressed as a percentage. A risk reduction of 50% means that treatment A reduces the risk of a particular outcome by 50% as compared to treatment B.

## 46.8 Precision of the Estimated Treatment Effect

It is important to realize that the measures of the size of the treatment effect, such as the odds ratio and the relative risk reduction, are point estimates and further information is required in order to measure the precision of these estimates. The confidence interval is the range within which the true treatment effect falls and provides important information on the precision of the estimated size of the treatment effect. By convention, the 95% confidence interval is used to measure the precision of a point estimate. Thus, a 95% confidence interval means that if the same study was repeated, there was a 95% chance that the estimated treatment effect would fall within this interval again. The 95% confidence interval largely depends on the sample size. With larger sample sizes, the estimated treatment effects become more precise and the 95% confidence interval becomes smaller. Thus, the clinician can be more confident that the true treatment effect is close to the treatment effect recorded in the outcome study. Vice versa, studies with smaller sample sizes typically result in larger 95% confidence intervals and with large confidence intervals, the clinician may remain uncertain where the true treatment effect lies.

## 46.9 Statistical Significance

The $p$ value provides another measure for the precision of the results. The $p$ value provides the probability of an α-error. An α-error means that a study observes a difference between two study groups when in fact there is no difference. By convention, a cut-off $p$ value of 0.05 is used in most clinical studies. Thus, a $p < 0.05$ means that there is less than 5% chance of recording a difference between two study groups when in fact there is no difference between these two groups.

Typically, the $p$ value is given great importance by authors, journals, and clinicians. Thus, a common perception is that reported differences are real whenever there is statistical significance, whereas reported differences supposedly are irrelevant when the data is not statistically significant. However, there are several issues with this viewpoint; there has been a recent trend to de-emphasize the importance of the $p$ value [31]. As stated above, the $p$ value only provides information on the size of an α-error and it does not provide any information on the size of the treatment effect. In addition, the 0.05 cut-off is arbitrary and in many scenarios changing only very few events may sometimes change the results from statistically significant to non-significant and vice versa (e.g., sample size). For this reason, it has been suggested by journal editors to avoid stating "significantly different," but rather providing the exact $p$ value [31]. Moreover, some

trauma outcome studies [32–34] have been criticized for artificially creating statistically significant results by deviating from the main hypothesis and performing multiple subgroup analyses with multiple repeat testing procedures that ultimately may yield *p* values that fall below 0.05 [35]. However, the implications of "statistically significant results" stemming from multiple repeat testing procedures remain questionable since repeat testing naturally increases the likelihood of finding at some point, a *p* value of less than 0.05 just by chance alone. For these reasons, the interpretation of "statistically significant" versus "statistically non-significant" results should be performed in a cautious fashion. In the interpretation of orthopedic trauma outcome data, it remains important to review all numerical results including not only the *p* value, but also the size of the treatment effect as well as the confidence intervals.

## 46.10 Implications for the Clinical Practice

When interpreting the outcomes of patients with extremity injuries, the foremost question remains how the results can be applied to clinical practice. In order to put an outcome study into a clinical context, it is important to consider several factors including the distinction between statistical significance and clinical significance, the inclusion criteria, the outcome measures used, and the study endpoints.

The distinction between "statistically significant" and "clinically significant" is an important concept. Sometimes, results presented are statistically significant, but the clinical significance of the detected difference remains questionable. For instance, a recently published level 2 study on surgical reconstruction of the anterior cruciate ligament compared the outcomes of two different reconstruction techniques [36]. These authors reported that the postoperative side-to-side difference for anterior tibial translation was significantly higher in one treatment group with a reported p value of 0.001. A closer look at the reported outcomes revealed that one group had a side-to-side difference for anterior tibial translation of 2.2 mm as compared to 1.1 mm in the other group. While statistically significant, these results raise the question if a 1-mm difference for anterior tibial translation represents a clinically significant finding since it can be assumed that most knee surgeons may not be able to clinically detect a 1 mm difference for anterior tibial translation. Moreover, the pertinent question remains if a 1 mm difference of anterior tibial translation results in a remarkable improvement of the patient's perceived health-related quality of life. Thus, in patients with extremity injuries, the results should always be scrutinized carefully in order to assess if the detected difference is not only statistically significant, but also clinically significant.

The inclusion criteria of an outcome study play an important role with regard to the implications for the clinical practice. It is important to be aware which particular patient population was enrolled in the study and recommendations can only be made for this particular type of patient population. For instance, a recently published randomized controlled trial suggested that primary arthrodesis of Lisfranc injuries results in superior outcomes as compared to open reduction and internal fixation [37]. However, these authors only included ligamentous Lisfranc injuries. In addition, patients with associated other orthopedic injuries were excluded from the study, as well. Moreover, patients with co-morbidities, such as diabetes, peripheral vascular disease, or rheumatoid arthritis were also excluded from this study. Thus, the patient population enrolled in this trial was very specific and probably different from most Lisfranc injuries that typically present to level 1 trauma centers as a result of high energy injuries when associated injuries and co-morbidities are common. Another example would be the investigations performed in the field of mangled lower extremity injuries (LEAP) [4, 5]. These investigations have been performed in civilian trauma patients. In contrast, combat injuries in soldiers represent a completely different scenario regarding the mechanisms of injury (blast injuries versus high speed motorized vehicle collisions) differences in immediate care,

rehabilitation resources, and access to the best prosthetics available to military personnel [38]. Mitchell et al. demonstrated in a study of 155 military patients with severe combat related upper extremity injuries no difference in reported outcomes between limb salvage and those undergoing amputations [39]. Therefore, one must be careful when extrapolating outcome data from civilian patients with mangled lower extremities to combat injuries in soldiers.

The used outcome measures also play an important role when putting outcome data of patients with extremity injuries into a clinical context. Thus, orthopedic outcome studies may frequently focus on fracture union as their main outcome measure which certainly appears appropriate since surgical treatment in orthopedic trauma typically aims at restoring fracture union. However, this may not allow for any definitive conclusions on patient satisfaction, functional outcomes, associated complications, or the need for re-operation. For instance, a well-designed randomized controlled trial investigated the differences of reamed versus non-reamed nailing in patients with tibial shaft fractures [40]. The authors reported that for most parts the outcomes were equivocal. However, there appeared to be a significantly higher rate of required nail dynamization in the non-reamed group. While this outcome suggested superior results in the reamed group, the authors emphasized that the need for nail dynamization was an outcome measure of lower importance and thus, appropriately moderated their conclusions and recommendations.

The clinical implications of an orthopedic trauma outcome study also strongly depend on the study endpoints. As stated above, patients with extremity injuries go through different stages of recovery. Along the recovery process, different variables become of interest at different time points. Thus, in the early perioperative period, early postoperative complications, length of hospital stay, and mortality rates are typically recorded, and important information can be gained during this phase. Within the first few months after surgery, the rates of successful fracture unions and return to daily activities and work can be recorded efficiently. Long-term outcome studies provide important information on health-related quality of life and late complications from treatment, such as posttraumatic arthritis and the need for late reconstructive procedures.

When extracting clinical implications from outcome studies, it is important to recognize which study endpoints were chosen. For instance, a hypothetical clinical study comparing the non-union rates between operative versus nonoperative treatment of clavicle mid-shaft fractures may use fracture union as an appropriate endpoint of the study. This may provide clinically important information on the union rates and the rate of required subsequent non-union surgeries following treatment of clavicle fractures. However, when using this information in the clinical setting, it is important to be aware that the study endpoint "fracture union" may not serve as a good source of information for questions about late adverse events, such as the need for hardware removal due to prominent hardware, etc. For these reasons, the study endpoints predict which specific clinical implications can be concluded from outcome studies in patients with extremity injuries.

## 46.11 Outcome After Lower Extremity Injuries

Multiple outcome studies in patients with lower extremity injuries have been performed over the last decades. Given the large spectrum of lower extremity fractures and the numerous treatment options, a detailed review of the outcomes of specific fractures or specific treatment options is far beyond the scope of this chapter. The goal of this chapter is to summarize the results of the most pertinent lower extremity outcome studies. Specifically, this review is focused on polytrauma patients with associated lower extremity injuries and patients with mangled lower extremities.

Over the last decades, improved preclinical and clinical emergency care has decreased the mortality and complication rates of polytrauma patients [41, 42]. Given the increased survival rates, the long-term functional outcome and patient satisfaction have gained importance in polytrauma care.

It has been shown by several investigations that the incidence of lower extremity injuries has a significant impact on the functional recovery of patients after polytrauma [43–47]. Pape et al. reinvestigated the social and medical aspects in patients 10 years post-trauma, demonstrating the worst outcomes in 30–44-year old's, several factors (anatomical location, physiologic response, insurance status, trauma mechanism) playing a major role. Moreover, those who regained complete social rehabilitation had better outcomes than expected [48].

The Hannover Rehab Study has provided important information on the long-term recovery of polytrauma patients [49–58]. Clinical outcome data with a minimum follow-up of years after polytrauma were recorded in this investigation. Detailed data analyses including binary logistic regressions from this study have suggested traumatic amputations and severe spine injuries to be significant independent predictors of poor long-term functional recovery after polytrauma [50]. In addition, it was recorded that patients with lower extremity injuries do significantly worse than patients with upper extremity injuries [50].

The Hannover Rehab Study also revealed that patients with injuries below the knee joint seem to be significantly limited in their functional recovery as compared to patients with lower extremity injuries above the knee joint [57]. The reasons for this phenomenon remain unclear. However, it can be assumed that the relatively thin soft tissue envelope surrounding the foot and ankle as well as the unfavorable distal circulation may contribute to this problem. Moreover, injuries below the knee joint include a large variety of complex fracture patterns, such as tibial plateau fractures, pilon fractures, talus fractures, and calcaneus fractures, which are also challenging to address from the reconstructive standpoint.

In polytrauma patients, injuries to the lower extremities frequently present themselves as mangled lower extremities with significant associated injuries to the surrounding skin, muscles, and neurovascular structures. These injuries frequently require multiple surgical reconstructions and the predominant question remains whether patients will benefit from limb salvage versus amputation. Ellington et al. utilized the Sickness Impact Profile (SIP) score to measure the outcomes in patients treated with standard BKA (below the knee amputation) compared to salvage requiring free flap or ankle arthrodesis. The SIP score is a self-reported health status questionnaire involving mobility, ambulation, emotional behavior, social interaction, alertness behavior, communication, body care and movement, eating, sleep and rest, home management, recreation, and work. A greater degree of disability is reported with a higher SIP score. Demonstrating worse SIP outcomes in those who required free tissue transfer or ankle arthrodesis, in contrast to those treated with BKA with typical skin flap closure [59].

The Lower Extremity Assessment Project (LEAP) study was initiated with the goal to provide answers to this challenging question [4, 5]. The study was performed at eight level 1 trauma centers in North America and represents a milestone in orthopedic trauma outcome research. A focused summary of the LEAP study will be provided in the following section.

The study focused on patients with severely mangled lower extremity injuries including (1) traumatic amputations; (2) grade 3A open tibia fractures with high degree of nerve, muscle, or bone injury; (3) grade 3B and 3C open tibia fractures; (4) vascular injuries below the distal femur; (5) major soft tissue injuries below the distal femur; (6) grade 3 open pilon fractures; (7) grade 3B open ankle fractures; and (8) severe open hindfoot and midfoot injuries. The rendered treatment of these patients was according to the treating surgeon and the study was performed prospectively, but in a non-randomized fashion. A total of 601 patients were enrolled in this study and the investigators recorded 7-year follow-up data on most patients.

Bosse et al. reported the outcomes of patients undergoing limb salvage versus amputation [60]. At 2 years after injury, there was no significant difference in the outcome scores between the two treatment groups. In both treatment groups, self-efficacy and social support were found to be significant predictors of the functional outcome. Predictors of poor functional outcomes included

the incidence of major complications, lower educational level, nonwhite race, low income, lack of health insurance, smoking, and involved litigations. Patients who underwent surgical reconstruction were also significantly more likely to have a secondary re-hospitalization.

Further cohort analyses of the LEAP study data focused on comparing the outcomes of patients with above knee amputation versus knee disarticulation versus below knee amputation [61]. Patients treated with above knee amputation showed no significantly different outcome scores than patients with below knee amputations. However, patients with amputations below the knee joint showed faster walking speeds. Patients with knee disarticulations had significantly worse outcomes than patients with above or below knee amputations.

A widely used indication for amputation in patients with mangled lower extremities has been the absence of plantar sensation. The LEAP study also investigated the outcomes of patients with absent plantar sensation [62]. This cohort analysis included 29 patients with initially absent plantar sensation who underwent limb salvage. In this cohort, only one patient continued to have absent plantar sensation at 2 years after trauma. The remaining 28 patient showed partial or even full recovery of their plantar sensation. Moreover, patients with initially absent plantar sensation showed no significantly worse functional outcome scores than patients with initially present plantar sensation. Therefore, the LEAP study refuted the widely held belief that absent plantar sensation should be used as a definitive indication for amputation in patients with mangled lower extremities.

The LEAP study also provided important descriptive data on the overall complication rates in patients with mangled lower extremities [63]. In patients undergoing amputation, the revision amputation rate was 5.4% and the overall complication rate was approximately 25%. In patients undergoing limb salvage, approximately 4% required a secondary amputation and the overall complication rate in this cohort was approximately 40%. This data represents useful information for preoperative patient counselling and patients undergoing limb salvage need to be educated that they are at high risk for complications, re-hospitalization, as well as secondary amputation.

As indicated above, healthcare utilization and treatment costs must be considered important outcome measures in patients with extremity injuries. This question was also addressed in the LEAP study [64]. The cost calculations included hospitalizations, rehabilitation, outpatient visits and therapy, purchase, and maintenance of prosthetic devices. At 2 years, limb salvage appeared to be associated with slightly higher costs than amputation ($91,106 versus $81,316). However, the projected lifetime costs appeared more than three times higher in the amputation group ($509,275 versus $163,282) which was mostly driven by the required renewal of lower extremity prosthetics. Thus, the LEAP study refuted an additional widely held belief, which is the assumption that amputation is a cheaper solution over limb salvage.

In addition, the LEAP study provided important information on the long-term recovery using 7-year follow-up data [65]. It was found that a total of 58% of patients with mangled lower extremities had returned to work at 7 years after trauma. Approximately 25% of patients experienced some degree of limitation with regard to performing their work. There was no significant difference between patients with amputation versus limb salvage. However, factors predicting a successful return to work included younger age, white race, higher education level, non-smoker, high self-efficacy, pre-injury tenure, and absence of litigation.

In summary, the LEAP study has provided a wealth of useful data that may guide the surgeon in counselling the patient. However, it appears that despite the tremendous efforts made by the investigators, the pertinent question remains which patients will benefit from limb salvage versus amputation. Moreover, it appears that the main outcome predictors, such as self-efficacy, age, race, education level, smoking, pre-injury employment, and litigations, cannot be controlled by the surgeon.

## 46.12 Outcome After Upper Extremity Injuries

As stated above, injuries to the upper extremity appear to cause fewer limitations in the functional recovery process of polytrauma patients than injuries to the lower extremity [50]. Moreover, the functional recovery of polytrauma patients with upper extremity injuries has gained little attention in the literature and most reports have focused on the outcomes of patients with specific upper extremity injuries. Data from patients with severe upper extremity injuries have suggested that associated brachial plexus injuries significantly limit the functional recovery of patients with severe upper extremity injuries [66, 67]. Further investigations in polytrauma survivors showed that approximately 50% of patients with shoulder girdle injuries continued to have functional impairments at 5 years after trauma [45]. Displaced and articular fractures were identified to be associated with long-term disability. Moreover, 45% of patients with shoulder girdle injuries and 62% of patients with upper extremity fractures complained of chronic pain [45].

Further data on the long-term functional recovery of polytrauma patients with upper extremity injuries has been provided by the Hannover Rehab Study [68]. At approximately 18 years follow-up, polytrauma patients with upper extremity injuries showed significant limitations from their upper extremity injuries with regard to range of motion, muscle weakness, and neurologic impairment. In particular, the combination of associated shaft and articular upper extremity injuries seemed to significantly impact the long-term functional recovery. Thus, decreased range of motion, joint contractures, and muscle weakness were significantly more common in patients with combined articular and shaft injuries as compared to patients with isolated shaft fractures or isolated articular fractures. These data indicate that multiple upper extremity injuries provide significant challenges from the reconstructive and the rehabilitation standpoint.

## 46.13 Conclusions

The functional long-term outcomes in polytrauma patients requires a critical evaluation of the available literature. Lower extremity fractures seem to significantly impact the functional recovery of polytrauma patients. In particular, fractures below the knee joint seem to be associated with significant long-term disability. With regard to limb salvage versus amputation, main outcome predictors such as self-efficacy, age, race, education level, smoking, pre-injury employment, and litigations seem to have a significant impact on outcome regardless of the surgical treatment rendered. It remains important to use valid and reliable patient-reported outcomes measures in orthopedic trauma patient populations in order to improve the study of long-term functional outcomes in these patients.

**Key Concepts**

- Research studies are rated by levels of evidence based on the quality of their overall study design. A higher level of evidence suggests lower risk of bias.
- Outcome measures need to identify their main outcome, be reliable and validated with an established outcome instrument.
- Loss of follow-up and length of follow-up function as important variables when assessing the validity of outcome data. Male gender, smoking status, illicit drug abuse, and lack of health insurance are associated with noncompliance and loss of follow-up. Major orthopedic journals request 6 months of follow-up for pure soft tissue injuries, 1-year patients follow-up for fracture care, and 2-year follow-up data for treatment of arthritic conditions.

- Differentiation between statistical and clinical significance must be assessed in order to provide relevant and clinically important information.
- Self-efficacy, age, race, education level, smoking, pre-injury employment, and litigations serve as main outcome predictors for patients with lower extremity injuries.
- Injury to the brachial plexus as well as combined articular and shaft injuries significantly limit the functional recovery of patients with upper extremity injuries.

**Take Home Messages**

- Standardized outcome measures such as the SF-36 became a reliable instrument and are frequently implement in orthopedic surgery. Patient-reported outcomes measures have been recommended by the American Academy of Orthopaedic Surgeons Board of Directors as a measure of general quality of life in orthopedic patients and should be incorporated in orthopedic populations.
- Despite the fact that limb salvage versus amputation remains at issue, according to the LEAP study there is no significant difference between the aforementioned and a decision must be made on a case-by-case basis. Main outcome predictors cannot be controlled by the surgeon, therefore patients who will undergo limb salvage have to understand the high risk for complications, re-hospitalizations as well as secondary amputations.

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# Correction to: Preclinical Management/Rescue

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The original version of this chapter was published with errors; the authors' surnames and forenames are inadvertently swapped. The names have been updated with this erratum. Further, the affiliations are also updated. The correct names and affiliations are given below:

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