An overview of the pathophysiology of blast injury with management guidelines

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Abstract
Explosive weapons remain the leading cause of death, injury, and disability to combatants in battle. Recent conflicts in Iraq and Afghanistan have seen considerable advances in the surgical knowledge and skills needed to save life and limb of multiply injured casualties. Global terrorism has seen explosive weapons move from battlefield to urban centres, often with devastating effects.

Orthopaedic training prepares for the management of general civilian trauma scenarios, but blast injury pathophysiology and management is rarely considered. It is important that future trauma surgeons have a working knowledge of blast injury and how it affects the musculoskeletal system so that they can manage such patients.

Keywords
amputation; blast injury; contaminated wounds; improvised explosive devices; open fracture; penetrating trauma; periosteal stripping

Introduction
Explosive devices account for the majority of deaths and injuries in combat. The conflicts in Iraq and Afghanistan have seen significant medical and logistical advances, including improvements in vehicles, body armour, point of wounding care and evacuation. The consequences of these changes include an unprecedented number of survivors, with multiple and often complex extremity injuries.

Recent world events have highlighted that civilian surgeons in densely populated urban areas, can be expected to manage these complex injuries in multiple casualty situations.

What is blast?
An explosive is a material capable of producing an explosion using its own energy. Upon detonation the explosive is converted into a hot (up to 6000 °C), high pressure (35 × 10^6 pounds per square inch) gas called the detonation products and a shock wave is propagated. As the detonation products rapidly expand, air is compressed (the blast wave) in front of the expanding gas volume, which contains the majority of the explosive’s energy.

The blast wave energy dissipates in an inverse proportion to the third power of the distance from the detonation point. The detonation products over-expand, leading to a sub-atmospheric pressure phase after which air is drawn back in. The resultant turbulence energizes debris into projectiles. The classical waveform (Friedlander wave) describes pressure changes at a fixed location relative to the explosive event in free field conditions.

The components of the blast wave that are responsible for the pathophysiological effects on biological tissue are the amplitude of the peak pressure, the impulse (the time integral of pressure), and the duration of the positive phase overpressure. It has also been proposed that the dynamic overpressure of the detonation products (blast wind) and thermal energy released in the explosion contribute to blast injury.

Blast injuries can be classified according to the mechanism by which they are produced and these are summarized below (Table 1).

Primary orthopaedic blast effects
Blast waves, interacting with the body, transfer energy at interfaces between tissues of differing acoustic impedance. Hull (1992) demonstrated that a goat limb, shielded from the effects of the detonation products, could be fractured by the blast wave alone when placed in close proximity to the point of detonation (seat) of the explosion. Using finite element modelling techniques, he predicted that a blast wave will reach the limb prior to any effect caused by the detonation products. If a blast wave penetrates a tibia from a lateral trajectory, the bending forces exerted, interacting with the geometry of the tibia, result in peak stresses being situated within the proximal third of the bone leading to fracture. This echoes clinical experience, where the most common site for traumatic amputation in these circumstances is the proximal tibia.
Secondary orthopaedic blast effects

Secondary blast injury is caused by penetrating trauma from materials within the explosive, fragments from its casing or debris energized by the explosion. These projectiles can cause fracture either directly or indirectly. High-energy fragments colliding with bone typically result in a highly comminuted fracture with extensive periosteal stripping. In addition, these high-energy transfer wounds are associated with significant contamination which, in conjunction with avascular bone, increases the risk of long-term infective complications. This has been reflected in military studies, for example Brown et al. (2010) reported a 24% infection rate in a review of long bone fractures.

Indirect fractures can be caused by a high-energy fragment passing in close proximity to bone. Such injuries occur due to the leading edge of a rapidly expanding temporary cavity (see below) causing high pressure on the bone surface. These fractures show little or no bone loss or periosteal stripping and are therefore likely to remain viable. The fracture configurations in these injuries are usually simple (i.e. transverse or oblique) with little comminution.

Secondary soft tissue blast effects

A propelled fragment colliding with the body directly damages soft tissue in its path and, if sufficiently energized, generates a radial high pressure compression wave in the tissues just as an explosion does in the atmosphere, as described above. The wave creates a temporary cavity of sub-atmospheric pressure as the fragment traverses, which pulls in external debris, increasing the risk of wound contamination.

The sizes of the temporary and permanent cavities are determined by the kinetic energy of the causative fragment and the nature of the tissue through which it passes. Areas of devitalized tissue can extend several centimetres and the zone of injury is often much greater than the remaining wound tract (Figure 3). Additionally, the irregular morphology of shrapnel in comparison to a uniform bullet, increases the transfer of kinetic energy to surrounding tissues, thereby inducing greater damage. As a consequence, simple surgical debridement of the wound track may not be sufficient to remove all non-viable tissue.

Mixed primary and secondary orthopaedic blast effects

If the victim is situated close to the seat of the explosion, the effects of the blast wave and detonation products occur almost instantaneously. Once bone has fractured due to the blast wave impact, the detonation products expose surrounding tissue to continuing destructive forces. Hull (1992) suggested that these forces are the likely mechanism of traumatic amputation.

The net result is either a total or sub-total amputation, with the zone of injury (including foreign debris and fragments) extending proximal to the fracture site.

Mixed primary and secondary soft tissue effects

Nechaev et al. (1994) described three major zones of injury following a mine blast, based on histological studies of combat casualties during the Soviet occupation of Afghanistan and on animal models (Figure 4).

Zone I, closest to the seat of the explosion, is characterized by traumatic amputation with widespread destruction of all tissues. There is significant contamination and, based on the degree of soft tissue injury, surgical amputations performed through Zone I are considered non-viable.

Within Zone II, arteriograms performed in animal studies demonstrate that there is persistent impairment of blood flow. Of note, focal areas of damage are seen, localized near neurovascular bundles and osteofascial planes, suggesting that the transmission of the blast wave is through these structures.

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**Table 1**

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**Figure 1** Blast overpressure plot.
The main features of injuries in Zone III are avulsion of arterioles, impaired venous return and reactive changes in the axons of peripheral nerves. Serial biopsies taken from Zone III, revealed that in the first 5 days there remains extensive tissue oedema with pronounced necrosis of the muscle margins. From days 6–14, biopsy of the peripheral nerves revealed hyperplasia of the Schwann cells and the formation of traumatic neuromas. Based on these findings, Nechaev et al. (1994)\textsuperscript{16} recommended that the optimal level for surgical amputation should be at the boundary between Zones II and III.

**Tertiary blast effects**

Tertiary orthopaedic blast injuries occur as a result of bodily displacement of the casualty or impact against solid structures.\textsuperscript{18} As such, the injuries have similar characteristics to those seen in civilian blunt trauma. When bone is subjected to external loads, local instabilities arise from osseous imperfections resulting in nucleation and propagation of micro-cracks, which proceeds to

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**Figure 2** (a) A blast wave interacts with a tibia; adapted from Hull.\textsuperscript{8} (b) Traumatic amputation of the femur. Note the absence of significant soft tissue disruption or and the short oblique fracture pattern.

**Figure 3** Temporary and permanent wound track cavities resulting from passage of a fragment through soft tissue. From Ramasamy et al (2013) In Press.

**Figure 4** The zones of injury following a mine explosion.
cause a macroscopic fissure (fracture). The pattern of the fracture is a function of the direction and intensity of the applied load, the geometry of the bone and the material properties of the loaded bone.

Kress et al. (1995) reported observations on long bone fractures induced using a pneumatic impactor directed perpendicular to the bone axis. The most common fracture was a tension wedge (Figure 5). Tensile wedge fractures originate directly opposite the point of impact. This suggests failure due to direct stress at the far cortex. Spiral fractures only appeared when the bones were subjected to additional torsion, and these only occurred when a pure torsion was applied, implying that failure is due to shear stress.

**Tertiary blast effects on soft tissues**
The displacement of casualties by the blast wind can result in severe soft tissue damage due to crush injuries caused by impacting solid objects, but also significant injury secondary to bone fracture. A critical effect of tertiary blast is the development of compartment syndrome. This is a limb-threatening condition observed when perfusion pressure falls below intra-compartmental pressure in an osteofascial space. Bleeding, oedema or inflammation may increase the pressure within a compartment, and a vicious cycle can arise that ultimately leads to ischaemic necrosis within 12 h. Once infarcted, muscles are replaced by inelastic fibrous tissue (Volkmann’s ischaemic contracture), leading to significant morbidity.

In a study from the USA, Ritenour et al. (2008) demonstrated that 17% of combat casualties undergoing fasciotomy required a revision procedure. In casualties who received late fasciotomies, amputation rates were twice that of casualties who had urgent fasciotomies in theatre (31% vs 15%). The authors concluded that there is a need for increased vigilance for compartment syndrome and they urge the early use of prophylactic fasciotomies in high-risk patients.

If a person is driven against a solid object or is trapped under debris, crush injuries can occur. The extent of the muscle injury is dependent on the magnitude and the duration of the force applied. If the crushing force is applied for less than 6 h the damage is a direct result of mechanical compression. On a cellular level, increased stress on the sarcolemmal membrane results in the ingress of Sodium and Calcium into the sarcoplasm, which draws extracellular fluid into the myocytes. Simultaneously, Potassium, Phosphate, Myoglobin and Urate leak from the myocytes with potentially toxic systemic effects. This may progress to crush syndrome, a reperfusion injury, which can ultimately lead to the need for renal dialysis. Bywaters and Beall’s reports of rhabdomyolysis during World War II provided the first description of a causal relationship between acute renal failure and rhabdomyolysis.

**Initial assessment and treatment**
The recent conflict in Iraq and ongoing military operations in Afghanistan have seen huge advances in the understanding and management of severe lower limb trauma sustained on the battlefield. Military surgeons rotating through the field hospital at Camp Bastion are exposed to a significantly higher volume of complex cases than they would see in their usual place of work. All deployed surgeons from the UK have a National Health Service (NHS) practice in trauma and the skills learnt should be transferrable across to civilian trauma practice. The mechanism of injury in the battlefield has changed over the years, with the improvised explosive device (IED) becoming the weapon of choice for insurgents. Blast injuries secondary to IEDs were the most common cause of coalition deaths in 2009 and 2010.

There has been a definite increase in very proximal lower limb amputations and unsalvageable leg injuries with associated pelvic trauma. The physical effects of a blast on the body are described above. The effects of blast at a cellular level is being investigated, but it has become apparent that a deep understanding and respect for the effect of blast on bone healing, systemic physiology and infection must be shown by treating surgeons. Improvements in personal protective equipment and in rapid evacuation have seen a reduction in the proportion of soldiers that die on the battlefield from exsanguinating torso trauma and this has led to many soldiers surviving to hospital level care. The majority of these soldiers will have complex injuries to limbs, including complex closed and open fractures, amputations or any combination of the above (Figure 6). The initial treatment of the patient with blast injuries relies on the skills of medically trained staff at the point of wounding. This first line or ‘buddy buddy’ care has been shown to have significantly reduced the mortality rate. These pre-hospital lessons are being transferred to civilian practice in the United Kingdom. Immediate measures such as the application of tourniquets (CAT) and the use of novel haemostatics have been shown to reduce or stop catastrophic haemorrhage. This practice is now mirrored in many ambulance services in the United Kingdom.

As the conflicts have matured, timely helicopter evacuation of blast patients to the regional medical facility at Camp Bastion has become the norm, the Medical Emergency Response Team deliver a hospital level of care to severely injured patients. This is now mirrored in the NHS, with severely injured patients being treated during transfer to major trauma centres by helicopters with well equipped and highly trained medical and paramedical staff. Patients with blast injuries need to be cared for by a multidisciplinary trauma team. As we have seen above, blast affects all body cavities. It is not uncommon for patients to suffer significant injuries to brain, lungs or intra abdominal viscera.

**Open fractures**
The patient with open fractures is assessed in the operating theatre as soon as possible, where surgery and resuscitation can occur.
Surgical debridement is preceded by irrigation using large volumes of warmed detergent solution to reduce gross contamination. Pre-debridement photographs are taken as a record of the injury. The basic principles of debridement are well described; all non-viable tissue must be removed; skin should be preserved unless it is obviously dead. Contaminated, dead fat and fascia should be removed. Muscle is deemed dead if it is non-contractile. Fasciotomies are undertaken if there is any clinical suspicion of compartment syndrome; they are also required after any vascular reconstruction. They should be along the full length of the muscle compartment, with care taken to maintain adequate skin bridges between incisions and the open wounds. Where feasible, wound dissection should be subfascial to protect the blood supply of the more superficial layers and to maintain the viability for later fasciocutaneous flaps.

Bone is deemed non-viable if it has no soft tissues attachments or fails ‘the tug test’. Formal muscle flaps should not be fashioned at the initial debridement, which may include partial or complete limb amputation. The acute reconstruction of nerves and tendons should not be attempted at the initial operation. The remaining wound should be a healthy bed in which future reconstruction can begin. Further irrigation of the wound with large volumes of low-pressure irrigation fluid is performed to lower the bacterial load. Stabilization of the injury should be undertaken to ease pain and aid transfer. The current military doctrine is not to perform definitive fixation at the first look. If grossly unstable, associated with vascular injury or large segmental bone loss, then simple monoaxial external fixation can be employed. Many of these fractures can be stabilized without external fixation — the Thomas splint is still used for the majority of femoral fractures, whilst most tibial fractures are rested in a back slab. The initial fracture management should not compromise definitive reconstruction.

The wounds are dressed with a topical negative pressure dressing (RENASYS EZ Smith & Nephew Healthcare Ltd). Second look surgery takes place approximately 24–48 h post injury. The wound will frequently have evolved and meticulous wound assessment and debridement by an experienced consultant-delivered orthopaedic team must again be carried out. Fracture fixation follows AO principles with the anatomical reduction of joints, the correction of rotation and the restoration of length.

**Paucimetallic fixation**

The spectrum of orthopaedic interventions available to manage limb fractures has the broad aim of reducing suffering, limiting bed days and enhancing functional outcome for the individual. Familiar robust and traditional constructions are used, but have often been adapted for use in this cohort of young, contaminated, frequently...
critically ill patients with injuries that are not isolated. Traditional surgical prescriptions for individual fracture management: plate, nail, frame, or ex fix, can be theatre-, resource- and time-consuming. Performing a series of “ideal for each fracture” procedures is often impossible due to on-table deterioration; performing them in parallel can be confounded by simple space constraints.

Where prolonged periods of critical illness and ITU support are certain, there can be infrequent and unpredictable opportunities for planned reconstruction surgery. Where five co-existing injuries would each individually have a major effect on functional outcome, treating four in a traditional manner, but leaving one untreated (for whatever reason) would give major functional disadvantage. By modifying standard treatment to all five injuries in a way that is “better than not at all” there is no untreated injury that lowers the functional ceiling.

Soft tissue envelopes that are open due to injury or fasciotomy and fragile due to energy laid down from projectile or blast are very vulnerable. Every effort is made to bring the skeleton to an anatomical position in order to reduce the volume of dead space within the injury zone and to bring muscles that are still attached to bony fragments back to their anatomical positions; muscles in the correct place are likely to optimize long-term function. Early reduction of fractures to an anatomical position takes advantage of the early healing response of bone, allows adherence of stripped soft tissues to the bone and allows early primary repair of nerves, tendons and the like over a stable local skeleton.

Where intramedullary nails are indicated the authors favour fracture reduction under direct vision using existing wounds and the use of undreamed, narrow devices to best preserve intra-medullary vascularity. This reduces operating time and avoids the systemic effect of reaming in a critically ill patient (Figure 10). However, if there is an anticipated risk of future amputation due to a more distal, separate injury, such as a distal third tibial fracture with calcaneal fracture, we frequently plate the bone within the zone of potential future amputation; the calcaneal fracture mandates a period on non weight bearing and rehabilitation is not delayed by a less robust tibial reconstruction.

It is essential to give meticulous respect to the tissues and use every technique possible to minimize further surgical stripping of soft tissues from each other and from bone. Wherever possible, access given by the injury is used as the window to approach the fracture and stabilize it without dissection of intact soft tissues.

Further reduction of soft tissue stripping can be achieved by downsizing the choice of implant. In a simple long bone fracture, after thoroughly washing the ends of the bone until they will never be cleaner, one or several lag screws may be used to oppose clean surfaces. The construct can then be neutralized with an external fixator distant to the zone of injury instead of by a plate within it. Reducing the volume of metal within the open wound reduces the surface area for biofilm formation and can allow simpler wound closure techniques to be used (Figure 6).

The use of therapeutic/suppressive antibiotics is essential. The duration of prescription is tailored to the individual patient’s physiology as well as the virulence of the infective organisms. This is facilitated by developing close working relationships with the microbiologists who form an integral part of the multidisciplinary team.

**Soft tissue reconstruction of blast injuries**

Blast injury, particularly that produced by improvised explosive devices, can produce a heterogeneous mixture of sharp, blunt and...
penetrating trauma, which may affect the entire body. These injuries are of discontinuous distribution. Manifestations of primary blast injury include fractures, amputations, crush injury, burns, cuts, lacerations, acute thrombotic occlusion of arteries, air embolism—induced injury, compartment syndrome, and others. Secondary injuries are the most common extremity blast injuries. Like primary injuries, they may necessitate limb amputation, they can be life-threatening, and can be associated with severe contamination. Tertiary blast injuries of the extremity may result in traumatic amputations, fractures, and severe soft tissue injuries. Quaternary injuries are most often burns. The presence of multiple injuries often leads to competing priorities of care and these are discussed at daily planning meetings by the ‘Role 4’ multidisciplinary team.

The principles of war surgery: arrest of haemorrhage; thorough wound debridement; temporary stabilization of fractures; removal of contamination and foreign bodies; copious wound lavage and administration of antibiotics are well recognized. In the reconstruction of blast injuries a hierarchy of management goals exists, these are to achieve:
- a clean non-contaminated wound;
- the removal of all dead tissue;
- timely coverage of exposed tendon and bone;
- timely coverage of open fractures;
- provision of robust, well vascularized coverage over nerve grafts and musculotendinous units, and;
- provision of robust soft-tissue coverage of amputation stumps.

It is usually not possible to reliably debride highly contaminated blast wounds in a single sitting, and severe infective complications can result from premature flap closure of open fractures in these injuries. It is important to delay soft-tissue reconstruction until the wounds are macroscopically clean, and remain so on two successive washouts 48 h apart with no physiological signs of sepsis.

The timing of reconstruction must be dictated by the clinical condition of the patient: a comprehensive reconstructive plan for each patient must be produced, balancing any competing reconstructive priorities. This plan must make the most advantageous use of often limited reconstructive options available. The decision of whether to embark upon immediate complex reconstruction in an acutely sick patient or to obtain wound closure by simpler methods, deferring complex reconstruction until the patient is stabilized, poses a challenging clinical conundrum for the treating clinicians. To aid this process it is worthwhile to ask three questions: What can the patient tolerate?, What must be done? and What can wait?

In general, in the multiply injured blast patient, it is wise to limit operative time, keeping reconstruction as simple as possible. However, complex microsurgical reconstruction should be considered when there is a clear benefit to be had from early (rather than delayed) reconstruction and the patient is physiologically well enough to tolerate prolonged surgery. In selecting flap options, every effort should be made to minimize donor morbidity in the often already disabled patient.

Local flap options are often not available due to extensive, discontinuous multiple fragmentation injuries. As blast wounds may take a considerable length of time before they are clean enough to close, it is possible to delay locoregional flaps, avoiding prolonged microsurgical operations. All patients should undergo angiography prior to free tissue transfer as fragmentation injuries to proximal pedicles may be present and thrombosis of recipient vessels can occur. The nature of blast-fragmentation injury means it is often not possible to get proximal to the zone of trauma and microanastomosis must be performed within the zone of trauma. However, if blood flow is good and the intima shows no sign of trauma, free tissue transfer can be safe and reliable. Flap selection is a challenge in young, fit patients. Potential donor site morbidity should be a major factor in flap selection. Low donor morbidity flaps should be first choice in the multiply injured patient, avoiding core stability muscles such as latissimus dorsi or rectus abdominis free flaps if at all possible.

Shoulder extension strength deteriorates permanently after removal of part of the latissimus dorsi muscle, even though subjective morbidity is minimal. Similarly, there is a clinically significant functional donor-site defect when measuring abdominal wall functional status following segmental rectus abdominis harvest. In an amputee these functional deficits could become significant. Bilateral amputees expend almost three times more energy than non-amputees when walking on prostheses and pectoral girdle strength is of great importance for the lower limb amputee, who will spend much of his time in a wheelchair.

The anterolateral thigh flap, if available, is an ideal fasciocutaneous flap (Figure 11). Muscle flaps should be first choice for open lower limb fractures, using gracilis or serratus anterior muscle flaps if possible; the gracilis is an expendable muscle and there is almost no functional deficit following its harvest. It can be harvested it from a contralateral traumatic above-knee amputation stump if necessary. The serratus anterior flap is very well tolerated with no reported weakness from patients.

Skin substitutes may be safely used in blast injured tissue following adequate debridement. Integra® (INTEGRA™ Bilayer...
Conclusion

The successful management of patients who have sustained injuries secondary to blast relies on the coordinated response of a large multidisciplinary team. A thorough working knowledge of both the physical and physiological effects of blast is the cornerstone of the reconstructive process.

Patients need to be aware that the process of bone and soft tissue healing and functional rehabilitation takes much longer than is observed with simpler injury patterns.

Disclaimer: the views expressed in this article are those of the authors and not necessarily those of the Armed Services.

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