Challenges in definitive fracture management of blast injuries

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Abstract The United States military remains engaged in the longest armed conflict in this nation's history. The majority of casualties in the global war on terror come from blast-related injuries. Multiple centers have published their experience and outcomes with these complex patients. Findings from the study of injured military personnel have implications for mass casualty events resulting from industrial accidents or terrorism in the civilian sector. This article will review the pathophysiology of blast-related injury. The authors will summarize treatment considerations, priorities, and techniques that have proven successful. Finally, the authors will discuss the incidence and management of common complications after blast-related injuries.

Keywords Blast-related injuries · Mass casualty events · Terrorism

Introduction

With the advent of industrialized warfare, there has been a steady increase in explosion-related injuries. Today, explosives, particularly improvised explosive devices (IEDs), account for roughly 80 % of combat injuries and deaths [1]. Explosives produce systemic polytrauma across multiple

body systems by simultaneous mechanisms. As such, they are clinically distinct from routine, single-mechanism trauma. Compared with penetrating injuries, blast-injured patients have more associated injuries, higher injury severity scores, and longer ICU and overall hospital stays [2]. This complex array of blast, ballistic, blunt, crush, and thermal injuries must be thoroughly understood to maximize patient outcomes.

The physics and effects of blast injuries have been described in detail elsewhere and will only be briefly summarized here [3]. Explosions result from the rapid conversion to a liquid or solid into a gas with violent energy release. The injury pattern depends on several factors: the shape, composition, and orientation of the explosive device; the distance from the detonation; whether the explosion happened in an open or closed space; and the protective equipment (vehicles or body armor) between the patient and the blast. Based on detonation velocity, explosives are classified as high or low order. The different orders exhibit distinct injury patterns and involve different treatment considerations.

High-order explosives include nitrogen-based fertilizers, industrially manufactured explosives like TNT, C4, or Semtex, and military munitions. They react very quickly, resulting in a supersonic, superheated pressure wave that moves (and can propel objects) at ballistic speeds between 3000–8000 m/s. The leading edge of this wave, called the blast front, can turn corners and reflect off walls with a shattering effect known as brisance. Near the explosion, the blast front produces traumatic amputation, evisceration, and sometimes immediate death. The pressure wave also causes barotrauma in air-filled cavities like the ear, sinus, lung, and bowel, as well as cellular injury to the central nervous system. These are collectively known as primary blast effects. They are more severe in close proximity to the blast, or when the blast occurs in an enclosed space. Farther away, fragments moving at ballistic speeds cause severe penetrating injury

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(secondary effects), usually over a wide distribution. Impact injuries occur from the body being propelled against solid objects or vice-versa (tertiary effects), and burns occur from primary or secondary combustion (quaternary effects). Low-order explosives like gunpowder, petroleum-based products, and the detonation fuses of most improvised explosive devices usually have a subsonic blast wave (<2000 m/s). They cause injury through secondary, tertiary, and sometimes quaternary effects. Low-order explosive casualties generally lack primary blast effects and are more similar to conventional community trauma.

This review will summarize current recommendations on acute blast wound treatment. The authors will discuss fracture and soft tissue management considerations unique to this condition. Finally, the authors will review the common complications found after such injuries and their outcomes.

Initial management

Urgent care for the blast-injured casualty includes resuscitation along standard Adherence to Advanced Trauma Life Support (ATLS) protocols. ATLS principles and early antibiotic administration occur in parallel with damage control resuscitation (1:1:1 ratio packed red cells (PRBC):fresh frozen plasma (FFP):platelets) and early initiation of massive transfusion protocols. These patients tend to be more severely injured, and they have a higher incidence of acute traumatic coagulopathy [4•]. To improve survival, steps should be taken to diagnose (by rotational thromboelastometry or clinical criteria) and address this condition [5, 6••]. Strong consideration should be given to use of tranexamic acid and measures to minimize hypothermia.

Patients very close to the explosion, or those with high-order explosive injuries, will sustain effects from brisance. They frequently present in extremis, with traumatic extremity amputations, poorly controlled junctional zone bleeding at the groin or axilla, unstable major long bone and pelvic fractures, and intra-abdominal injuries. Preparation begins with early notification of the trauma and anesthesia teams, as well as notification the laboratory and operating room personnel. Upon arrival, these patients require aggressive, highly organized care. It is critical to obtain early airway control and central venous access. Beyond screening radiographs, choose imaging studies based on patient stability. Pursue CT scanning only if hemorrhage is controlled and the patient responds to resuscitation or if there are lateralizing neurological signs such as hemianopsia, hemiplegia, or hemiparesis. Next, the patient moves rapidly to the operating room. There, after determining the presence of rectal injury and need for fecal diversion, multidisciplinary teams work simultaneously to control hemorrhage and perform thorough debridement, followed by pelvic/extremity external fixation. Tailor all surgical activity to the

patient's hemodynamic response. It is not unusual to operate for a limited time, transfer the patient to the ICU for resuscitation, then return to the operating room to finish surgical procedures. Summaries of the military experience with complex dismounted blast casualties provide a strategy for managing these challenging, resource-intensive patients [7, 8••].

Wound management

Initial care of the injured extremity includes immediate administration of antibiotics and tetanus toxoid or immunoglobulin followed by gentle normal sterile saline irrigation of open wounds to remove gross contamination. Do not discard any viable tissue. Control bleeding with compression whenever possible. Avoid vessel ligation or tourniquet use unless there is concern for exsanguination. Gently reduce the fracture and cover it with a moist, occlusive dressing. Splint extremities to prevent ongoing soft tissue injury, document a thorough physical and neurological examination, obtain photographs of the wound if practical, and then complete a radiographic evaluation.

The extensive soft tissue damage poses the most difficulty for the treating surgeon. An explosion strips the soft tissues from the bone and dissects along fascial planes, producing heavy polymicrobial contamination and injuries far more extensive than may be clinically apparent. High-speed fragments often have innocuous appearing, distant entry sites, and may traverse intervening joint spaces without clear external indication. The subsequent massive inflammatory response can occlude the microcirculation and produce ongoing, evolving tissue necrosis.

Aggressive surgical debridement is the first step in surgical reconstruction and the best defense against infection. Hemorrhage control with a tourniquet facilitates wound evaluation. Widely extend the wounds until normal tissue can be clearly seen, preferably along standard surgical approaches or along improvised ones that respect local angiosomes. Debride in a systematic fashion, taking care to protect intact neurovascular and tendinous structures. Skin should be taken back to healthy bleeding edges. Compartment syndrome is possible in all blast injuries, so the need for fasciotomy should be considered during every debridement. Damaged muscle is unlikely to recover after injuries of this magnitude, so all nonviable, non-contractile tissue must be removed. Deliver bone ends into the wound and debride them to the level of healthy periosteum and visibly perfused osteons (the “paprika sign”). Temporarily shunt torn vascular structures until the patient and the wound bed are stable. Debride injured neural structures to healthy-appearing fascicles and tag them for later reconstruction. Consider a saline challenge to all joints, even those without obvious proximate wounds. Release the tourniquet and inspect the wound. Debride further until the wound surface

is uniformly clean and vital. The surgical goal is a complete wound excision down to healthy, bleeding tissues, taking care to maintain any viable tissue for potential future use. Guillo-tine amputations are not recommended.

Besides the primary open wound, the patient will be peppered with multiple smaller fragment wounds. Extensive debridement of all fragment wound tracts is not required. Smaller, high velocity projectiles often do not cause large temporary cavities. Elastic soft tissue generally heals well if the blood supply is intact, and time to antibiotic administration plays a large role in mitigating infection. With multiple fragment wounds, one should focus on removing intra-articular fragments and those expected to directly interfere with muscle, nerve, or tendon function [9, 10]. After debridement, all wounds should be thoroughly irrigated with high volume normal sterile saline delivered by gravity flow. The authors cannot recommend for or against the routine use of antibiotic or soap additives.

Temporary stabilization

Temporary skeletal stabilization is performed during or after resuscitation and debridement and is especially important in severe wounds that require multiple debridements. It confers many benefits, including decreased blood loss, improved resuscitation, prevention of further soft tissue injury, pain relief, and easier nursing care. For extremities, the authors favor uniplanar double-stacked frames with bicortical pins placed outside the zone of injury whenever possible. The authors routinely predrill half pins to minimize soft tissue injury and bony necrosis. In the pelvis, the well-described technique of supra-acetabular pin placement gives powerful control of the true pelvis, and the low profile frame permits unrestricted abdominal access for the general surgeons [11]. Iliac wing pins can be safely placed without fluoroscopy. To prevent pin site infection, cleansing with hydrogen peroxide, chlorhexidine gluconate (CHG), or saline appears safe and beneficial [12]. In addition to external fixation, percutaneous fixation using Kirschner wires or screws have been shown to be valuable adjuncts in temporary management of fractures and dislocations of both upper and lower extremity injuries [13].

Antibiotic bead pouch

Proper debridement frequently results in large, irregular wounds with significant bone and soft tissue defects. Active ongoing wound management is critical to decrease infection risk and facilitate definitive closure/coverage. Henry et al. first reported on the antibiotic bead pouch (ABP) technique using Tobramycin impregnated polymethylmethacrylate (PMMA) beads in open fractures [14]. ABPs have been shown to

prevent deep infection in wounds with segmental defects or significant dead space. Antibiotic-impregnated PMMA beads elute high local antibiotic concentrations antibiotic while minimizing systemic toxicity. Elution is biphasic with a rapid early phase and a slow secondary phase that can last for weeks. The concentration of eluted antibiotics in the ABP environment greatly exceeds minimum inhibitory or bactericidal concentrations of most organisms and biofilms [15]. Factors associated with antibiotic elution include bead surface area, porosity, antibiotic concentration, and use of more than one antibiotic. The most common antibiotic choices are an aminoglycoside (Gentamicin or Tobramycin) and Vancomycin due to their broad spectrum of activity and synergistic elution characteristics. Typically, antibiotic-impregnated beads are made intraoperatively by hand or using molds. Once prepared, they can be gas sterilized and stored for later use without impairing the elution characteristics [16].

Currently, the authors use 40 g PMMA mixed with 2–4 g Vancomycin and 1–2 g Tobramycin depending on the injury and contamination level. Beads are strung together using metallic wire or a nonabsorbable monofilament suture. Next, an occlusive non-permeable dressing (Ioban, 3 M, St. Paul, MN) is applied to seal the wound. Patients return to the operating room at clinically selected intervals for bead exchange and repeat debridement. When the wound appears clean and serum inflammatory markers are declining, negative pressure wound therapy is begun in preparation for definitive coverage or closure.

Negative pressure wound therapy

First described for wound management in open fractures, negative pressure wound therapy (NPWT) encourages formation of granulation tissue and re-epithelialization [17]. The sealed dressing prevents contamination between procedures, minimizing infection risk. NPWT requires a thoroughly debrided wound bed, adequate vascular supply, low bacterial load, and optimized host parameters (i.e., glycemic control, nutrition, metabolic deficiencies). Contraindications include necrotic tissue, exposed neurovascular structures, active hemorrhage, malignancy, and osteomyelitis.

Civilian and military surgeons have successfully used NPWT in the management of open blast and gunshot injuries [18, 19]. In addition to open traumatic wound management, NPWT has beneficial effects on fasciotomy incisions, skin graft sites, and closed surgical incisions at risk for infection or dehiscence [20]. The authors' preferred technique consists of firmly apposing the reticulated foam to the vertical skin edges to the prepared wound bed. Cleansing the skin with sponges soaked in dilute hydrogen peroxide solution will improve adhesive seal. Achieving an adequate seal may be difficult in the setting of bleeding, external fixator pins, or

irregular wound edges. The closed system is then complete and continuous suction is typically set at 125 mmHg. A soft padded dressing and splint are then applied, taking care to separate the suction tube from direct contact with the skin. After placement, dressing changes are recommended at 2–3 day intervals under anesthesia or at bedside depending on the debridement schedule and patient tolerance.

Limb salvage versus amputation

The decision to amputate or salvage a mangled extremity remains subjective. No reliable scoring system predicts which patient is best suited for acute amputation. Younger, healthier patients, even those injured by blast mechanisms, should be considered for limb salvage with a mangled extremity surgery score of 7 or less [21]. The only absolute indications for acute amputation are completion of a grossly contaminated traumatic amputation, the physiologically unstable patient with a mangled extremity, irreparable vascular injury, or an extremity with warm ischemia time greater than 6 hours.

Severe foot and ankle injuries secondary to a blast mechanism can be particularly disabling. Polytraumatized individuals with foot and ankle injuries have significantly greater disability scores than those without, and more sequelae, including post-traumatic arthritis, residual deformity, healing problems, and osteomyelitis [22]. In one series, only 40 % of patients with severe foot injuries returned to work [23]. Calcaneus fractures in particular have high complication rates. Authors of one study of combat injured patients demonstrated 38 % rate of infection and a 45 % rate of amputation rate with calcaneal blast fractures from vehicle explosions; 28 % were amputated acutely and 10 % required delayed amputation for chronic pain [24]. The LEAP study also confirmed that the subset of patients with severe foot and ankle injuries who required free flap coverage or ankle fusions had significantly worse outcomes at 2 years than those who underwent transtibial amputation [25••].

Strategies for soft tissue closure/coverage

As mentioned earlier, definitive reconstruction of the blast-injured patient begins with the initial debridement. Addressing the evolving zone of injury with serial, sharp, aggressive debridement over the first 7–10 days ultimately leaves the surgeon with a healthy soft tissue envelope ready for closure or soft tissue coverage. The soft tissue reconstruction of blasted extremities represents the greatest management challenge. While the challenges and the principles are similar, the soft tissue reconstruction of blast-related amputations and that of salvaged limbs must be considered separately.

Soft tissue coverage: blast-related amputations

The soft tissues should determine the ultimate residual limb length in blast-related amputations. Ipsilateral fractures proximal to the area of the most distal viable soft tissue should be reduced and stabilized with standard techniques (as discussed later in this review). Both muscle and skin coverage are routine challenges, but muscle coverage of bone and neurovascular structures is the most common limiting factor in the maintenance of residual length. Creative use of local muscle flaps, followed by split-thickness skin grafting (STSG), is by far the most common method of achieving durable soft tissue coverage. The use of collagen dermal replacement matrices, such as the Integra bilayer collagen matrix (Integra Life Sciences, Plainsboro, New Jersey), allows for a durable dermal layer which, when covered by STSG, results in a thick, mobile pseudodermis that can tolerate the compressive and shear forces encountered in prosthetic sockets [26].

In selected cases, escalation up the reconstructive ladder is warranted [27]. Pedicled rotation flaps are useful for acute coverage of exposed neurovascular structures, as well as after vascular repair. During Operation Iraqi Freedom, pedicled local flaps were used nearly four times as often as free flaps. Some authors prefer pedicled flaps because of simpler execution, less donor site morbidity, and low failure rates in this complex, often colonized combat wounds [28]. While there is no clear difference in success rates between rotational and free flaps in the war-related literature, the authors recommend caution when rotating a pedicled flap within the zone of injury, especially early in the treatment of high-order explosive injuries. The blast wave causes extensive damage to the microcirculation, and some tissues will not behave predictably once rotated. If rotating injured tissue is clinically necessary, the surgeon should strongly consider a delayed flap to minimize failure risk. Rotational flaps are more successful than free flaps when used in the delayed setting. Burns et al. retrospectively compared rotational versus free flap coverage performed an average of 20 days after injury in severe open tibia fractures from combat. In their series of 67 patients, those treated with free flap coverage were more likely to have flap failure, require additional procedures, and go on to eventual amputation [29]. The largest series from the current conflict examined 75 pedicled rotational and free flaps with an average time to coverage of 21 days. Of note, 40 % of the wounds were culture positive on admission and 70 % of the colonization was *Acinetobacter baumannii*. The flap success rate was 97 % and early infection rate was 13 %, both comparable to civilian literature on delayed coverage. The authors suspected that serial debridement necessary in combat limb-threatening injuries allowed the surgeon to accurately characterize the “zone of injury,” and delayed tissue coverage provided a better

match between the ultimate wound size and an appropriate coverage procedure [30].

In transtibial amputations, reconstructive efforts focus on maintenance of a ligamentously stable knee joint with good muscular control. This requires durable soft tissue coverage over the distal residual limb. While maintaining tibial segment length is important, the residual tibial can be shortened from the patient height-determined optimum to allow for healthy muscle and sensate skin over the weight bearing residual limb. Once the residual limb is healed and stable, it can be lengthened using Ilizarov methods or an internal motorized implant (Precice Nail, Ellipse Technologies, Irvine, CA). In cases where this would result in an extremely short tibial segment, free flap coverage of the exposed tibia, in conjunction with dermal matrix and STSG coverage, is justified given the importance of maintaining a functional knee.

In transfemoral amputations, the quality of the thigh soft tissue envelope remains the most important factor in determining residual limb length. Multiple techniques can stabilize the soft tissue envelope, including myodesis, myoplasty, and allograft or autograft myofascial stabilization. A traditional adductor myodesis, followed by either myodesis or myoplasty of the hamstring and quadriceps mass, is preferred. Unfortunately, in the setting of blast-related transfemoral amputations, the soft tissue envelope of the thigh is significantly damaged, necessitating creative use of “flaps of opportunity” to achieve durable coverage. Loss of adductor muscle mass or attachment creates an especially challenging problem, both for medial soft tissue coverage of the residual limb and for prosthetic use and gait. Though the residual healthy adductor muscle belly is poor tissue to accept sutures for myodesis, it is important to obtain the best possible adductor attachment to the femur, at a residual limb length that allows for the use of the neighboring tissues to provide for adequate soft tissue padding of the limb [31].

Functional outcomes after knee disarticulation have not been proven superior to those of transfemoral amputation, so conversion to a transfemoral level is advised, particularly in patients with bilateral lower extremity amputations. This typically allows a more standard reconstruction through healthier tissue farther from the zone of injury. It also allows symmetrical placement of the knee centers of rotation.

Soft tissue coverage: blast-related limb salvage

As discussed previously, the injury to the surrounding, surviving tissue from a blast mechanism, presents challenges for soft tissue coverage of reconstructed limbs as well as traumatic amputations. The damage is often extensive, and 82 % of associated fractures are open [32]. Many of the patients have other injuries or amputations limiting free flap options. Furthermore, the local soft tissues are often damaged to the degree where their use for rotational flap coverage is not feasible.

This leads to a challenging situation with few good options for soft tissue coverage.

The principles and options for soft tissue coverage in blast-related limb salvage are similar to corresponding injuries from other mechanisms. Gastrocnemius and soleus rotational flaps are utilized when appropriate for type IIIB tibia fractures but are often too severely damaged. Free tissue transfer is often required, sometimes incorporating arteriovenous loops to increase pedicle length so the anastomoses can be placed outside the zone of injury.

When free tissue transfer is not feasible (in the setting of a one-vessel lower leg, or with limited donor tissue in the setting of multiple amputations), local tissue is employed. The use of external tissue expanders such as the Dermalose device (Wound Care Technologies, Inc., Chanhassen, MN) can facilitate primary closure by converting type IIIB to IIIA fractures [33, 34]. Similarly, acute shortening and angulation in a circular fixator can be very effective to facilitate primary closure. Gradual correction to normal limb alignment may obviate the need for flap coverage [35, 36].

Fracture fixation in blast injuries

The choice of fixation modality is highly variable in blast-related fractures, yet the general principles of fracture fixation remain unchanged. Many of these fractures are similar to their civilian counterparts and can be treated identically. Others, however, are high-energy injuries, with large, highly contaminated soft tissue wounds, and present as high-severity open injuries, with segmental tissue loss. These cases require special considerations with respect to implant choice.

Plate and screw constructs are largely reserved for periarticular injuries requiring joint reconstruction difficult to obtain by other means. For most femoral shaft fractures, the robust soft tissue envelope, in conjunction with the practical difficulties of circular external fixation of the femur, renders intramedullary nail (IMN) the treatment of choice. In contradistinction, combat-related tibial shaft fractures, especially those resulting from a blast mechanism, can be treated with IMN but are more commonly treated with circular external fixation. Circular fixators are much more easily tolerated in the tibia, and yield reliable results, potentially mitigating concerns for infection with the use of tibial IMN [37]. While there is no direct comparative data to support this preference, there is currently an ongoing multi-center study comparing IMN and circular external fixation in the treatment of severe open tibia fractures, including those resulting from combat and blast mechanisms. Circular external fixation, with or without limited articular internal fixation, can also be used for periarticular injuries with soft tissue injuries that preclude placement of permanent, deep implants.

In the setting of traumatic amputations with a more proximal ipsilateral fracture, the soft tissues, not the fracture, should be the determining factor for the level of amputation [38]. This can be safely done by plate fixation of the fracture within the open wound, or with an IMN, either antegrade, or retrograde through the open wound at the time of definitive closure of the amputation [39]. Tibial plateau fractures proximal to an ipsilateral transtibial amputation present a specific challenge. Performing open reduction and plate fixation creates further surgical insult to an already compromised soft tissue envelope, but this remains our preferred method of management, as maintaining a functioning knee joint is considered worth the risk of placing permanent implants in the setting of a blast-injured limb.

Complications/problems specific to extremity blast injuries

Extremity blast injuries have reported complication rates from 35–87 % [38, 40]. Complications include poor function secondary to segmental composite tissue loss, infection, heterotopic ossification, arthrofibrosis, and late conversion to amputation.

Infection

Infection remains one of the most serious complications of blast injury, due to the high-energy mechanism, the massive soft tissue damage, and the amount of gross contamination. Despite conscientious serial debridement and appropriate use of both locally delivered and systemic antibiotics, approximately 15 % of patients will develop osteomyelitis, and 17 % of those infections will relapse or recur [41]. Bacterial infections are managed identically to community injuries, with surgical debridement, and organism-specific systemic antibiotics. In the setting of deep infections in amputation closures, the bone ends are typically trimmed 1–2 cm at the time of repeat closure. While this is often necessary merely to obtain repeat soft tissue coverage, it has the added benefit of resecting the potentially organism-harboring cut bone ends and rarely results in the loss of an amputation level.

Invasive fungal infection (IFI) is disproportionately common in the multiply injured blast injury patient. The infected tissue has a grayish appearance, and the diagnosis is verified by biopsy and fungal cultures. Independent risk factors for developing IFI have been shown to be blast injury while on foot patrol, above knee amputations, and massive transfusions (>20 units) of packed red blood cells within 24 h post-injury [42]. IFI must be treated with serial, aggressive debridement and often result in the loss of large volumes of muscle tissue, as well as length of the residual limb. These wounds often require systemic antifungals and debridement every 24–48 h

until the infection is brought under control. Dakin's solution at 0.025 % strength has been shown to be effective when used in dressings [43], or the wound can be intermittently bathed in Dakin's solution via instillation vacuum dressing (KCI). Recent data suggests, however, that 0.0025 % Dakin's may be preferable [44].

Heterotopic ossification

Development of heterotopic ossification (HO) is perhaps the signature complication of combat related blast trauma. HO develops in damaged muscle tissue as the result of dysregulation of a BMP-mediated healing response [45]. In multiple series, HO occurs in approximately 65 % of all combat-related amputations [46, 47]. Anecdotally, the incidence approaches 100 % in the sub-population of high bilateral lower extremity amputations (the complex dismounted blast injury). Available prophylaxis includes anti-inflammatory medications and radiation, but the combination of polytrauma and extensive wounds renders prophylaxis largely impractical.

HO lesions may be focal or can present as extensive, coral-like networks of bone. They can cause significant long-term problems, particularly in the residual limbs of blast-related traumatic amputees. HO can cause pain, skin breakdown of the overlying skin, compression of nerves and vessels, and difficulty with socket wear and prosthetic use. Approximately 40 % of combat-related amputees who develop HO will require surgical resection, which is performed after the HO has matured. In our experience, this can be done as early as 6–8 months post-injury without risk of recurrence. HO resection carries a 25 % complication rate, the possibility of significant blood loss, and delays prosthetic fitting [48].

Arthrofibrosis

Arthrofibrosis after blast injury can be the result of normal post-surgical scar formation, an overly robust inflammatory reaction about an injured joint, or from prolonged immobilization and disuse. It is very difficult to maintain range of motion of all joints in these severely and multiply injured patients, particularly when they remain in the intensive care setting for extended periods of time. The orthopedic surgical team must be proactive and take all possible joints through a full range of motion at each trip to the operating room. In 61 knees with arthrofibrosis from combat-related events, early manipulation resulted in better improvement in arc of motion with fewer complications than did surgical arthrolysis, which tended to occur more remotely from injury [49].

Late amputation

The ultimate goal of salvage is to reconstruct a limb with well-aligned bony architecture and a stable soft tissue envelope.

However, among patients initially treated with limb salvage, the frequency of late amputations (>12 weeks) has been reported as high as 15 % [50]. Risk factors for poor functional outcomes include complex regional pain syndrome, neurologic injuries, persistent or recurrent infection, and severe injuries to the hind foot or distal tibia. Late amputation has been shown to result in a high degree of patient satisfaction and improved functional outcomes in selected patients [51]. It was more common in combat injured patients requiring free flap coverage or those who had infectious complications [52]. Recent advances in bracing and rehabilitation for patients with combat extremity trauma show promise for improving function, reducing pain and decreasing the rate of late amputation. In fact, after fitting with the Intrepid Dynamic Skeletal Orthosis (IDEO) and completing an integrated 8 week rehabilitation program, 82 % of patients with severe lower extremity injuries chose limb salvage over delayed elective amputation [53].

Summary

Trauma and injuries from explosions occur routinely in combat and terrorist attacks. Explosive devices have become the preferred weapon of domestic and foreign terrorists since they are inexpensive and easy to manufacture. Secondary blast injury has been the predominant wounding mechanism in the global war on terror and has produced the most complex casualties. However, blast injuries can also occur from natural disasters, domestic terrorism, and industrial accidents as well. Civilian surgeons can be called on at any time to treat patients with blast injuries, often under difficult circumstances.

A well-organized team approach is critical to maximize the survivability and function of the blast-injured patient. The key to managing these complex injuries is to realize they are a clinically distinct, multimodal systemic injury. ATLS protocols must be combined with an aggressive search for and correction of acute coagulopathy of trauma. Surgical debridement remains the cornerstone of early wound management, both to minimize infection risk and set the stage for subsequent reconstruction. Debridement should be aggressive, thorough, and frequent until the wound stabilizes. After that, a thorough understanding of the reconstructive ladder, combined with considerations, techniques, and technologies summarized above, can produce encouraging results.

Compliance with Ethics Guidelines

Conflict of Interest Kevin Kuhn, Greg Staeheli, and David Dromsky declare that they have no conflict of interest. Wade Gordon reports personal fees from Orthofix, Ltd.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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