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Explosive Injury

Explosives can cause multiple severely-injured casualties in a single incident. They currently pose the most prevalent threat to troops operating in conflict regions. However, recent explosive events on UK mainland have ensured these injuries are no longer solely the signature of military conflict. This briefing provides a background to explosive injury, explores developments in mitigation science, and highlights research priorities.

Overview

- Explosions cause expansion of gases, shock waves, and also energise fragments, all combining to cause unique injury patterns.
- Experience in treating explosive injuries can result in improved trauma care more generally, if diligence is exercised in analysing lessons learnt.
- The long-term collection and analysis of population data, coupled with research on injury mechanisms and environmental impacts is needed to improve treatments.
- Military medical research can inform civilian practice in this area, particularly in the field of rehabilitation; reductions in military medical resourcing and its medical research commitment could have wider societal implications.

Injuries resulting from explosives have dominated the medical response to every conflict since the beginning of the 20th century. Heightened exposure of doctors to explosive trauma as a result of recent conflicts has enhanced their understanding of its care, the speed with which it is managed, and the mechanisms through which it is mitigated. Preventing injury in the first instance, and improving both the long-term health and quality of life of those disabled by explosive blast is reliant upon continued research in this field. This POSTnote provides an overview of the:

- physics of explosions;
- effects of explosion on the human condition;
- health costs of explosive injury treatment;
- current state of research to mitigate the effects of explosives, and future priorities.

Explosives Physics and Injuries

Physics

Explosive Devices (EDs) can be sub-divided into: blast devices, which are sometimes formed from conventional military ordnance, and can be surface laid or buried; Explosive Formed Projectile devices; and suicide bombs[1].

Although varied in nature, EDs share certain features: they are composed of an initiator and explosive encased in a container. The manner in which they cause harm can be understood in 3 phases.[2]

- **Initiator**: the trigger excites the explosive main charge, and a chemical reaction converts the explosive into a hot, high-pressure gas, producing a shock or high pressure wave. The shock wave and the hot, high pressure gas released by the explosive propagates through its surroundings (casing, soil etc).
- **Gas**: expands rapidly under pressure typically in excess of 1 million times that of the Earth's atmosphere, at 6,000°C.
- **Ejecta**: If trapped, the gas vents through gaps in the fractured container and soil at about 4 km per second, thus violently energising its container and surrounding structure (rubble, metal, soil etc.) by forcing it out of the way.

The three main ways that explosions cause injuries are via the shock wave, the expansion of the gas and the consequent energised fragments. It is the first and second of these that give explosive injury its unique character. If an explosion occurs in a confined space, the blast wave reflects off surrounding structures, increasing the severity of harm caused.

The Effect of Explosives on Humans

Classically, any injury from an explosion can be divided into five categories (Box 1). Often, the severity of injury caused by each of these is dependent on the body region affected. Studies from the UK/US Joint Theatre Trauma Registries have shown that following an explosion, over 7 in every 10 combat wounds are to the extremities. Head and neck injuries account for 1 in 5 wounds. Improved body armour means that torso injuries are seen in less than 1 in 10 combat casualties[3].

Head and Face

Because the ear is very sensitive to pressure changes, it is commonly injured by explosions[4]. Both the transmission of shock through the brain, and the acceleration/deceleration force caused by the blast wave can cause a spectrum of injuries, from concussion to traumatic brain injury. Such injuries can manifest as headaches, altered sleep patterns, sensations and behaviours[5], and are easily missed. The majority of these cases resolve themselves. Post Traumatic Stress occurs in 7% of combat troops; this is likely to be higher in injured combat troops. Fragments from explosions can also cause severe facial and eye injuries[4].

Spine and Nerve

Increasing numbers of casualties survive with complex extremity wounds; for instance 13% of combat casualties from Iraq and Afghanistan sustained a nerve injury[6]. Often, these require a significant period of treatment, and are very different from the nerve injuries seen from other types of trauma. There is a strong relationship between spinal fractures caused by explosions and lower limb injuries[7].

Arms and Legs

Traumatic amputations as a combined effect of both shock and blast waves are common after explosions, particularly affecting the lower limbs[3]. The treatment of severe, life and limb-threatening injuries often necessitates an immediate or early decision between limb reconstruction or amputation. Such injuries carry a high psychological cost.

Chest, Abdomen and Pelvis

Blast wave impact to the chest can cause death immediately. Survivors of the initial insult[4] may also die due to the expansion and bursting of lung tissue. This is difficult to diagnose in blast survivors, and challenging to manage, often requiring treatment in a specialist intensive care unit[5]. Although abdominal injuries are less common than chest injuries, they primarily affect the colon, and often are only apparent days after the event. Genital injuries, occurring in 4% of blast casualties, can reduce fertility and result in urinary dysfunction.

Box 1. Explosive Injury

The specific location of an explosion can intensify its severity, potentially causing more harm, but injuries from explosions are usually classified as follows.

- Primary: caused by a sudden increase in pressure after an explosion, affecting air-containing organs, such as the lungs.
- Secondary: result from bomb fragments and debris being energised by the explosion. These have varying levels of lethality; larger fragments can transfer more energy, increasing the harm caused.
- Tertiary: caused when the casualty is thrown by the explosion and collides with nearby objects. They can have both local and global effects; local deformation of the floor of a protective structure for example, or global acceleration of the structure itself with the casualty inside it.
- Quarternary: related to the thermal effects of the blast, toxic effects, and any risks resulting from the incident, such as drowning (vehicle roll over into river) or freezing (shelter destruction).
- Quinary: often referring to illnesses, injuries, or diseases caused by chemical, biological, radiological and nuclear attacks ('dirty bombs'), and responses to explosions not immediately apparent[3].

Other Considerations

The indiscriminate nature of explosions means that both children and women, including pregnant women, can be injured. Disruption of the placenta, and fetal skull fractures can occur as a result of these events in pregnant women. Children suffer a greater proportion of injuries to the head due to its larger size compared with the rest of the body[4].

Health Costs of Explosive Injury

The costs of explosive injury are broadly unknown, and largely dependent upon the severity of injuries sustained. However, the costs can be broken down into those relating to acute care, rehabilitation and on-going care.

Acute Care

The estimated costs of all medical treatment as a result of military operations in 2008/09 was £71 million[8], with operational healthcare accounting for £41 million and the cost of UK hospital treatment £23 million.

Rehabilitation and Recovery

The estimated cost of rehabilitation from military operations in 2008/09 was £7 million[8]. In addition to this are the costs of longer-term rehabilitation of military personnel and veterans through the Personnel Recovery Capability. This is funded at a cost of £8 million a year to the MoD, and £5 million a year to The Royal British Legion for the next 10 years. Furthermore, Help for Heroes has committed £70 million to infrastructure capital expenditure in support of this capability. For instance, it is building a Personnel Recovery and Assessment Centre and two Personnel Recovery Centres.

On-going Care

The total costs of caring for chronic injuries, affecting both physical and mental health beyond rehabilitation and recovery, are unknown. The Royal British Legion spends approximately £1.4 million a week on *'wrap-around'* services to supplement the provision of care by the NHS to injured veterans. Social care costs associated with explosive injuries are unknown. In addition to the costs directly related to the provision of healthcare, the government is also liable for costs associated with compensation schemes (Box 2).

Box 2. Armed Forces Compensation Scheme (AFCS)[9]
Below are two examples of compensation for a 21-year old private soldier, discharged after different patterns of blast injury sustained in the course of service.

- Case 1 - having suffered a below knee amputation, typical compensation might result in a lump sum payment of £140,000, and a tax-free Guaranteed Income Payment (GIP) of £15,699 a year.
- Case 2 - having sustained a loss of both legs from the knee down, ear injury as a result of the blast, a mental disorder causing functional limitation lasting between 2 and 5 years, and persistent limb pain, typical compensation might result in a lump sum payment of £406,000, and a tax-free GIP of £20,932 a year.

Explosive Injury Mitigation and Recovery

Medical, scientific and technological advances as a result of explosive events since World War II have improved the chances of humans surviving explosive injuries. Four areas of particular importance include:

- physical protection;
- acute treatment;
- rehabilitation and recovery;
- emergency preparedness.

Physical Protection

There have been improvements in personal protective equipment, vehicle and infrastructure protection against explosive events over the last century.

Personal Protective Equipment

Personal eye protection, torso and pelvic body armour are worn by all front-line personnel in a threatening environment. Although designed to prevent injury from low speed weapons, they have a role in preventing fragment and blunt injuries in explosions. Explosive protective suits used by those in regular close contact with explosives use a modification of this technology, but cover all of the body surface area. Improvements in this equipment are focussed on reducing weight for the same level of protection, and improving the performance of the wearer[10].

Vehicle Protection

Explosive mitigation in vehicle design involves achieving a balance between protection and tactical agility. The most modern of armoured vehicles are heavy-weight and made out of armoured materials; some may also have a V-shaped hull, wide wheel bases and blast deflecting wheel arches. The most technologically advanced are modular; all modules are designed to be sacrificed in preference to the crew compartment. This improves survivability through energy loss as a result of progressive failure. Armoured plates for vehicles are typically composed of:

- a threat *disturber*;
- an air space;
- a force *absorber*;
- the body of the vehicle;
- a liner called the *spall shield*.

Future development will focus on materials used in manufacture, retrofitting extra armour plates and improving the balance between protection and tactical agility.

Infrastructure Protection

The first line of defence available to infrastructure is afforded by erecting hostile vehicle barriers distant to potential targets. Beyond this, the material and structural properties of buildings have undergone extensive tests to ensure blast survivability. Much like the case of sacrificial modules in vehicle design, work has focussed on predicting progressive collapse of buildings, and manipulating crowd flow away from these areas through intelligent design.

Acute Treatment

Medical and organisational advances resulting from conflicts of the last 10 years will affect wider trauma care.

Tourniquets, Pressure Dressings and Haemostats

Use of a tourniquet to stem bleeding in explosive trauma can be life-saving. Alongside this, a blood-clotting agent made of chitosan (sea crustacean shells) called *Celox* is now used in conjunction with a pressure dressing to great effect, as are techniques used to determine the body's own ability to stop bleeding (using a diagnostic system called *Rotem*)[11]. *Rotem* can guide clinicians in replacing blood-clotting products when the body has exhausted its own supply, and has made a significant difference in massive trauma survival[11].

Damage Control Resuscitation and Surgery

In massive trauma, there is a role for resuscitation in an operating theatre. The principle of operating on an injured person initially to restore circulating blood volume, followed by repairing other injuries 24-48 hours later has resulted in improved outcomes from explosive trauma[11]. These approaches have enabled a staged evacuation to specialist trauma centres within the NHS where the best care can be received.

Dedicated Trauma Facilities and Training

Explosion victims in conflict zones are managed in a dedicated military trauma facility, with an outreach team of specialists who rapidly transport the casualty from the point of wounding to hospital. The dedicated trauma centre model established in the NHS is projected to save 450 to 600 lives a year in England[12]. Establishing cooperative NHS-Military teams creates mutual benefits in preparing for and managing major trauma, as skills in planning, patient care and academia are identified, retained and deployed effectively. Essential to providing this level of integrated trauma care is team-work among specialists; the Military Operational Surgical Training course ensures effective team-working amongst medical staff to produce the best outcome for their patients[13].

Rehabilitation and Recovery
Complex physical trauma can present real challenges in rehabilitation, requiring intensive, inpatient and holistic management. Recent developments in prosthesis design, fit and materials have changed the lives of amputees, as have advances in chronic pain management. There are opportunities for lessons to be transferred to civilian complex trauma rehabilitation. Super-infections, infertility, unwanted bone growth in muscle and nerve dysfunction still pose challenges in these patients.

Emergency Preparedness
No two explosive events are the same, causing difficulty in planning and resource allocation. Explosive events are relatively rare in the civilian arena. Medical responses to them suffer from communication and logistical failures. Ineffective response and limited capacity in managing unexpected events are related to poor outcomes[14]. Critical to resilience is pan-agency training at all levels, optimised inter-operability, continual translation of practice and intelligent resourcing. Furthermore, rapid deployment of blast and ballistic experts in support of explosive event management is critical.

The process of emergency preparedness must be able to establish why and how people die from an explosive event. This can now be achieved through both permanent imaging recording of injuries (Computed-Tomography Post-Mortems)[15], and mechanisms for reviewing and developing practice. The military uses the Joint Theatre Trauma Registry to achieve this; the NHS uses a similar mechanism called the Trauma Audit and Research Network, and both military and civilian specialists use the same common language, and classification system to describe injury patterns.

Gaps in Understanding/Future Research
Improving outcomes after blast injury is dependent upon collaborative research into blast effects and blast mitigation. Fundamental to this is a fusion of long-term epidemiologic data with *blast dose-injury response* data.

Blast Effects Research
Very little is known about the multi-scale effect of explosive injury, at the molecular level, in cells and tissues, even in whole organs, a knowledge that is critical to diagnosing and treating the latent effects of blast. Indeed, the wider effects of blast overpressure on the body are only now being appreciated. Further work is needed to measure incapacitation of human performance as a result of explosions, and to predict the effects of trauma over time. Critical to this is an understanding of the cost of explosive injury to both the individual and society as a whole.

Blast Mitigation Research
Current models of explosive damage are limited in their ability to predict complex interactions with urban infrastructure, and subsequent effects on human injury. Improved prediction tools will enhance accurate medical planning and resource management, and help security personnel to identify and address vulnerabilities. A particular issue is the design of blast protecting vehicles; not only do we need to maintain a balance between crashworthiness and blastworthiness, without impairing tactical agility, but we need to optimise a vehicles response to blast to improve the survival of its passengers.

Although eye and torso personal protective equipment has improved substantially, further research and detailed studies are needed to develop improved protection for the prevention of concussive head injury from blunt trauma.

Research Collaboration
The Ministry of Defence and the Department of Health have worked closely in recent years to share best practice in treating blast injuries. Their clinical leaders have worked cooperatively between departments and across government to achieve this. Exemplars of successful collaboration established to allow both military and civilian clinicians and scientists to work together to advance clinical practice include the NIHR Surgical Reconstruction and Microbiology Centre at Queen Elizabeth Hospital, Birmingham, the King's Centre for Military Health Research at King's College London and the Imperial Blast initiative at Imperial College London.

Endnotes

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