Skeletal Reconstruction

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30.1 Introduction

In 2015, the National Consortium for the Study of Terrorism and Responses to Terrorism found that over 35,000 people were injured and 28,000 killed in over 11,000 blast or firearm related terrorist attacks worldwide [1]. Much of our current understanding on how to treat these injuries has come from the lessons learned during military conflicts and terrorist attacks.

As seen in several epidemiologic studies worldwide, the extremities are most commonly injured. While 45–65% of these injuries are soft tissue injuries that may be treated as an outpatient, they frequently have devastating orthopaedic related injuries that can require urgent surgical management due to the degree of soft tissue damage or bone loss [2–5].

30.2 Injury Characteristics and Challenges

When evaluating a penetrating ballistic wound on the battlefield or in the hospital setting, the amount of energy transferred at the time of injury must be considered in order to avoid underestimating the corresponding zone of injury. The degree of energy imparted on the superficial and deep soft tissues is often a surrogate of the weapon or type of offending agent as described in greater detail in Chaps. 2, 3, 4 and 5.

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The degree of injury can often be underestimated due to small visible entrance wounds despite a devastating underlying soft tissue or bony injury. As such, clinical assessment must be focused on determining the degree of contamination, concomitant abdominal injury or bowel perforation, possible vascular injury, type of weapon, whether high velocity or low velocity, and proximity to the blast origin as these will dictate operative and reconstructive measures.

In those injuries requiring operative intervention, definitive bony reconstruction cannot begin until there is a healthy tissue bed. This may require temporary skeletal stabilization but will certainly require thorough excision of all heavily contaminated and non-viable tissue. Furthermore, in those penetrating injuries where the zone of injury is not immediately apparent, repeated assessment in the operating theatre with further tissue excision if required as described in Chap. 21.

Special attention should also be paid to penetrating abdominal and pelvic injuries where the projectile crosses the abdominal viscera as these injuries are at high risk of requiring repeated surgical treatment or systemic antibiotics due to bowel content contamination of a fracture site or joint as shown in Fig. 30.1. Retrospective studies have shown up to a four times higher infection rate when a bowel injury has occurred from a gunshot wound and concomitant fracture [6, 7].

Peri-articular injuries often have severe cartilage loss and/or bony defects that can complicate the final reconstructive options due to the need for additional bony or

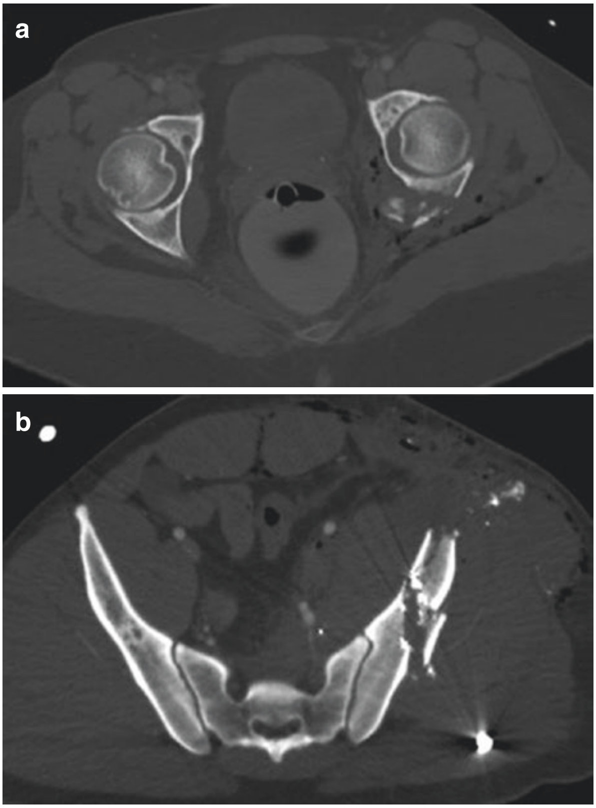

Fig. 30.1 A posterior column fracture (**a**) and a fracture of the ilium (**b**) are shown. Both did not require operative fixation, but did undergo exploratory laparotomy due to associated bowel injuries

implant augmentation. Intraarticular fragments should be excised either arthroscopically or through an arthrotomy, if required, in order to diminish the likelihood of plumbism and the mechanical effects to the cartilaginous surfaces (Fig. 30.2) [8, 9].

A high rate of vascular injuries have been seen in battlefield blunt and penetrating extremity trauma as described in Chap. 21. These injuries often play a vital role in determining the role of damage control orthopaedic principles and final reconstructive options. If immediate definitive vascular repair is not feasible, temporary shunting with a Javid or Argyle shunt can be placed to restore distal blood flow. These repairs often require the addition of a temporary external fixator placed during the initial operative intervention in order to protect the vascular repair. This can subsequently be converted to definitive fixation when the vascular repair has been deemed successful. Alternatively, if definitive fixation can occur expeditiously, i.e. tibial intramedullary nailing, and the bone and soft tissue injury is amenable, it can occur immediately prior to the vascular reconstruction.

Ballistic and blast injuries are often associated with critical bone loss. This is defined as the smallest defect in a specific bone which does not heal spontaneously,

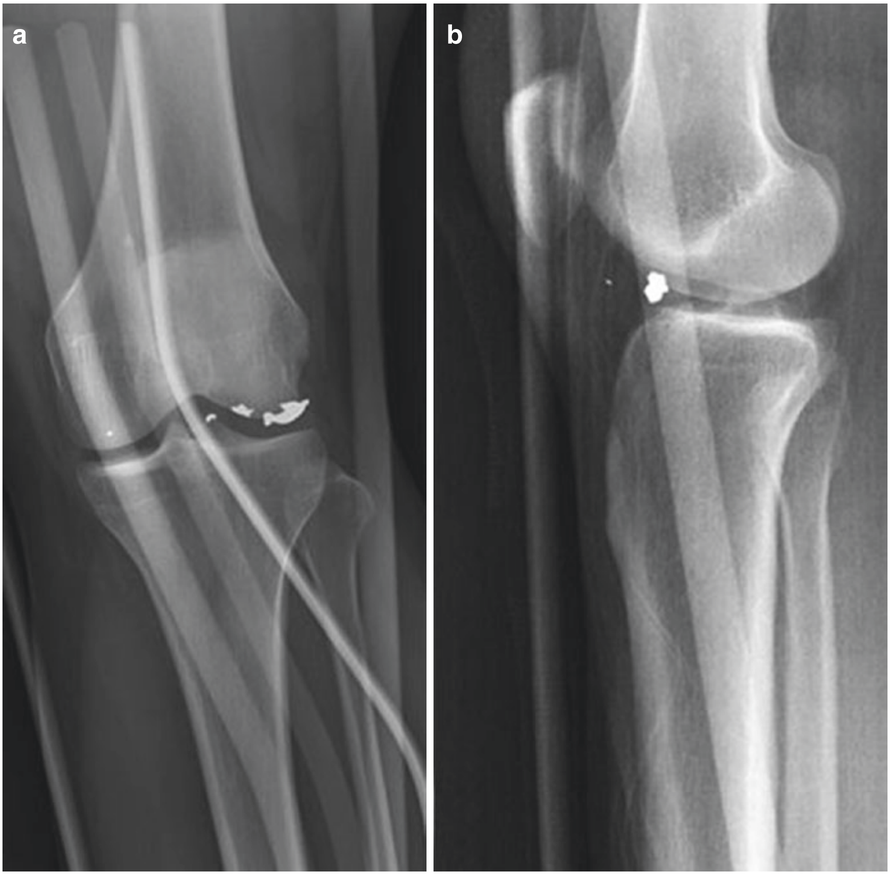

Fig. 30.2 AP (**a**) and Lateral (**b**) X-rays are shown demonstrating intra-articular fragments following a low-velocity gunshot wound

Fig. 30.3 Following debridement after a high-velocity ballistic injury, this patient was left with a 6 cm segmental defect of the tibia

which is often 2–3 times the diameter of the involved bone (Fig. 30.3) [10–13]. These defects will frequently require various temporary stabilization techniques, bony and soft tissue augmentation, and/or concomitant nerve and vascular reconstruction. As such, these devastating injuries require a multidisciplinary approach, are associated with a prolonged treatment course, and are often wrought with complications. Ultimately, the patient must understand that the acute treatment course and subsequent recovery process is not linear and that there are often late, unanticipated complications. It is important that this is discussed early to assist with managing the patient's expectations so that they can begin to recognize that their recovery may have a long, protracted course.

30.3 Immediate Assessment and Care

30.3.1 Pre-Hospital

Immediate prehospital care should consist of patient stabilization and transportation to an appropriately equipped medical treatment facility. Initial focus should be on saving life and normally following ballistic trauma this is focused on controlling haemorrhage as is discussed in detail in Chap. 8.

The role of splinting in the prehospital setting cannot be understated as it can prevent additional tissue damage and bleeding while assisting with pain control. There should be a low threshold for pelvic stabilization with an appropriate binder (e.g. Sam Sling®) if the patient has been close to an explosion or it there is clinical suspicion of a pelvic fracture. Rapidly applied, non-circumferential temporary splints (e.g. SAM splint) and non-invasive extremity traction (e.g. Kendrick Traction Device®, Buck's Traction splint®) should be considered in unstable fracture patterns. The immediate use systemic antibiotics in open fractures is mandatory [14].

30.3.2 Imaging

Upon arrival to the hospital, appropriate trauma and life-support guidelines should be initiated to appropriately evaluate and treat the patient to include pelvic imaging. Ideally, if there is suspicion of a pelvic injury CT imaging should be performed. If initial imaging occurs when a pelvic binder is *in situ* and is negative, it should be repeated when the patient is stable when the patient is stable following pelvic binder removal.

In the setting of extremity ballistic and blast injuries, the entire extremity, to include the joints above and below the level of injury, should be fully imaged in orthogonal planes using plain radiography. Penetrating wounds should be marked with a radio-opaque marker.

In cases of an intra-articular injury, CT imaging should be performed of the involved extremity in order to determine the extent of articular comminution and to guide further surgical reconstructive interventions. The treating surgeon should consider that in the setting of damage control orthopaedics, delaying CT of an intra-articular fracture until after reduction and temporary stablisation might yield greater information for planning the definitive fixation procedure. Furthermore, CT angiography or a formal angiogram may be indicated in cases of suspected vascular injury.

30.3.3 Antibiotics

Multiple studies have elaborated on the role of early systemic antibiotic administration, wound debridement and early soft tissue coverage in decreasing the risk of infection in high-energy orthopaedic trauma. Low velocity ballistic wounds not requiring operative stabilization may be treated by a short course of oral antibiotics and local wound care without an increase in infection risks [15–17].

In those injuries where severe comminution or osseous defects occur, typically from high velocity ballistic injuries, early systemic and local antibiotics should be considered. Antibiotic impregnated absorbable carriers (e.g. calcium sulfate, antibiotic powders, etc.) should be considered in wounds that can be definitively closed to further deter infectious complications [18, 19]. Furthermore, in cases where a large defect remains and future reconstructive procedures will be attempted non-absorbable antibiotic carriers such as Poly-Methylmethacrylate (PMMA) should be considered to allow the local bacterial control while providing dead-space management and further soft-tissue healing.

Topical negative pressure wound dressings with or without silver augmentation should be considered in all cases in at risk wounds or to assist with temporization in patients not ready for definitive management [20–22]. Locally administered antibiotics via antibiotic beads, absorbable chitosan sponges, or directly applied antibiotic powders should also be considered to further augment negative pressure wound therapy as these have all be shown to effectively decrease local bacteria in contaminated wounds [18–20, 23].

While a first generation cephalosporin is commonly recommended for ballistic injuries, special consideration should be given in the management of fractures with a concomitant bowel injury as the literature suggests that the use of broad-spectrum antibiotics administered for 48–72 h are optimal for minimizing the risk of infection [15].

30.4 Initial Surgical Management

It is important to note that not all ballistic injuries require operative stabilization or bony reconstruction. The literature has demonstrated that low velocity ballistic injuries can be safely managed with local debridement and irrigation, tetanus prophylxais when required, and antibiotics followed by splinting or casting as long as an adequate reduction can be obtained and maintained (Fig. 30.4) [24]. However,

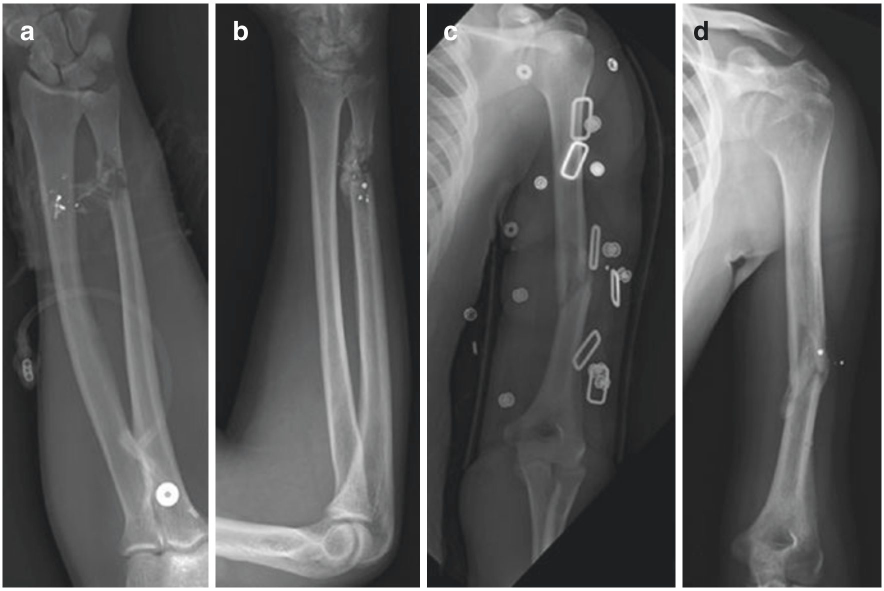

Fig. 30.4 A low velocity ballistic injury to the ulna (**a**) and humerus (**c**) went on to union (**b** and **d**) without the need for surgical intervention

for those fractures caused by low velocity ballistic injuries that are unstable or whose reductions cannot be maintained, they can often safely be managed with acute definitive operative fixation and stabilization if patient factors allow.

In a patient *in extremis*, the principles of damage control orthopaedics should be followed and temporary stabilization via external fixation performed with consideration of future operative plans. Studies have shown that definitive intramedullary nailing and open reduction and internal fixation can occur in the setting of severe open lower extremity fractures without an increase in infection rates provided concurrent wounds are closed or covered with viable soft-tissue [25]. As such, if soft tissues allow, all attempts should be made to definitively stabilize the fractures. In those cases where soft tissues are tenuous, repeated debridement and irrigation is indicated, or soft tissue coverage is required, an external fixator is often applied that can be later converted to definitive fixation.

Dead space management can be obtained using non-absorbable antibiotic carriers such as PMMA beads [18]. Soft tissue approximation should proceed as soft tissues allow using monofilament sutures. Negative pressure wound dressings, progressive soft tissue closure techniques (e.g. Jacob's ladder) and negative pressure wound therapy can assist with non-closable or at-risk wounds.

The surgeon should maintain a low threshold to perform fasciotomies in high energy ballistic or blast injuries as compartment syndrome is a well-documented complication [26]. Furthermore, in the setting of a vascular insult or prolonged tourniquet times, fasciotomies should be considered due to the concern for a reperfusion induced compartment syndrome. When performed, fasciotomies should be progressively closed or grafted with a split-thickness-skin graft. Dermal substitutes and acellular dermal matrices can further assist in cases of exposed tendinous or bone structures prior to skin grafting when further soft tissue coverage cannot reasonably occur [27, 28].

30.5 Definitive Fixation

When discussing management of the high-velocity ballistic injury to an extremity, it is important to consider the tenets of the limb salvage process. Internal fixation should only occur at the time of or after the soft tissue wounds have been closed or covered. Implants should never be used if wound closure is not possible.

Definitive fixation can only occur if the patient and the limb have been appropriately prepared:

1. Resuscitation of the patient: physiological stabilization is required, if this cannot be achieved due to the extent of the injury, amputation should be considered.
2. Resuscitation of the wound: Thorough irrigation and debridement, stabilization of the bone, and liberal use of fasciotomies when indicated.
3. Secondary management: Reassessment of the wound with continued debridement of nonviable tissue. There is a continued emphasis on the prevention of infection to include the management of soft tissue defects and dead space

management. Through each subsequent operative intervention, the patient should be one step closer to definitive reconstruction.

4. Definitive management: This period is marked by stabilization of the patient's general health status as well as limb injury evolution. This definitive phase involves reconstruction of bone and soft tissues using a variety of techniques.

It is important to note that the patient with an isolated extremity injury from a low velocity projectile with no associated vascular injury may progress rapidly to definitive management if the patient, bone and soft tissues are amenable.

There are three principle methods of skeletal stabilization in the treatment of ballistic injuries requiring operative stabilization.

1. Plates
2. Intramedullary Interlocking Nails
3. External Fixation

30.5.1 Plates

Plates can be applied to perform various functions such as compression, protection (neutralization), buttress, tension band, or bridging. Depending on the technique used, the plates can function to provide either absolute or relative fracture stability. Due to advances in modern nailing, open reduction and internal fixation with traditional plating systems is commonly reserved for upper extremity fractures and periarticular fractures of the lower extremity.

Plates are commonly used for the management of upper extremity fractures (Fig. 30.5) due to the need to obtain anatomic reductions, i.e. radius and ulna fractures. They also have the advantage of providing optimal fixation for very short proximal or distal bone fractures, i.e. periarticular injuries, where intramedullary implants may not be able to provide adequate fixation.

Through traditional plate osteosynthesis, a significant surgical exposure is often required to anatomically reduced and stabilize the bone. Variations to these approaches such as minimally invasive approaches can be used to minimize the soft tissue injury incurred using traditional approaches. Furthermore, due to the degree of soft injury and zone of injury sustained from high-energy ballistic trauma, unconventional surgical exposures may be required to allow for appropriate debridement and irrigation and successful fracture fixation. Standard surgical exposures can be used for low-velocity ballistic fractures, when a surgical debridement and irrigation of the projectile path or cavity is not necessary. In high-velocity injuries, where a surgical debridement and irrigation is recommended, the wounds are extended to allow thorough debridement of all nonviable tissue. Since these wounds are often not along traditional surgical soft tissue planes, they may necessitate alternative surgical approaches as to not cause further soft tissue damage.

While many ballistic injuries are amenable to compression plating and absolute stability, which allows primary bone healing, injuries with extensive comminution or bone loss may require bridge plating (Fig. 30.5). The application of a bridge plate

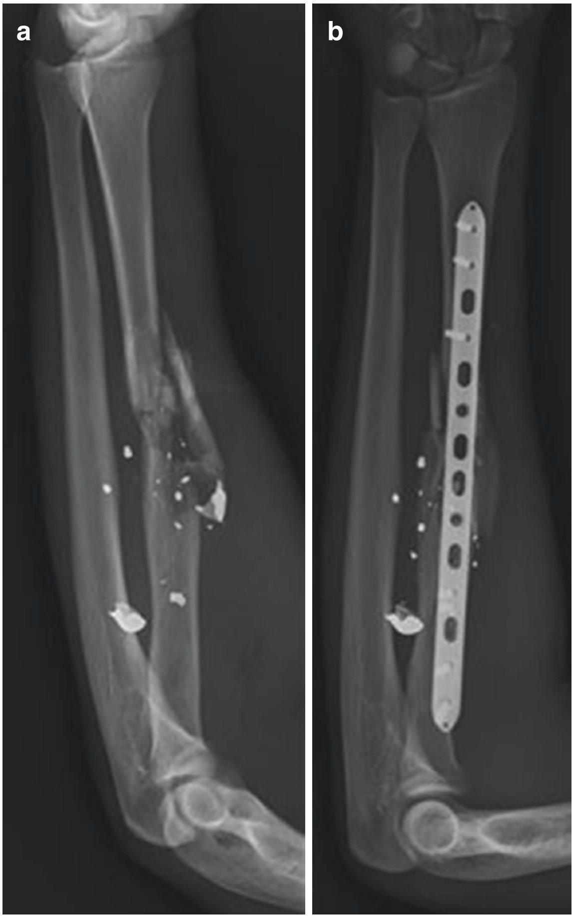

Fig. 30.5 A low velocity ballistic injury to the radius resulting in shortening and loss of radial bow (**a**) was treated with bridge plating to restore length and alignment (**b**)

spans the comminution or area of bone loss creating a relative stability construct, which will heal through secondary bone healing and subsequent callus formation.

30.5.2 Intramedullary Nails

Modern intramedullary nails (reamed with interlocking bolts) have the significant advantage of offering satisfactory biomechanical stability to allow early weight bearing. In addition to the ability to often allow early, if not immediate, weight-bearing following fixation with an intramedullary nail, these intramedullary implants are also ideal for the management of tibia fractures where delayed union is more common.

Intramedullary nails offer several additional benefits. It is a familiar technique to most orthopaedic surgeons and minimizes soft tissue dissection, which can be beneficial in an extremity that already has a significant amount of soft tissue injury due to the ballistic injury. One concern for the use of an intramedullary nail in the setting

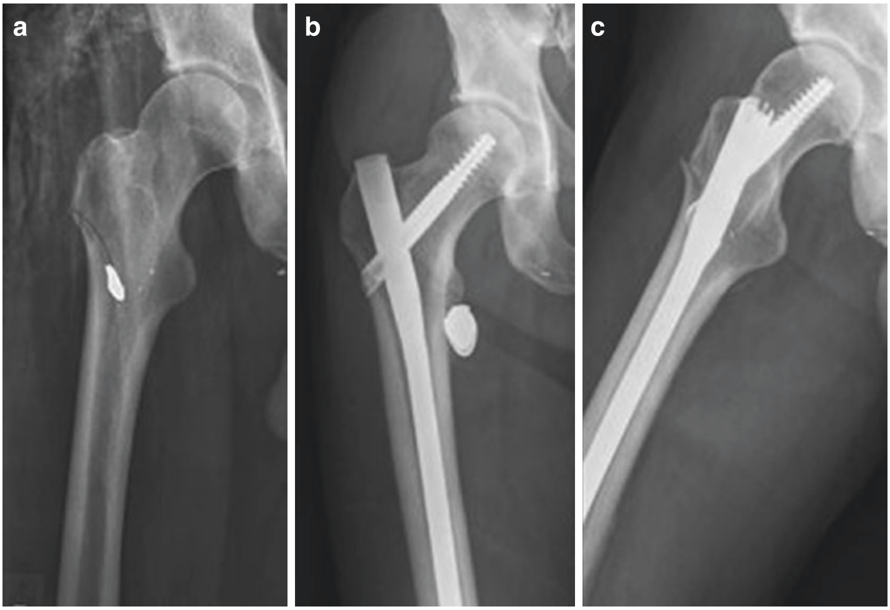

Fig. 30.6 After a low-velocity ballistic injury causing a *right* intertrochanteric hip fracture (**a**), the hip was stabilized with a cephalomedullary nail (**b** and **c**)

of ballistic or open fractures is the risk of infections and difficulty treating it should one occur with an intramedullary implant. However, the literature suggests that they can be safely used in these injuries, although as the severity of injury increases, so does the risk of infection [29–32].

For low-velocity injuries requiring operative stabilization amenable to an intramedullary nail, the fracture can be treated similar to a closed injury without the need for a surgical debridement and irrigation of the soft tissue wound (Fig. 30.6) [29]. For high-velocity injuries, a surgical debridement and irrigation should be performed of the wound, which is often followed with temporary external fixation depending on the extent of the soft tissue injury. Definitive fixation can occur once the soft tissues are amenable.

30.5.3 External Fixation

External fixation is versatile and can provide rapid and safe stabilization of severe open fractures, whether from high-velocity or low-velocity ballistic injuries [33]. They can be used to restore limb length and alignment and can provide adequate bony stability while allowing access to the wound for vascular or plastic surgery if needed.

The goal of temporary external fixation is restoration of length and general alignment without concern for achieving anatomic reduction (Fig. 30.7). It avoids unnecessary trauma to the tissues and can be performed rapidly. When placing a

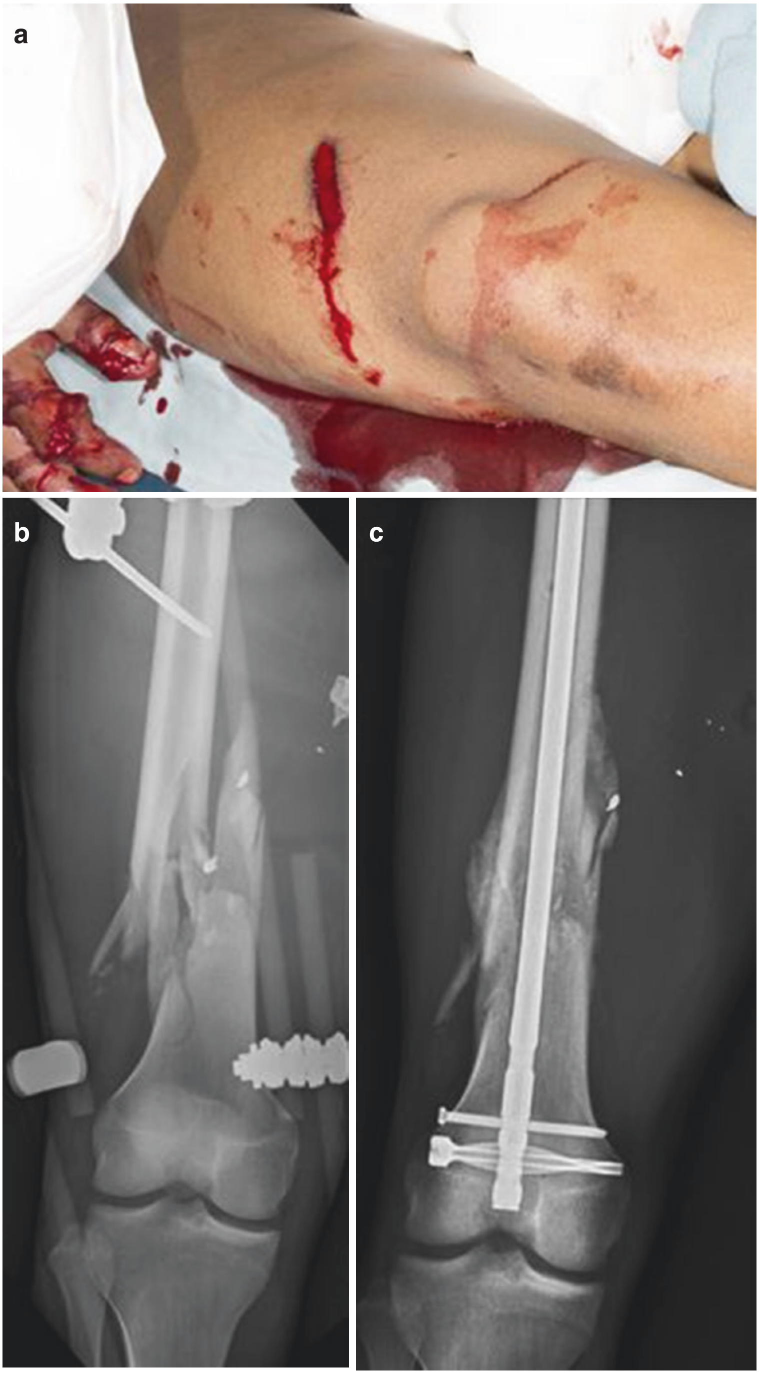

Fig. 30.7 This patient sustained multiple ballistic injuries to his chest and abdomen in addition to his *right* thigh (**a**) and presented to the hospital hemodynamically unstable. As a result, he underwent temporary external fixation of his *right* femur fracture (**b**) and was converted to definitive intramedullary nail 1 week later (**c**, shown healed)

temporary external fixator, it is important to try and keep Schanz/half pins out of the zone of injury, and when possible, distant to any planed definitive fixation. However, pin-plate overlap has not been demonstrated in the literature to increase the risk of infection [34]. Due to decreased stability with uni-planer frames, ringed fixation is commonly used for definitive management in an external fixator. Good results have been achieved using this method in the management of severe open tibia fractures in both the military and civilian setting. When temporary external fixation is used, it is ideal to convert to the definitive method of fixation within 2 weeks if using plates or an intramedullary nail in order to decrease complication and infection rates [35, 36].

An additional benefit to the use of ringed external fixation is the ability to manage both the bone and soft tissue injuries. For injuries that have both segmental bone and soft tissue loss, an acute shortening (Fig. 30.8) or a shortening and angulation can be performed [37–39]. In other cases, the limb can be deformed at the fracture site to achieve wound closure. If there is segmental bone and soft tissue loss, to include a neurovascular injury, the limb can be shortened to allow end to end repair of the neurovascular structures. Once epithelial healing begins, length can be restored through distraction osteogenesis via a distant corticotomy. When performing these procedures, care is taken to ensure adequate

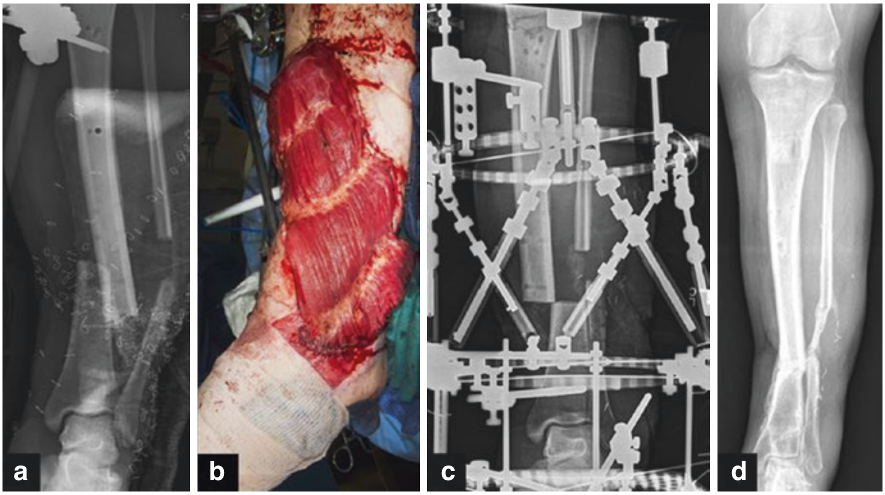

Fig. 30.8 An AP radiograph of a severe open lower extremity fracture with significant bone loss that underwent acute shortening (**a**), which was performed in conjunction with a free flap (**b**) due to the combined bone and soft tissue loss. Distraction osteogenesis was then performed with a ringed external fixator (**c**) to achieve restoration of limb length and alignment (**d**)

limb perfusion is maintained throughout the process with the use of a Doppler. Any change in the quantity (number of audible vessels) or quality (diphasic, triphasic) of the signal requires modification followed by reassessment of the signal.

30.6 Special Considerations: Bone Loss

Bone loss can occur acutely following ballistic injuries, particularly in the setting of a high-velocity injury. It can also occur as a result of the complications following the initial management of these injuries. For example, if a patient develops an infected nonunion, infected or nonviable bone may need to be debrided resulting in subsequent bone loss (Fig. 30.9). There are critical size bony defects that require additional treatment strategies because they will not heal independently—commonly referred to as segmental defects. They are frequently managed by the following two methods: (1) Masquelet Technique/Induced Membranes and (2) Distraction Osteogenesis.

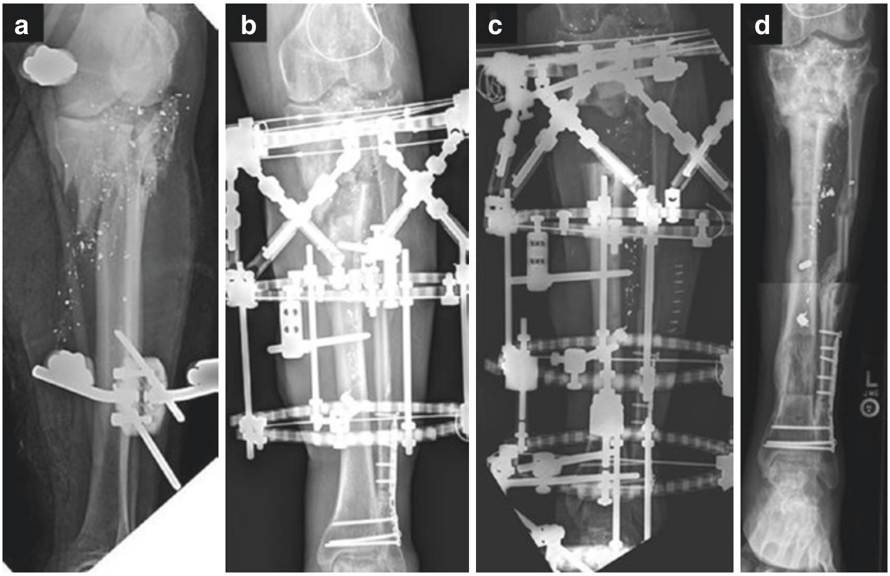

Fig. 30.9 After a high-velocity ballistic injury causing a devastating intra-articular proximal tibia fracture (**a**), the patient went on to develop an infected nonunion (**b**). His frame was modified to perform distraction osteogenesis after 5 cm of necrotic bone was excised from his proximal tibia (**c**) and eventually went on to union (**d**)

30.6.1 Masquelet Technique/Induced Membranes

In patients with a segmental defect and a stable fracture following fixation, the defect is filled with PMMA, typically loaded with an antibiotic to help minimize the risk of infection. Four to 12 weeks later, the membrane is incised and the PMMA is removed [40]. The timing for performing the bone grafting is important. Historically, it was done between 10 and 12 weeks after initial placement of the PMMA spacer; however, recent evidence suggest that the growth factors within the induced membrane that forms around the PMMA spacer are at their optimal levels at 4 weeks [41].

Care is taken not to disrupt the membrane that has formed around the PMMA other than enough to remove the PMMA. The bone ends are prepared to ensure that they remain viable with healthy bone bleeding and autograft is placed within the defect and the wound is closed. The choice of the autograft is up to the treating surgeon as there are many options to consider, including: the iliac crest (posterior or anterior), the femoral canal via use of the Reamer-Irrigator-Aspirator (RIA), or the proximal tibia. Quantity of bone required, location of the defect, and surgeon experience are all factors that can influence the choice. Alternatively, allograft bone graft and bone graft substitutes can be used, but autograft is considered the gold standard. As a result, they are commonly used as bone graft extenders rather than in isolation.

30.6.2 Distraction Osteogenesis

Distraction Osteogenesis refers to the tension-stress model where slow steady stress, or in this case distraction, causes the bone and soft tissues to become metabolically active, which results in a controlled bone growth. In order to perform distraction osteogenesis an implant must be used that can also ‘grow’. These commonly include ringed or mono-lateral rail external fixators. In the setting of a segmental defect, the fixator is applied to stabilize the limb. A distant corticotomy is performed, usually in the metadiaphyseal region of the bone due to the regenerative characteristics of this region (Fig. 30.10). After a short latency period, the segment where the corticotomy was performed is lengthened at a rate of 1 mm per day and the segment where the defect is located is shortened at the same rate. As a result, the defect is closed as new bone and soft tissue are regenerated at the distant site. This continues until the defect is closed and limb length has been restored [42, 43].

If an acute shortening was performed initially, where bony contact is achieved without a segmental defect, then the distant site is distracted until limb length is restored. If there was shortening and/or angulation performed, the deformity can be corrected gradually through the use of a ringed external fixator once soft tissue healing occurs followed by lengthening if required.

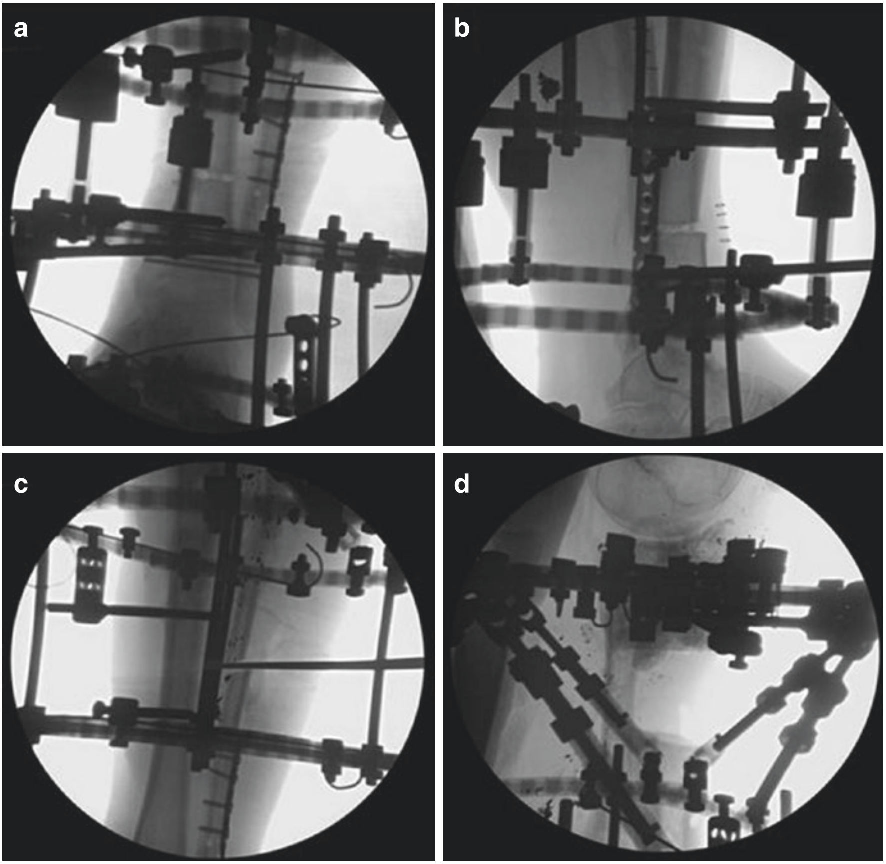

Fig. 30.10 A corticotomy was performed in the metadiaphyseal region of the distal tibia (**a** and **b**). A corticotomy must also be performed of the fibula to allow distraction, but this is done at a distant site (**c**). This will allow the *middle* segment of the tibia to be transported into the large defect (**d**) while bone regenerates distally

Conclusion

There is a wide spectrum of bone and soft tissue damage that can occur as a result of ballistic injuries. It is important to treat each one individually as the treatment may vary depending on multiple factors, the most important being the patient's physiologic status. For the definitive management of all fractures, there are a variety of techniques that are possible. The choice of one technique over the other depends on the individual surgeon's clinical experience and technical expertise.

Conflict of Interest The views/opinions expressed in this presentation do not reflect the views/opinions of the United States Government, the Department of Defense, or the U.S. Army.

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