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Blurred front lines: triage and initial management of blast injuries

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Abstract Recent armed conflicts and the expanded reach of international terror groups has resulted in an increased incidence of blast-related injuries in both military and civilian populations. Mass-casualty incidents may require both on-scene and in-hospital triage to maximize survival rates and conserve limited resources. Initial evaluation should focus on the identification and control of potentially life-threatening conditions, especially life-threatening hemorrhage. Early operative priorities for musculoskeletal injuries focus on the principles of damage-control orthopaedics, with early and aggressive debridement of soft-tissue wounds, vascular shunting or grafting to restore limb perfusion, and long-bone fracture stabilization via external fixation. Special considerations such as patient transport, infection control and prevention, and amputation management are also discussed. All orthopedic surgeons, regardless of practice setting, should be familiar with the basic principles of evaluation, resuscitation, and initial management of explosive blast injuries.

Keywords Blast injury · Damage-control orthopedics · Triage

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Introduction

The use of explosives as a weapon of war is not new. Black powder-based explosive weapons have been utilized by nation-states since at least the late 1200s [1]. The invention of more stable explosive compounds and reliable fuses in the 1800s advanced the development of more powerful explosive weaponry, which continues today. The use of explosives as a tool of terror is also not new. From Guy Fawkes' Gunpowder Plot in 1605, to the bombing of New York City's financial district in 1920 using a horse-drawn wagon, to modern acts of terror around the world, groups of all political stripes have frequently utilized explosives to kill or maim their enemies while sowing fear in the wider populace [2].

What is new is the scale on which explosives are employed in the modern era. Widespread proliferation of homemade explosives and military-grade ordinance make blast injuries increasingly prevalent. Blasts causing civilian casualties have occurred not only in Baghdad, Damascus, Karachi, and Kabul, but also London, Madrid, Boston, New York City, Paris, and Atlanta. Most victims of these attacks do not perish immediately, and most who survive the initial attack sustain musculoskeletal injuries. Proper care of injuries in the immediate aftermath of an explosive attack is key to minimizing mortality and maximizing functional recovery. The purpose of

this article is to review basic triage in mass-casualty situations and detail the principles of early management of blast-injured extremities.

Background

While clinicians do not need a detailed understanding of blast physics, a working knowledge of how explosions occur is necessary to recognize the characteristic injuries they produce. An explosion is the rapid conversion of a solid or liquid into a gas, producing a nearly instantaneous increase in pressure that propagates outward at supersonic speed [3]. This force may produce injury directly or indirectly, and so blast injuries are commonly divided into several sub-categorizations based on their respective mechanisms [4, 5]. Primary blast injuries result from blast overpressure from the initial shockwave, and principally affect hollow organs such as the lungs, gastrointestinal tract, eyes and ears. Primary blast injury has also been implicated as a cause of traumatic brain injury (TBI), especially mild TBI (mTBI). Secondary blast injuries are ballistic wounding from debris or fragments propelled by the blast wave. These injuries may affect any portion of the body, and their location and severity is dependent on the distance and orientation of the body to the vector of the blast. Tertiary blast injuries result from physical displacement of the victim by the force of the blast, and resulting injury patterns are similar to patients who have experienced a fall from height or ejection from a motor vehicle. Quaternary blast injuries encompass other indirect blast-related trauma such as burns, smoke inhalation, and exacerbation of pre-existing conditions. The type of injury sustained by individual patients depends on the magnitude of the explosive force, the nature fragments carried by the blast, and proximity of the victim from the blast epicenter. Musculoskeletal injuries are principally secondary, tertiary, and occasionally quaternary injuries, although vascular trauma in the extremities can result from the primary blast wave through shearing of the endothelium.

Today, the majority of blast-injured patients cared for in the western world are military casualties, mainly from the conflicts in Iraq and Afghanistan. Opposition forces in both nations, facing dramatically larger and better-equipped coalition forces, rely heavily on the use of improvised explosive devices (IEDs). These weapons are inexpensive, easy to construct, and inflict injury and death without exposing fighters to return fire. Large database analyses and prospective evaluations of American combat units have reported 79–87.4 % of all casualties result from explosive munitions [6, 7]. Explosive munitions disproportionately affect the extremities, owing to their typical detonation on or under the ground, and our inability to armor extremities without impairing combat maneuverability. A study of over 3500 combat extremity wounds found that 81 % were secondary to explosives, and that 26 % resulted in fracture (82 % of which were open fractures) [8]. A separate cohort found that 7.4 % of major extremity injuries resulted in limb amputation [9].

Even with widespread use of so-called *up-armored* vehicles, intended to protect occupants from IEDs and other explosive rounds, the terrain our forces fight on, as well as counter-insurgency strategy, often requires foot patrols and dismounted movements. This has been especially true in Afghanistan, where the enemy utilizes rough, mountainous terrain to mask their position and facilitate ambush attacks [10]. Ceramic body armor and Kevlar helmets have significantly reduced the rate of combat-related deaths from all weapons, but do nothing to protect the extremities [11, 12]. Military medical professionals are thus left with greater numbers of severely injured personnel who are more likely to survive their wounds.

While less commonly injured by blasts, civilian populations have not been spared. A total of 9707 acts of terrorism occurred globally in 2013, up from 6771 in 2012 [13]. These attacks killed more than 17,800 people, and 57 % were carried out using explosives. Terrorist bombings vary considerably, from large coordinated attacks as occurred in Oklahoma City in 1995 (163 killed, 680 injured) [2] and London in 2005 (42 killed, >700 injured) [14], to relatively small scale attacks such as the Boston Marathon bombings (3 killed, 264 injured) [15]. It is also worth noting that similar principles of triage and injury management apply after natural disasters and other non-blast mass-casualty events. The wounding patterns seen after the 2010 earthquake in Haiti and 2011 tornado in Joplin, Missouri (among others), bore a striking resemblance to those seen in combat or terrorist attacks, with high proportions of open fractures, large soft-tissue defects, and uncommon infections [16–18].

General principles of triage and resuscitation

Most blast and mass-casualty incidents have a predictable pattern of patient flow [19]. Victims in closest proximity to the blast die immediately or very soon after the explosion. Other victims will experience injuries roughly inversely proportional to their distance from the blast epicenter, and the majority will not have critical or severe injuries. Depending on the speed of medical response, many of these minimally injured patients will transport themselves to medical treatment facilities before more critically injured victims arrive. This is usually closely followed by the arrival of seriously wounded patients, brought in decreasing order of severity by first responders. Minimally injured patients continue to arrive for hours or days after the incident, creating constant pressure on the local medical system and continuing to overload available resources.

Triage of multiple patients in a blast incident or other mass-casualty situation is centered on the concept of providing the greatest benefit for the greatest number of patients [19, 20]. This is a fundamentally distinct concept from the *triage* performed in most Emergency Departments, where it is used to direct resources to patients in order of injury severity. Triage in a blast incident directs resources to those with the greatest need, who also have the best chance for survival. In practice, this demands that providers performing triage rapidly screen patients for the presence of serious injury, and immediately determine whether (1) a rapid, lifesaving intervention is necessary, and (2) such an intervention is possible given the current situation and available resources.

The US military utilizes four triage categories: immediate, delayed, minimal, and expectant [21]. Immediate casualties require lifesaving surgery, with the caveat that the surgery not be time-consuming or complex. Delayed casualties are badly injured, but their general condition permits delay in surgical treatment without endangering their lives. Minimal casualties have relatively minor injuries, and can be temporized with self-care or be initially managed by non-medical personnel. Expectant casualties have injuries of such severity that survival is unlikely even with application of all available medical resources. Other triage systems have been and are currently employed, but all follow the same general hierarchical model of injury severity.

The underlying premise of triage in blast incidents is that the number of casualties requiring care will rapidly outstrip the availability of medical resources, both material and human. Consequently, there will be patients whose injuries are either too severe or too minor to warrant immediate medical attention. This concept runs counter to traditional medical training, and can be morally and emotionally taxing on medical professionals called upon to decide who will receive care. The tendency for triaging professionals is to *up-categorize* casualties, directing that they receive more immediate care than their condition actually warrants. However, several studies have demonstrated that this tendency, far from being compassionate, actually increases the overall case fatality rate in blast and mass-casualty events [22–24]. It is absolutely critical that any provider conducting triage be adequately trained in the assessment of patients, understand what resources are available at their location, and possess the courage to assign patients to the expectant category when appropriate.

Following appropriate triage, initial management focuses on the identification and rapid treatment of potentially life-threatening injuries. Both the civilian Advanced Trauma Life Support (ATLS) [25] course and the military's Tactical Combat Casualty Care (TCCC) [26] course teach the same basic algorithm. Ensure the airway is open, and place an advanced airway if necessary; confirm adequate respiration, and provide ventilatory support as needed. Assess circulatory status and if it is not, provide support with fluids. Stop any significant hemorrhage and, in accordance with recent recommendations from the American College of Surgeons, tourniquets should be used without hesitation, when indicated [27]. Special attention should be paid to penetrating cranial injuries which may alter triage categorization, and thoracoabdominopelvic injury requiring application of a pelvic binder to prevent circulatory collapse. In the hospital setting, these *ABCs* are assessed simultaneously by multiple providers at once, but in the setting of a blast injury with multiple casualties, and single physician or para-medical provider may be responsible for all of them. It is critical that assessment be performed rapidly, and that appropriate interventions are performed at each step and not deferred. Only after these steps are complete should attention be turned to care of non-exsanguinating musculoskeletal injuries.

Military versus civilian response

Case fatality rates in modern combat have fallen significantly due not only to improved armoring [11, 12], but also because of medical innovations like the windlass tourniquet [28–30], chitosan-based hemostatic dressings [31, 32], and improved massive transfusion protocols [33, 34]. None of these advancements would make any difference, however, were it not for the regular and realistic training conducted by military medical and non-medical personnel. Training allows military medicine to overcome many of the inherent barriers to trauma care in a combat setting, such as the lack of cross-matched blood products, the need to perform care while under fire, and limited availability of surgical resources [35–37].

When civilian providers respond to blast incidents, there is always a risk that personnel will be emotionally overwhelmed by the scale of the incident and severity of the wounds they encounter [38]. Multiple after-action reports from responders to mass-casualty events have cited prior preparation as defining the success or failure of the medical response [39–43, 44•]. Clear chains of command, familiarity with team members and institutional procedures, pre-defined evacuation routes, and previous realistic training exercises are all key to proper preparation.

Initial operative management and priorities

After initial primary and secondary surveys have been performed, providers should shift their focus towards the principles of damage-control surgery/orthopedics (Table 1). The initial phase of damage control focuses on treatment of potentially life-threatening injuries and associated hemorrhage [45]. Because of the high incidence of concomitant intracranial, intra-abdominal, vascular and soft-tissue injuries, a multidisciplinary approach is crucial to formulating a plan of attack

Table 1 Phases of damage-control orthopedics/surgery

Phase	Conditions targeted	Interventions
Initial receipt and stabilization	Intra-abdominal injuries Hemorrhage Long-bone fracture Unstable pelvic fracture Compartment syndrome	Laparotomy External fixation Initial wound debridement Fasciotomy
Medical optimization	Metabolic imbalance Hypothermia Acidosis Coagulopathy Pulmonary injury	Transfusion Fluid administration Electrolyte replacement Warming
Definitive care	Soft-tissue injury Infection Fracture	Wound closure/coverage Antimicrobial therapy ORIF/IMN

to identify and treat these patients upon arrival [46]. The specific concerns regarding need for hemorrhage control and management of penetrating intra-abdominal trauma have also been addressed previously. During the initial receipt and stabilization phase, exploratory laparotomy should be undertaken, if indicated. However, the procedure should be limited in scope as the emphasis should be on speed and transition of the patient to the second phase of damage control [47]. The orthopedic contributions to this phase of treatment are typically focused on external fixation/stabilization of fractures associated with hemodynamic instability (e.g., pelvis) as well as possible external fixation of long-bone fractures [48].

Following this initial treatment, the patient is subsequently transferred to an ICU setting for stabilization and optimization of the common metabolic disorders that accompany blast-associated polytrauma. Specifically, avoiding the *Lethal Triad* of hypothermia, acidosis, and coagulopathy are points of emphasis for management and treatment during this evaluation period [49]. These treatment principles align with civilian lessons learned prior to the Global War on Terror regarding damage-control orthopedics and delaying non-urgent surgery in the severely injured/unstable patient. Wartime advances, such as refined blood product transfusion ratios (i.e., 1:1:1 ratio of FFP to platelets to packed RBC, or whole blood administration), has changed rapid transfusion protocols in stateside facilities [50]. Stateside teams do not face the additional logistical challenges associated with medevac transport to higher-level care centers and/or limited resources at forward-deployed medical treatment facilities.

Soft-tissue injuries

The principles of management regarding soft-tissue injuries resulting from a blast mechanism have also shifted significantly based upon lessons learned from recent wartime surgical experiences. Vietnam-era teachings attempted to provide systematic recommendations regarding the width and quantity of debridement based upon the nature of the injury or the dimensions of the projectile that would result in significant tissue devitalization [51]. Current approaches to management of soft-tissue wounds sustained on the battlefield are far less systematic and, while thorough debridement is crucial, a greater emphasis is being placed on viable soft-tissue preservation with an eye towards definitive closure at a later date. There is strong evidence to support that rapid initial debridement is associated with a decreased risk of infection [52]. With a blast injury, there is often a substantially higher degree of tissue destruction and contamination than what is seen with other mechanisms of injury such as gunshot wounds. In fact, much of the trauma is not identifiable at time of injury and will only become apparent during subsequent procedures [5]. Initial surgical treatment of these injuries focuses on infection control and includes irrigation, debridement of non-viable tissues, and leaving contaminated wounds open. These patients often require multiple irrigation and debridements as well as *wound checks* to allow the extent of the trauma to declare itself with time. The use of negative pressure wound therapy (NPWT) have been effective at providing temporary wound coverage in austere settings and also to prepare the wound bed for definitive closure at a later date [53]. Antibiotic bead pouches have also been shown, in smaller studies, to be equally or more effective than NPWT dressings but at a significantly lower cost [54]. Antibiotic pouch therapy had also previously offered the benefit of serving as a *work around* for US military restrictions on using NPWT dressings on MEDEVAC flights, though these restrictions have since been lifted [55].

Fractures

When applying damage-control principles to blast injuries, much of fracture fixation occurs during the third phase of management. Fracture management in the initial evaluation and resuscitation phase is largely limited to external fixation of long bones and pelvic fractures associated with hemodynamic instability [56]. While external fixation is ideal in extremity fractures with associated vascular injury, provisional stabilization in austere settings is often limited by time and resources. When compared to splinting, external fixation offers the additional benefit of allowing visualization of the associated soft-tissue injury and compartment assessment during the transition to higher-level care [57]. Management of blast injury in the military setting is also complicated by the fact that the phases of damage control and subsequent definitive management of fractures will often take place in different

facilities. Both in civilian and military settings, casualties will oftentimes require transport after initial evaluation and treatment to an ICU setting for physiologic stabilization and correction of metabolic abnormalities via ongoing rescucitation [58]. As has been stated previously, blast injuries are associated with open fractures and soft-tissue destruction. Much has been published in the civilian literature showing outcomes for open fractures are primarily driven by time to transfer to a trauma care center as well as time to administration of antibiotics, with much less emphasis being placed upon time to debridement [59]. This data, however, must be interpreted cautiously in the setting blast trauma. Owing the aforementioned wide zone of injury with heavy contamination, early and regular debridement likely plays a much more central role in blast injury management than in other modes of injury.

Amputations

Providers should remain mindful of the previously mentioned principles of preserving length and tissue and of the likely need for multiple subsequent procedures, possibly to be performed by subsequent providers at different facilities [60]. The determination of the appropriate level of amputation in the acute setting is often complicated by the surgeon's inability to discern tissue that has sustained critical damage but has not *declared* itself. For this reason, blast injuries require serial reassessment during the later phases of damage-control surgery [61]. Applying these principles in the phase of initial management of blast injuries should steer surgeons away from debridement in the name of making *textbook* flaps—rather, we advocate open, length-preserving amputations with salvage of all viable tissue. Amputations resulting from blast injuries are also often associated with fractures proximal to the level of injury. While management of these injuries has been shown to be associated with a high complication rate, fractures have been shown to have a high rate of union with acceptable patient functional outcomes and globally successful residual limb length and level preservation [62]. The treatment algorithm for surgeons when deciding between limb salvage and amputation has shifted dramatically over the past 30 years. Specifically, the LEAP and METALS studies have contributed significantly to changing providers' indications for amputation as well as changing understanding of the impact of the procedure, both upon the individual as well as societal cost [63, 64•].

Later phases of damage control

After initial stabilization and treatment, the patient is transferred to an intensive-care setting for physiologic stabilization/optimization. With the exception of pelvic stabilization and possibly long-bone external fixation (especially in the setting of superimposed vascular injury), orthopedic involvement in the initial stage can be somewhat limited. Principles of Damage Control Resuscitation, based largely on the aforementioned emphasis on blood product administration being superior to crystalloid, should be relied upon to prepare for a *second-look* procedure [65]. Optimal resuscitation, as determined by base deficit and serum lactate levels, often needs to be balanced against the need to perform a *second look* within 24–48 h [66]. Rhabdomyolysis (and subsequent renal failure), traumatic brain injury as well as *Blast Lung* are common complications of blast injuries [5, 67]. Management and optimization of these additional injuries as well as timing of *second look*" and subsequent procedures should be handled using an interdisciplinary team approach. Surgeons managing blast injuries at higher-level care facilities should be mindful of the geographic location of occurrence and the risks associated with that locale. Invasive fungal infection is a rare but potentially catastrophic complication of blast injuries sustained in the Afghan theater of operations. Such infections have led to high rates of repeat debridement, amputation, and increased mortality [68]. When suspected, broad spectrum antifungal agents such as liposomal amphotericin B and voriconazole, as well as local antimicrobial interventions such as antifungal beads and or application of dilute hypochlorite (i.e., Dakin's solution), should be started empirically and subsequently narrowed according to results of cultures and sensitivities [69].

Transport

Patient transport issues confront surgeons managing blast injuries in both austere and developed settings. Recent high-profile, mass-casualty blasts that have occurred in the USA and with multiple tertiary care facilities situated nearby. However, physicians encountering blast injuries in non-urban settings may be more challenged with initial stabilization of the patient and subsequent transfer to a tertiary care center. Similarly, surgeons managing blast injuries sustained in a forward-deployed setting are faced with the challenge of initial receipt and stabilization with an eye towards transport to higher-level care for definitive management. However, the forward-deployed provider's ability to transport is often limited by additional factors such as vehicle/aircraft operability, weather, and safety on the ground. A recent 10-year review of outcomes for Operations Iraqi Freedom and Enduring Freedom casualties found that increased transport time to the regional level IV facility (Landstuhl) had no statistically significant impact on mortality rates [40]. Initial restrictions based on concerns regarding an increased risk of wound complications with the use of NPWT are no longer in place. Subatmospheric wound dressings offer a quick, simple method of wound treatment for blast injuries in a forward-deployed management setting that has been shown to have a positive outcome on

infection rates and limb salvage efforts during definitive treatment [53]. As previously mentioned, the use of external fixation offers greater visualization and monitoring of soft-tissue injury of the injured extremity during prolonged transport to higher-level care compared to circumferential splinting. It is important to note, skeletal traction is infeasible during aeromedical evacuation. High-energy injuries are associated with a high incidence of compartment syndrome and many providers espouse a low threshold for prophylactic fasciotomy to address concerns for development during long transport to higher-level care facilities [70]. Recent studies looking at patient outcomes from extremity injuries with vascular injury have shown statistically significant reductions in amputation rate, infection rate, and total hospital stay when comparing patients who underwent prophylactic, early fasciotomy to those who did not [71•].

Conclusions

In both military and civilian settings, the importance of proper management of blast injuries has become evident over the past decade. Lessons learned from recent attacks such as the Boston Marathon bombing as well as extended combat operations in Asia illustrate that blast injuries can occur in any setting. For initial management, the principle of ATLS as well as damage-control orthopedics/surgery focus on primary and secondary surveys as well as addressing life-threatening wounds upon receipt of the patient. The orthopedist's role in both settings is often limited to external fixation of unstable pelvic or long-bone fractures, particularly in the setting of vascular injury or significant soft-tissue damage, and initial debridement of contaminated wounds. The high incidence of these associated injuries also requires the orthopedist to work closely with other services and to approach management as a team. The benefits of external fixation when compared to splinting have been mentioned previously and external fixation should be employed as time and resources allow. Beyond initial stabilization, providers in both settings must decide when transfer to higher-level care is appropriate. Regardless of whether a patient is transferred to a different facility/provider or not, this mechanism of injury is often associated with significant soft-tissue injury not always apparent at presentation. As such, after the patient is physiologically stabilized, providers should plan for multiple *looks* to debride and re-evaluate wounds as needed in order to assess for infection and necrosis

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Compliance with Ethics Guidelines

Conflict of Interest George C. Balazs, Micah B. Blais, Eric M. Bluman, Romney C. Andersen, and Benjamin K. Potter declare that they have no conflict of interest.

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• special report from collaboration between JBJS & JOSPT.
• critical and detailed examination of every aspect of prehospital & hospital care provided during 2013 Boston Marathon bombings.
This thorough and comprehensive report draws on the knowledge and experience of dozens of physicians, administrators, and para-medical personnel who were intimately involved in the response to the Boston Marathon bombings. Honest and detailed, this report should be considered required reading for any surgeon who may be called upon to care for victims of mass casualty incidents.
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• A retrospective cohort study of 324 injured military personnel who underwent either lower extremity amputation or limb salvage.
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• Early fasciotomy associated with lower rates of amputation and infection, and shorter length of hospitalization.
This cohort study of 612 patients with lower extremity arterial injury who subsequently underwent fasciotomy validates the deleterious effects of late fasciotomy in patients with vascular trauma. Surgeons should be sensitive the relationship between vascular injury and compartment syndrome, and maintain a low threshold for early fasciotomy in the presence of suspicious clinical signs.