What the intensive care doctor needs to know about blast-related lung injury

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Explosions are currently the primary cause of military combat injuries. A minority of civilian trauma is also caused by explosions. People hurt by explosion are likely to present with complex injuries. The aim of the article is to explain the mechanism underlying these injuries and the associated physiology to help the intensive care clinician manage these casualties properly. The generic term 'blast injury' is applied to a collection of injuries caused by explosion. Components of blast injuries have precise definitions relating to the elements of the explosion that caused the injuries: primary blast injury is due to a shock wave, secondary blast injury is caused by fragments and debris colliding with the victim and tertiary blast injury is due to the casualty being thrown against solid objects. Primary blast injury results in damage principally in gas-containing organs, eg the lungs (blast lung) and can lead to impaired pulmonary gas transfer and hypoxaemia. Secondary blast injuries are often penetrating and can lead to haemorrhage while tertiary blast injuries are often blunt and involve substantial tissue damage. Survivors of explosions in confined spaces are more likely to exhibit primary blast injury than those injured in open spaces. The current military approach to immediate management is to apply the C ABC principle (arrest catastrophic haemorrhage first and then deal with airway, breathing and circulation) to achieve Damage Control Resuscitation. Early administration of blood products (plasma as well as red cells) is advocated for those suffering significant haemorrhage. Initial resuscitation is hypotensive to minimise risk of dislodging nascent clots. However, if evacuation is protracted (longer than one hour) then consideration should be given to improving blood flow / oxygen delivery by adopting a revised normotensive blood pressure target to reverse the deleterious consequences of the hypotensive shock state. Animal studies have shown that titrating FiO_2 to a target SaO_2 of 95% can improve survival and 'buy time' during hypotensive resuscitation. Ventilator strategies should use a lung-protective approach with permissive hypercapnia if necessary. Blast casualties are often a challenging group of patients needing expert, tailored, care. Outcome can be good especially in young, otherwise fit, casualties with more than 96% surviving to ICU discharge, although this figure may be lower with a mixed civilian group.

Keywords: *blast injury, treatment of blast injury*

Introduction

The majority of human injuries consequent to an explosion used to be confined to the battlefield and were very much the domain of the military clinician, but this is no longer the case. Over the last 40 years the UK civilian population has experienced a number of explosions related to acts of terrorism (**Table 1**) and in addition, injured UK military personnel requiring on-going hospital care are now managed within the National Health Service. Given the ever-present threat of acts of terror, civilian health professionals and the NHS are likely to encounter more rather than fewer blast injuries.

People seriously hurt by explosions are likely to present with complex injuries. Understanding the underlying mechanisms of injury and the associated physiology will help intensive care clinicians manage these people appropriately.

What happens in an explosion?

When an explosive detonates, it generates an extremely rapid increase in pressure in the immediate vicinity of the explosion (**Figure 1**): this rise in pressure is almost instantaneous with a rise time of a few microseconds.

This has a 'knock-on' effect on the surrounding air, transferring the high pressure as a wave travelling outwards faster than the speed of sound from the site of the explosion. The entire pressure waveform – consisting of the initial high pressure, called the 'peak overpressure,' followed by a rapid fall in pressure to sub-atmospheric levels, before returning to normal – usually lasts for only a few milliseconds at any one point. This is called the 'shock wave.' The magnitude of the peak overpressure declines as it travels away from the site of the explosion, initially by an inverse cube relation, in which a doubling of the distance reduces the pressure to one-eighth.

As the shock wave is a very brief event with conventional explosives, it does not cause the target (object or casualty) to move any great distance; this is not the part of the explosion that 'throws things around.' The shock wave can, however,

Date	Type	Location	Fatalities	Injured
22 Feb 1972	VBIED	Aldershot, Hampshire	7	18
05 Oct 1974	Two IEDs	Guildford, Surrey	5	69
21 Nov 1974	Two IEDs	Birmingham	21	119
30 Mar 1979	VBIED	Houses of Parliament	1	0
20 Jul 1982	VBIED and IED	Hyde Park and Regent's Park, London	11	50
17 Dec 1983	VBIED	Harrods, London	6	90
10 Apr 1992	VBIED	Baltic Exchange, London	3	91
20 Mar 1993	Two IEDs	Warrington	2	56
26 Jul 1994	Two IEDs	London	0	26
10 Feb 1996	VBIED	Canary Wharf, London	2	39
18 Feb 1996	IED on bus	London Aldwych (bus)	3	8
15 Jun 1996	VBIED	Manchester	0	212
17 Apr 1999	IED + nails	Brixton, London	0	48
24 Apr 1999	IED + nails	Brick Lane, London	0	13
30 Apr 1999	IED + nails	Admiral Duncan pub, London	3	87
04 Mar 2001	VBIED	Shepherd's Bush, London	0	1
07 Jul 2005	Four suicide bombers	London	52	584
30 Jun 2007	Failed VBIED	Glasgow airport	1	5

Table 1 Forty years of terrorist bombs in England and Scotland.
Key IED: Improvised explosive device. VBIED: Vehicle-borne IED

cause serious injury which will be considered below.

Fragments of the munition casing and pre-formed fragments (such as ball bearings or metallic cubes) contained within the device and surrounding debris energised by the explosion are propelled outwards and can collide with the target. In addition, the explosion gives rise to a very large volume of hot gas. This literally pushes air and debris outwards, causing more projectile hazards, and acts over a sufficiently long time course to physically throw casualties against other objects. This is called the 'blast wind.' The shock wave and the blast wind are sometimes collectively called the 'blast wave.'

Finally, for those close to the explosion there is also a large amount of heat which can also cause injury. Armed with this information we are now in a position to classify blast injuries.

How do explosions kill and injure people?

Injuries caused by an explosion can be classified as primary, secondary, tertiary, quaternary or quinary.[1,2] There is a high degree of agreement between authors as to what constitutes primary through to tertiary injury, but considerably less agreement for quaternary and quinary injury.

Primary blast injuries result from the interaction of the blast wave with the body. Injury is classically thought of as being predominantly confined to the air-containing organs, such as the lungs, bowel and ears, often without external signs of injury.[3] Recently there has been heightened suspicion that primary blast injury may also occur to the brain[4-6] even in the absence of gross macroscopic changes at post-mortem examination or on brain computerised tomography. A commonly cited example of a primary blast injury is 'blast lung.' This can be life-threatening and when severe can be rapidly fatal.

Secondary blast injury results from the impact of fragments and larger missiles accelerated by the blast. The source of these missiles may be the device itself or from the environment within which the device detonates and may be comprised of a variety of materials including soil, stone, glass, brick, metal, wood and bone, among others. Injuries caused by these fragments can be further categorised as penetrating or non-penetrating. This group accounts for the majority of blast injuries in survivors, particularly when the explosion has occurred in an open space.

Tertiary blast injury results from the acceleration of the whole body or parts of the body causing impacts with the ground or other fixed objects. Some published injury definitions include building structural collapse with blunt and crush injuries (including crush syndrome) in this tertiary category.

There is less agreement in the literature regarding the classification of other types of injury. A recent definition used by the US Department of Defence[7] has the additional features:

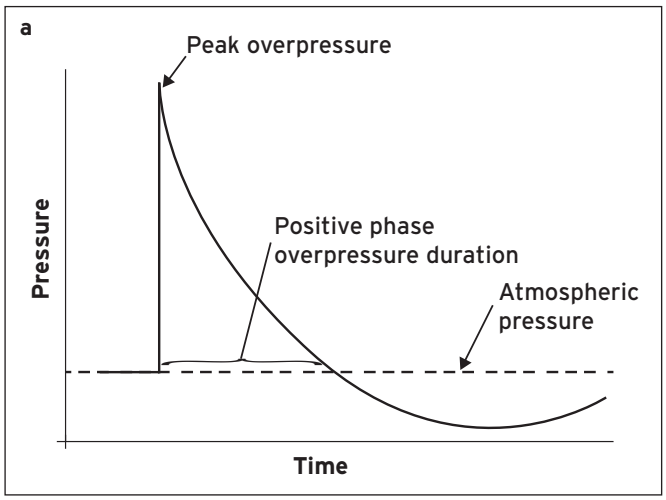
Quaternary blast injury being other 'explosive products' effects: heat (radiant and convective) and toxidromes from chemical products of the explosion causing burn and inhalation injury.

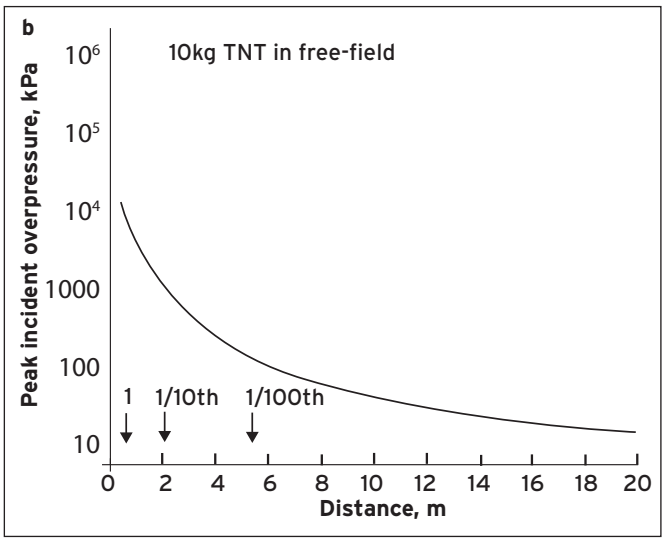
Quinary blast injury is the clinical consequences of 'post-detonation environmental contaminants' including bacteria (deliberate and commensal, with or without sepsis), radiation (dirty bombs), and tissue reactions to fuel and metals.

Other authors[8] are more restrictive in their definition of quaternary and quinary injuries, confining them, respectively, to 'thermal and chemical injury from the blast including inhalational injury' and 'delayed immunological response to the blast wave.'

Unfortunately some authors have confused the literature by using the unqualified term 'blast injury' to indicate 'primary blast injury.' This has the capacity to confound discussions on the matter and perhaps a safer option now is to avoid the generic term 'blast injury' and use instead 'blast-related injury' which does not presuppose any specific category.

So, let us consider a bomb placed within a car that detonates. People close by could be injured or killed by the overpressure from the explosion (primary), by fast moving fragments from the car and bomb casing (secondary), and by burns from the heat of the explosion and that generated by the ignition of fuel (quaternary). Those very close to the explosion





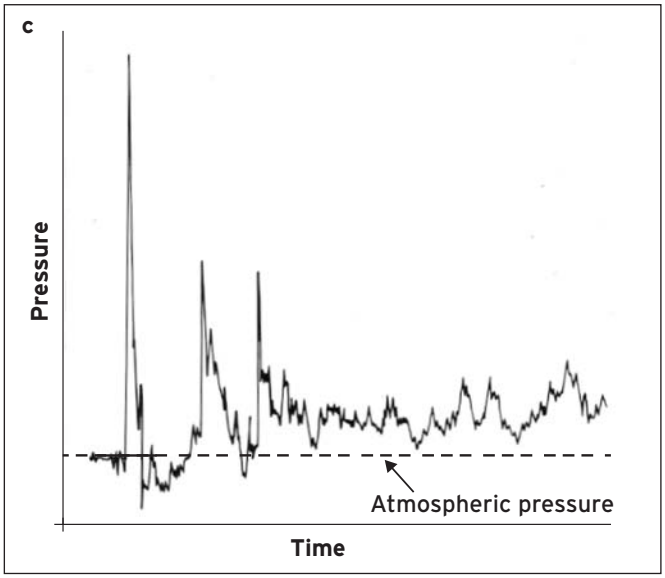


Figure 1 Schematic representation of a shock wave generated by the detonation of an explosive; **a**) Pressure versus time at a single point in a 'free field' (away from structures that can reflect the shock wave such as walls or even the ground). **b**) Pressure versus distance from point of detonation in a free field. **c**) Pressure profile associated with an explosion in an enclosed space, eg a room, note multiple peaks from a single explosion due to reflection of the shock wave by solid surfaces.

may suffer traumatic amputation of limbs, which is discussed in detail later. Traumatic amputation is viewed as a tertiary blast injury by most authors, although a component of this aspect of injury, the initial fracture of long bones, is more likely the consequence of the shock wave. The shock wave can cause damage to gas-containing organs which includes the lungs (see below) and intestines, which may go on to perforate at a later stage.[9-11] Bystanders could also be knocked over and/or thrown about by the explosion (tertiary). People further away may be at a sufficient distance to avoid serious primary, quaternary or even tertiary injury, but may still be hurt by flying debris (secondary).

The environment within which the explosive device detonates has a profound effect on the nature of the injuries seen. Solid surfaces reflect the blast wave and, where incident and reflected blast waves overlap, the peak overpressure becomes the sum of the overlapping pressure waves, which can be extreme. Furthermore, because of the reflections, the casualty may be subjected to a very complex pattern of blast loading including several shock waves from a single explosion (see **Figure 1c**). In enclosed spaces, therefore, the overpressure any individual experiences is significantly determined by their relative position to the point of detonation and the precise geometry of their surroundings, resulting in a significantly increased likelihood of primary blast injuries and sometimes surprising patterns of fatalities and survivors. In addition, a bomb detonated within a building may produce all of the above injuries as well as structural collapse (tertiary).

Explosives and amputations

An explosion interacts with the musculoskeletal system to cause extensive injury through a combination of the blast wave, penetrating fragments and rapid bodily displacement. If the victim is situated close to the explosion, such as an improvised explosive device (IED) explosion involving dismounted troops, the effects of the blast wave and detonation products occur almost instantaneously. Upon detonation, the blast wave is transmitted directly into the limb, resulting in a brisance or shattering effect on the bone. One or two milliseconds post-detonation, the detonation products and any fragments contact the limb causing destruction of traumatised soft tissue and the application of maximal stresses on bone previously damaged by the blast wave.[12] The net result is either a total or sub-total amputation of the limb, with the soft tissue injury and contamination extending more proximally than the damaged bone.

These are common injuries, but were usually seen in fatalities rather than survivors. Several authors have reported an incidence of approximately 1% in survivors compared to approximately 20-40% of fatalities following terrorist bombings.[13-17] These findings led to the assumption that significant blast loading was required and that this would cause such severe pulmonary damage that survival was unlikely. However, recent UK experience has been that haemorrhage, rather than lung injury, is the leading cause of death following traumatic amputation. As such, with the significant advances

Time from blast of injury generation	Mechanism	Time from blast of clinical manifestation	Lung pathology	BRLI: Primary	BRLI: Early	BRLI: Late
Milliseconds to seconds	Blast wave	Minutes to hours	Scattered foci of alveolar haemorrhage Alveolar disruption (blast emphysema) Parenchymal laceration Pneumothorax			
Seconds to minutes	Blast ejectate Blast wind propulsion Building collapse/crush injury Airway obstruction Smoke inhalation Aspiration of stomach contents/water Bone fractures	3 to 18 hours	Contusion Laceration (+ haemopneumothorax) Negative pressure pulmonary oedema Inhalation/aspiration Pneumonitis Fat embolism			
Hours to days	Over-resuscitation and/or LV dysfunction Massive blood transfusion Injurious mechanical ventilation Pulmonary inflammation	8 to 36 hours	Fluid overload and/or coronary air/fat emboli Transfusion-associated lung injury Ventilator-associated lung injury Acute respiratory distress syndrome (diffuse alveolar damage)			

Table 3 Blast-related lung injuries (BRLI).

- Diagnostic criteria applied within hours (<12) from the time of the blast
- Exclusion of secondary or tertiary lung injuries
  - Penetrating thoracic injuries
  - Presence of fractures of the ribs, clavicles, or scapulae
- Objective evidence of lung injury based on the presence of both radiological abnormalities and internationally agreed oxygenation criteria for acute lung injury

Table 2 Stringent criteria for the detection of primary blast injury of the lung.

in haemorrhage control and resuscitation that have been made, survival is not only possible, but common. A review of recent UK experience has noted that casualties are more likely to survive a traumatic amputation than to die of their injuries (Walker *et al*, unpublished, 2012).

A closer look at overpressure and primary blast lung injuries

The lungs of casualties hurt in explosions can be injured by a number of mechanisms, some of which will be familiar to intensivists and some less so. The blast wave travels ahead of any materials encasing or around the explosive and is too short-lived to physically displace casualties. Nevertheless the blast wave itself is responsible for a particular pattern of injuries which are referred to as 'primary blast injuries.'

Primary blast injuries: the enigma of 'blast lung'

Primary blast lung injury (PBLI), commonly referred to simply as 'blast lung,' is believed to be caused by the interaction between the blast wave and lung tissue. This interaction is characterised by a longitudinal high-frequency stress wave followed by a transverse, low-frequency shear wave.[18] This results in 'spallation', the process by which fragments of material are ejected from an object due to impact or stress, and 'brisance', the shattering capability of an explosive. Spallation occurs when the blast wave passes from tissue of high density (such as the alveolar capillary) to one of low density (the alveolar lumen) because of the rapid acceleration of the final layer of denser tissue.

Where the force of acceleration exceeds the denser tissue's tensile strength, the denser material is locally disrupted. In the lung this manifests as widely scattered foci of alveolar haemorrhage within the parenchyma secondary to alveolar capillary rupture.[19-22] The shear waves following immediately behind the stress waves typically cause parenchymal tears, especially between fixed and mobile tissues. These range in size from foci of 'blast emphysema' to pneumatoceles and pneumothoraces.

Most people injured by a blast receive a complex mixture of primary, secondary and tertiary blast injuries. Identification of the small minority with pure primary blast lung injury requires the application of very specific criteria (**Table 2**). Identification of these patients is more of academic than clinical interest and few, if any, reports on blast lung have rigorously identified this group of patients.

In a recent study where strict criteria were applied[23] only 3.6% of the 71% of combat casualties admitted to medical treatment facilities during 2003-2006 as a result of explosions were found to have (pure) blast lung injury. Their definition of blast lung will have excluded cases co-existing with other types of thoracic injury, which is common with conventional munitions and terrorist bombs and is likely to have underestimated the occurrence of blast lung in current military casualties. By contrast, a more recent assessment[24] found an

incidence of approximately 11% in casualties who also suffered other, particularly penetrating, injuries.

Secondary, tertiary and quaternary blast injuries to the lung

Materials encasing and around the explosive device travel in the vanguard of a rapidly expanding sphere of hot gas and cause secondary injuries by colliding with casualties. They may cause either blunt or penetrating injuries depending on their energy, size, density, and shape. Injuries may include thoracic fractures (ribs, clavicles, scapulae, vertebrae), pulmonary contusions, and pulmonary lacerations.

The blast wind itself has formidable destructive force, capable of collapsing buildings and throwing casualties for significant distances. Tertiary blast injuries consequently may include crush injuries and asphyxiation. Injuries sustained by the casualty on impact with other objects, technically tertiary, cause an injury pattern that is generally indistinguishable from blunt secondary injuries, with the single exception of impalement. As with any traumatic event, casualties injured by any of the mechanisms mentioned above may also regurgitate and aspirate gastric contents, or inhale hot or toxic gases released during the explosion or generated by a subsequent fire, leading to either an aspiration pneumonitis or an inhalational injury. These are characterised as quaternary injuries.

The range of possible pulmonary injuries following exposure to blast are presented in **Table 3**, clarifying the point that only injuries caused by the shock wave itself are properly classified as primary blast injuries. It is important to note that none of the available literature on primary blast injury of the lung uses sufficiently stringent selection criteria (**Table 2**) to confidently exclude secondary and tertiary blast injuries or detect the presence of covert lung injury in the population at risk by systematic lung radiology and arterial blood gas analysis.[15,23,25-29]

Clinical injury patterns

Rapid death

Rapid death in patients with no obvious external signs of fatal injury is still an incompletely understood phenomenon. Damage to pulmonary blood vessels creates the opportunity for air ingress, leading to systemic air embolism, especially of the cerebral and coronary circulations. Arterial air embolism in the cerebral and coronary circulations have repeatedly been demonstrated in animals following experimental blast[30-33] and using an implanted Doppler probe, emboli have been recorded in the carotid artery of a beagle for 30 minutes following an LD50 air blast.[34]

Evidence of air embolism in humans is sparse because of the failure to look for it in survivors and because of the loss of evidence caused by the inevitable delay in performing autopsies in non-survivors. Post-mortem evidence of systemic air embolism in air-blast was found in a retrieved kidney from an Israeli soldier who died shortly following a nearby explosion[35] and more recently post-mortem examination of civilian air-blast fatalities showed pulmonary venous air embolism in four of eight subjects.[22] Improvements in the speed and quality of immediate care, certainly in a military context, means that casualties who would have died at the scene only a decade ago are now able to reach tertiary care facilities alive. The possibility of significant air embolism should therefore be borne in mind, especially in cases where hypovolaemia alone does not seem to explain the degree of circulatory failure.

Apnoea has been reported in a number of species (eg rat and pig) in experimental studies of blast exposure. With moderate blast loading the apnoea is transient and respiratory rhythm returns spontaneously, however with severe blast loading, the apnoea may be prolonged and can be associated with early death.[36]

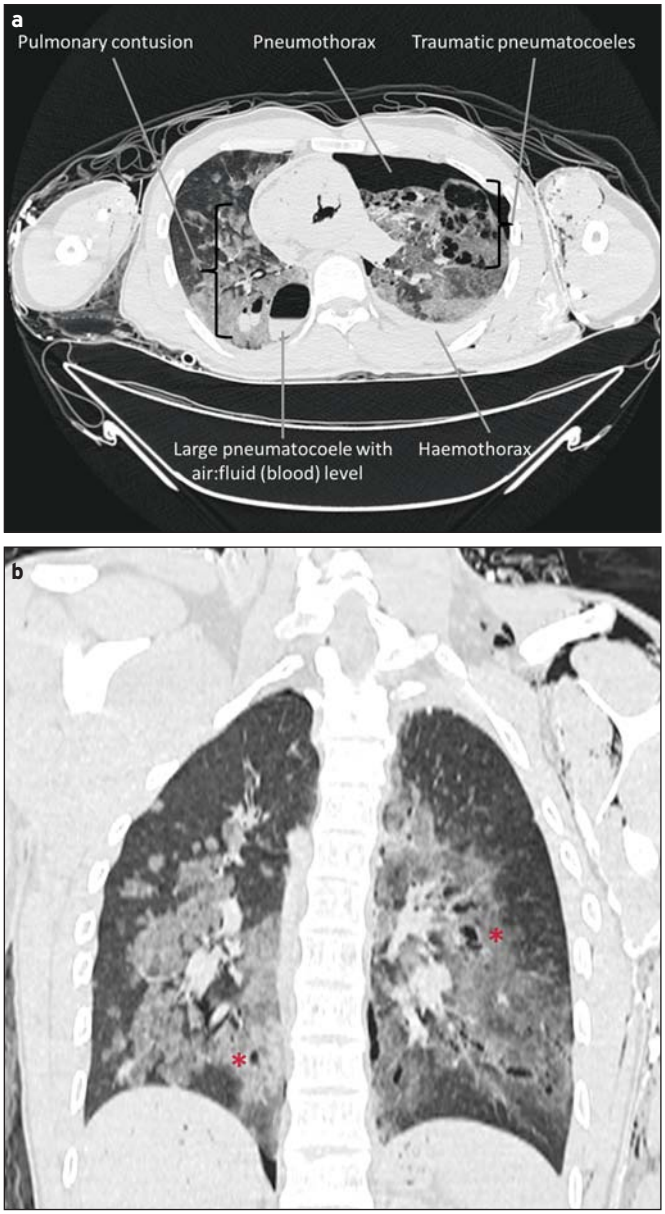


Figure 2 **a**) Axial CT chest image showing severe primary blast lung injury with widespread traumatic pneumatocoeles and a haemopneumothorax on the victim's left an on their right significant pulmonary contusion and a sizeable posterior traumatic pneumatocoeles with air-fluid(blood) levels. **b**) Coronal CT chest image showing bilateral PBLI with well defined, patchy pulmonary contusions in both lungs and bilateral traumatic pneumatocoeles (red asterisks).

Early blast-related lung injury

Contusion

While it has long been recognised that pulmonary contusions can occur without external injuries[37] the differentiating feature from primary blast lung injury is that contusions do not occur throughout the lung parenchyma[20] and are not associated with interstitial emphysema.[20,22] Initial plain chest radiology generally underestimates the extent of pulmonary contusion[38] and abnormalities develop over 24 hours following injury. More recently, computerised tomography has been of value in determining the extent of pulmonary injury after blast exposure (**Figure 2**). Blood-filled alveoli reduce pulmonary compliance and worsen ventilation/perfusion matching, resulting in hypoxaemia and dyspnoea. Cell rupture within the contused lung releases damage-associated molecules[39] causing inflammation, ingress of leukocytes and, in animal models, immunomodulation.[40] Computerised tomography protocols can define the proportion of lung affected by contusion, providing a measure that has been shown to be associated with outcome.[41]

Other than by the time-course of their onset, pulmonary contusions cannot clinically be separated from aspiration/inhalation injury, fluid overload, transfusion-associated lung injury (TRALI), or embolisation.[38] Aspiration or inhalational injury can be documented by finding gastric content in the airway or soot around the glottic opening at intubation.

Fat embolism

Autopsy series in trauma patients suggest that pulmonary fat embolism (PFE) can be detected in over 75% of cases[42,43] although it is accepted that the incidence of clinically significant fat embolism syndrome (FES) is much lower.[44] The incidence of PFE and FES in blast-related injury is poorly defined; FES was reported in a small series of combat casualties, eight of 15 of whom had been injured in explosions,[45] while PFE were found in one of three miners[46] killed in an underground explosion in Lancashire in 1979 and, more recently, in five of eight civilian blast fatalities.[22] Leavell comments[47] that PFE was considered a common occurrence in battle casualties during World War II although none were found in an undefined subset of Savage's autopsy series.[21] McCaughey discussed fat embolism in the context of two women injured in a bomb explosion in Northern Ireland because FES was in their differential diagnosis for respiratory failure.[48] They could not find fat emboli in the blood larger than 10 microns in diameter, but they made no mention of looking in the urine or fundi. Subsequent reports have largely overlooked this as an issue. This may be because many of Gurd's diagnostic features of FES[49] (neurological symptoms/signs, hypoxaemia and pulmonary infiltrates, thrombocytopaenia, pyrexia, tachycardia, high erythrocyte sedimentation rate) are non-specific findings in patients with blast-related multiple trauma. A systematic search for evidence of FES in blast-injured casualties has yet to be performed and would need to rely on other diagnostic features, such as a petechial rash,[49] fat globules in sputum, urine, or on fundoscopy,[50] diffusion-weighted magnetic resonance imaging,[51] or broncho-alveolar lavage.[52,53]

	Risk of TRALI per unit	
	Silliman[83]	Ozier[84]
Platelets	1 in 432	–
Platelets (apheresis)	1 in 1,224	1 in 13,000
Packed red blood cells	1 in 4,410	1 in 80,000
Fresh frozen plasma	1 in 19,411	1 in 13,500

Table 4 Risk of developing transfusion-related acute lung injury (TRALI)[86] by type of blood product.

Late blast-related lung injury

Transfusion

TRALI describes a pulmonary syndrome clinically indistinguishable from the acute respiratory distress syndrome (ARDS) that develops in susceptible patients within six hours of receiving blood or blood-derived products[54] (platelets, fresh frozen plasma), although histopathologically the two are quite distinct.[55] In the USA in the period 2005-2010, TRALI was the single largest cause of transfusion-related fatalities, causing 145 of the 307 (47%) reported deaths, but the background risk per unit transfused is low (**Table 4**). The risk of TRALI in patients injured by blast is increased only in proportion to their requirement for blood products, in contrast to their risk for developing ARDS and/or multiple organ failure. Transfusion-associated circulatory overload (TACO) is a distinct entity that simply describes volume overload in the context of blood-products, as opposed to circulatory overload provoked by colloids or crystalloids.

Ventilator-associated lung injury (VALI)

Clinical experience in the second world war,[56] as well as later animal data, suggested that early post-injury positive pressure ventilation and/or anaesthesia resulted in much poorer survival. Based on this, subsequent authors suggested that intubation, positive pressure ventilation, and anaesthesia were contra-indicated in the early phase following injury.[57,58] More recent experience in the Middle East has shown that early respiratory support or anaesthesia is, in many cases, both unavoidable and life-saving. In these circumstances an exacerbation of the pulmonary injury may be minimised by adopting a lung-protective ventilation strategy with permissive hypercapnia.[59] The importance of this strategy throughout the patient's ventilation pathway is emphasised by recent evidence that the risk of developing acute lung injury is independently associated with the initial tidal volume.[60] The use of positive end-expiratory pressure (PEEP) is similarly unavoidable[61] and contributes to a lung-protective strategy by minimising both cyclical recruitment and prolonged exposure to high fractional inspired oxygen concentrations (FiO_2). Despite the desire to avoid prolonged exposure to a high FiO_2 in the medium- and long-term (>24 hours from injury) to reduce the risk of VALI, there is evidence from an animal model of blast injury to suggest that a high FiO_2 may be beneficial in the immediate post-injury phase.[62]

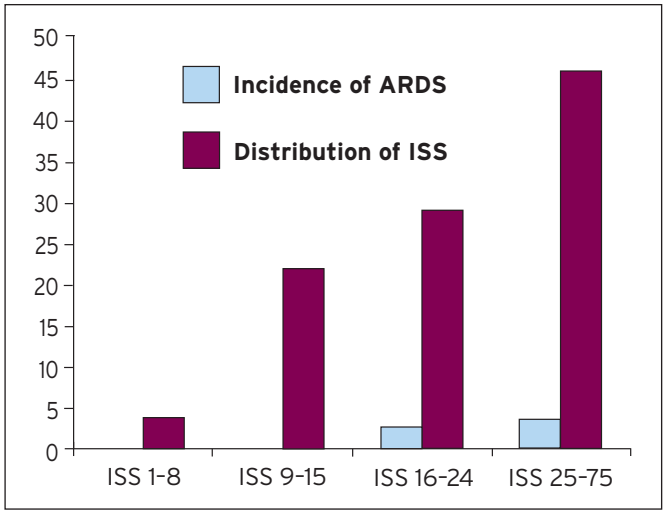


Figure 3 Incidence of the acute respiratory distress syndrome (ARDS) by injury severity score (ISS), adapted from White[63] and distribution of injury severity scores following terrorist bombings in Israel.[85]

Acute respiratory distress syndrome

The incidence of post-traumatic ARDS in the UK is about 1 in every 200 patients[63] and varies in proportion to injury severity (**Figure 3**); in the US the incidence is reported to be between 4.1% and 6.8%, depending on hospital type[64] and injury severity.[65] Other independent risk factors for the development of post-traumatic ARDS include the transfusion of packed red blood cells[66] as well as fresh frozen plasma.[67] The incidence of ARDS in victims of explosions has not been specifically reported, either in military or civilian patients, but the association with injury severity and blood products suggests that they are a high risk group.

Epidemiology

The concept of epidemiology is relatively meaningless in the context of an injury that is so dependent on physical circumstances at the moment the explosive detonates. In general, explosions in enclosed spaces, such as trains, buses, or buildings, generate much higher peak overpressures than similarly powered explosions in the open, as well as increasing the subject density within the immediate vicinity of the blast. Both effects increase the proportion of subjects killed or seriously injured.[68]

Clinical presentation and management

Experimental work in rats has demonstrated that immediate survivors of blast experience a vagal-driven period of transient apnoea, associated with hypotension and bradycardia[36] but no direct evidence for this phenomenon exists in man, possibly because measurements have not been made in human casualties within the first few seconds/minutes after injury. Thereafter, an immediate threat to life is presented by bilateral or tension pneumothoraces which need to be identified and dealt with urgently. Common complaints among those with lung injuries include severe chest pain and dyspnoea, often accompanied by cyanosis, haemoptysis and tachypnoea. Confusion and agitation are also commonly reported and may

- Immediate airway management ± intubation
- High FiO_2 for first 8 to 24 hours in all patients, thereafter use lowest possible FiO_2 to achieve modest oxygenation targets and avoid hyperoxia (PaO_2 >11 kPa).
- Lung-protective ventilation
  - Tidal volume 6 mL/kg lean body weight
  - PEEP selected by FiO_2
  - Limit peak inflation pressures to a maximum of <35 cm H_2O
- Permissive hypercapnoea; manage $PaCO_2$ to aim for a pH between 7.15 and 7.3. If pH <7.15 with haemodynamic instability (ie requirement for vasopressors or inotropes) consider use of alkalinising agent.
- Consider permissive hypoxia (PaO_2 6 to 8 kPa) if PF ratio ≤10 kPa and no suspicion of cardiac or neurological ischaemia.
- Consider inhaled nitric oxide, if facilities for delivery are available.
- Consider high-frequency oscillatory ventilation within four hours of the onset of refractory hypoxaemia.
- Consider extra-corporeal membrane oxygenation providing there is no evidence of on-going pulmonary haemorrhage.

Table 5 Key ventilatory recommendations.

be secondary to a direct effect of the blast wave or the result of cerebral air embolism. In-field haemorrhage management with tourniquets and haemostatic dressings together with initial hypotensive resuscitation and immediate airway management are valuable lessons that have been learned from the military (**Table 5**). The seriously injured blast casualty may be suffering from blood loss and lung injury. Hypoxia from the lung injury may be immediately apparent or develop over time as the injury matures. High concentration oxygen in the initial phase of resuscitation may have a role in dissolving gas emboli and has been associated with improved survival in animals,[62] although evidence of this phenomenon from fundoscopy and examination of the tongue (Liebermeister's sign, ie sharply defined areas of pallor in the tongue) and electrocardiogram should be deferred to the secondary survey. Similarly, otoscopy to detect tympanic membrane rupture is not a high priority as its presence does not correlate well with the presence of primary blast lung injury.

The current military approach to immediate management is to follow a <C> ABC paradigm[69] to achieve Damage Control Resuscitation.[70] <C> ABC is a UK military adaption of the 'Airway, Breathing, Circulation' approach to trauma care that UK anaesthetists are familiar with, but prioritising rapid management of catastrophic bleeding (the <C>) with tourniquet and pressure dressing in the blast- and ballistic-injured casualty. Tranexamic acid is given early – often during the initial helicopter medevac of the critically injured casualty. Damage Control Resuscitation is a 'systemic approach to major trauma encompassing clinical techniques from point of wounding through to definitive treatment aimed at minimising blood loss, maximising tissue oxygenation and optimising outcome.'[70] It encompasses Damage Control Surgery (DCS).

DCS is 'an operative strategy that sacrifices the completeness of the immediate surgical repair in order to address the

FiO_2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.7	0.8	0.9	0.9	0.9	1.0	1.0	1.0	1.0
PEEP	5	5	5	8	8	10	10	10	12	14	14	14	16	18	20	22	24

Table 6 Recommended settings for positive end-expiratory pressure (PEEP) based on the fractional inspired oxygen concentration (FiO_2) used in the ARDSnet study.

physiological consequences of the combined trauma of injury and surgery.'[71]

Digital radiology is used to assess early lung injury and help diagnose pneumo- and haemo-thoraces which are drained. Arterial blood gases are measured as soon as practical.

Fluid resuscitation in the seriously injured is achieved with blood and blood products guided by point-of-care coagulation testing.[72] In the first hour following injury the emphasis is on minimising blood loss, with volume resuscitation targeted to the maintenance of a palpable radial pulse. Thereafter, and especially once surgical control of the major bleeding points has been achieved, volume resuscitation should be targeted to achieve normotension.[62] Right-sided filling pressures may be elevated in patients who are hypovolaemic if there is significant blast-related pulmonary hypertension, pericardial effusion, or ventricular dysfunction. The latter may be more common in a civilian context where the prevalence of ischaemic heart disease will reflect the age distribution of the casualties. These points are worth bearing in mind because fluid overload will also contribute to worsening hypoxaemia.

A lung-protective ventilation strategy with permissive hypercapnia[59] should be adopted from the outset together with an adequate level of PEEP. In the absence of evidence to the contrary we recommend selecting PEEP on the basis of the FiO_2, as in the original ARDSnet study[73] (**Table 6**). Pressure-controlled mechanical ventilation with a peak airway pressure between 25 and 30 cm H_2O will minimise alveolar over-distention in heterogeneously affected lungs. Inverse ratio mechanical ventilation and airway pressure-release ventilation, on the other hand, may improve oxygenation but at the expense of air-trapping and alveolar over-distention and should be used with caution, if at all.

In the context of severe lung injury, careful consideration should be given to the oxygenation target that the clinician sets, balancing the real risk of VALI against attempting to achieve 'normal' arterial oxygen values. Animal studies have shown that targeting an arterial oxygen saturation of 95% by increasing FiO_2 is associated with improved survival time during hypotensive resuscitation in a model of complex injury which includes blast lung and hypovolaemia.[62] Evidence of benefit more than eight hours from injury is lacking and after 24 hours a high FiO_2 (>60%) to achieve hyperoxia (>12 kPa) or even normoxia (>10 kPa) may cause more harm than good.

Early and severe hypoxaemic respiratory failure has been successfully managed with high-frequency oscillatory ventilation (HFOV) and inhaled nitric oxide.[61] Our own experience in the face of refractory hypoxaemia (P:F ratio ≤8 kPa for more than four hours) suggests that outcomes are improved by early recourse to HFOV. This has been used successfully even in patients requiring frequent transfers from the ICU to the operating theatre for surgery. In these circumstances, HFOV is discontinued on leaving the ICU and re-instituted immediately on the patient's return. HFOV can be safely used in patients with both traumatic brain injury and refractory hypoxaemia providing intracranial pressure is measured continuously. In some very severe cases, it may be necessary to supplement HFOV with extra-corporeal membrane oxygenation. However, patients presenting with severe diffuse alveolar haemorrhage from PBLI present a very challenging problem because extra-corporeal membrane oxygenation may be complicated by uncontrollable pulmonary haemorrhage.[29] The early use of tranexamic acid in trauma is now supported by a large randomised trial[74] and may have additional benefit in patients with significant alveolar haemorrhage.

Initial anecdotal reports from Israel (Martinowitz, personal communication, 2008) suggest that intravenous recombinant factor VIIa (rFVIIa) can reduce the severity of blast lung and associated clinical problems. A randomised controlled trial in terminally anaesthetised pigs investigated the effects of a single dose of rFVIIa (180 µg/kg) given 30 minutes after the onset of hypotensive resuscitation after combined blast injury and haemorrhagic shock. However, rFVIIa did not significantly improve survival time in this study, although it did result in a small improvement in arterial oxygenation compared to the placebo group.[3] The dose of rFVIIa had previously been shown to increase survival time in a model involving resuscitation after haemorrhage and uncompressed bleeding from an aortotomy.[75] By contrast, supplementary oxygen resulted in a far greater improvement in arterial oxygenation and increased survival time in this model.[76]

A number of case studies have reported that rFVIIa can limit intra-pulmonary bleeding, particularly diffuse alveolar haemorrhage, and consequently improve arterial oxygenation in a range of medical conditions where other therapy had failed. Two of these reports[77,78] warrant special attention since the rFVIIa was instilled via the airway (on one occasion given by nebulisation) rather than the conventional intravenous route. In the case series by Heslet *et al* intrapulmonary rFVIIa (50 µg/kg, repeated if necessary) resolved the bleeding in all six patients studied,[78] including the first where intravenous administration (120 µg/kg) had been ineffective. Success was also reported with 50 µg/kg rFVIIa in the second series of two cases.[77] The authors postulated an intra-pulmonary rather than a systemic mechanism of action. There are also a smaller number of case studies reporting successful use of rFVIIa (60-100 µg/kg given intravenously, the lower dose being repeated once) to limit intrapulmonary bleeding after gunshot wounds[79] and blunt trauma.[80,81] As a consequence of these positive reports, particularly given the effectiveness of intrapulmonary rFVIIa to control small vessel bleeding in the lungs, the potential effectiveness of inhaled rFVIIa for the treatment of blast lung is currently being investigated in an experimental study.

In our experience of military blast casualties sufficiently

severely injured to require intensive care, just over 96.3% survive to ICU discharge.[82] Given the youth and extreme fitness of these patients on the one hand, and the rather particular mode of injury on the other, it is not clear how applicable these data might be to a civilian population. Long-term outcome and sequelae from severe blast-related lung injury is currently unclear.

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Disclaimers and conflict of interest

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