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Review Article

Primary blast lung injury - a review

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Abstract

Bomb or explosion-blast injuries are likely to be increasingly encountered as terrorist activity increases and pre-hospital medical care improves. We therefore reviewed the epidemiology, pathophysiology and treatment of primary blast lung injury.

In addition to contemporary military publications and expert recommendation, an EMBASE and MEDLINE search of English speaking journals was undertaken using the medical subject headings (MeSHs) 'blast injury' and 'lung injury'. Review articles, retrospective case series, and controlled animal modelling studies published since 2000 were evaluated.

6-11% of military casualties in recent conflicts have suffered primary blast lung injury but the incidence increases to more than 90% in terrorist attacks occurring in enclosed spaces such as trains. The majority of victims require mechanical ventilation and intensive care management. Specific therapies do not exist and treatment is supportive utilizing current best practice.

Understanding the consequences and supportive therapies available to treat primary blast lung injury are important for anaesthetists.

Key words: blast injuries; explosions; lung injury

Once the preserve of the military physician, primary blast injury will increasingly be seen by civilian medical practitioners as industrialisation of developing economies progresses, and also as terrorist activity continues to increase significantly.[1] Primary blast injury syndrome is a potentially life threatening, multi-system disease, of which primary blast lung injury (PBLI) is a fundamental component. It results from exposure to blast overpressure after an explosion. Whilst responsible for significant numbers of immediate fatalities, improving personal protection in the military context means that more survivors of blast exposure are presenting to the medical services with the condition.[2] Though a vast amount of blast injury animal research has been undertaken since the Second World War, this has predominantly been concerned with delineating either safe or lethal exposure limits. Despite this research, the mechanism of primary blast injury at the cellular level remains mainly speculative, though gross cardiovascular and lung injury patterns are well recognized. Most casualties with PBLI require management in a critical care environment but the sporadic nature of the disease means that it is unlikely that a controlled evidence base will ever guide this care. Crude non-animal models exist, none of these however replicate the complex and multifaceted biological response to blast exposure, and none are based on human data.

Editor's Key Points

- Aftermaths of terrorist activity are likely to impact many health professionals.
- Explosions produce high energy pressure waves and extreme heat
- Bomb-blast injuries are often lethal but in survivors there is often haemorrhagic shock and multi-organ failure.
- High-pressure injury to the lung results in acute lung injury.

Explosives and blast waves

An explosion occurs when "energy is released over a sufficiently small time and in a sufficiently small volume so as to generate a pressure wave of finite amplitude travelling away from the source".[3] An explosive is any substance that can undergo exothermic oxidation turning from a solid or liquid into a gas very quickly using its own energy. All explosives are a mixture of an oxidizing agent, a fuel and an initiator.[4] In "low order" explosives such as gunpowder, these are mixed as separate powders and burns at a rate below the speed of sound in a process known as deflagration. They produce gaseous products that will only explode if confined (e.g. pipe or pressure cooker bomb). "High-order" explosives are chemical substances which contain the fuel and oxidiser within the same chemical compound. They do not burn but detonate when a shock wave passes through the material producing large pressure and temperature gradients. The detonation wave travelling through such explosive material will propagate at some 8,000 m s^{-1}, reach pressures of up to 250,000 atmospheres and temperatures of up to 7,000 °C.[5] Such a detonation generates a shock wave of very high pressure in the surrounding air that radiates away from the source supersonically as the explosive shock wave. Blast waves are described as being either simple or complicated in nature.[6] A simple (or 'Friedlander') blast wave occurs when a spherical high-explosive detonates whilst suspended in an open-air environment. It is characterised by an instantaneous increase in pressure to a peak value followed by an exponential decrease in pressure to below atmospheric levels, creating a negative pressure phase (Fig. 1). The energy from such an explosion is dissipated in three dimensions and thus deteriorates as the inverse cube as a function of distance from the centre. As such this "stand-off" distance is a fundamental factor in determining the likelihood of suffering primary blast injury. Depending on the explosive power, circumferential zones of injury pattern will be created. In order of proximity this will be; non-survivability, risk of primary blast injury (and other injury patterns) and then other injury patterns only.

Complex waves are generated when the detonation occurs in the presence of reflecting surfaces such as within buildings[1] or vehicles (Fig. 2). They are the product of reflected waves enhancing each other and the original shock wave in a directly additive effect. This then results in a significantly greater positive pressure phase (up to a 20-fold increase) and so greater injury. The chaotic nature of complex waves in confined spaces means that the stand-off distance becomes less important. The shock wave is then followed by the blast wind, a high-speed body of gas moving away from the explosion at up to 2,000 km h^{-1}. This may be followed by a release wave. This is a flow of gas back towards the epicentre as the vacuum created by the blast wave is filled with now non-energised gas particles. The combination of the shock wave and blast wind is known as the blast wave.

Most explosions are short duration with a positive pressure phase of 10 milliseconds or less.[7] Injury resulting from such explosions is related to the blast impulse, a function of pressure multiplied by time. Examples of long duration blast waves would be nuclear or volcanic explosions or explosions caused by specialised blast (thermobaric) weaponry.

Primary blast lung injury

PBLI is defined as "radiological and clinical evidence of acute lung injury occurring within 12 h of exposure and not due to secondary or tertiary injury".[8] The nomenclature of other blast injury patterns after an explosion is outlined in Table 1. This classification does not recognise the significant psychological injury suffered by witnesses and first responders to explosive events, which should perhaps be regarded as a quinternary injury pattern. In reality, the different blast injury mechanisms will rarely exist in isolation and a single casualty will suffer a spectrum of blast injury mechanisms. Secondary blast injury (fragmentation) predominates in most recent conflicts.[9]

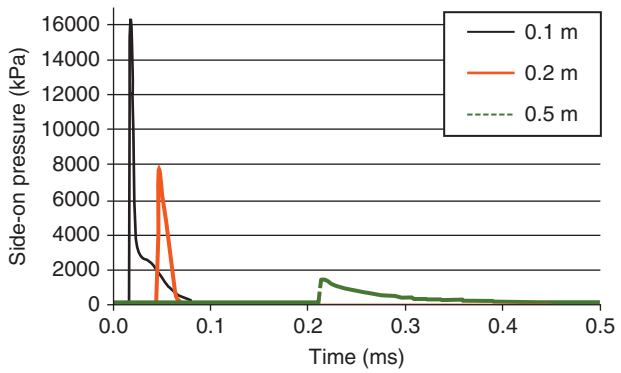

Figure 1 Simple wave. Blast over-pressure at different distances from a free field explosion generated by a 160g spherical mass of TNT. A negative pressure phase is not demonstrated in this example. Courtesy of Professor Ian Horsfall, The Defence Academy, UK.

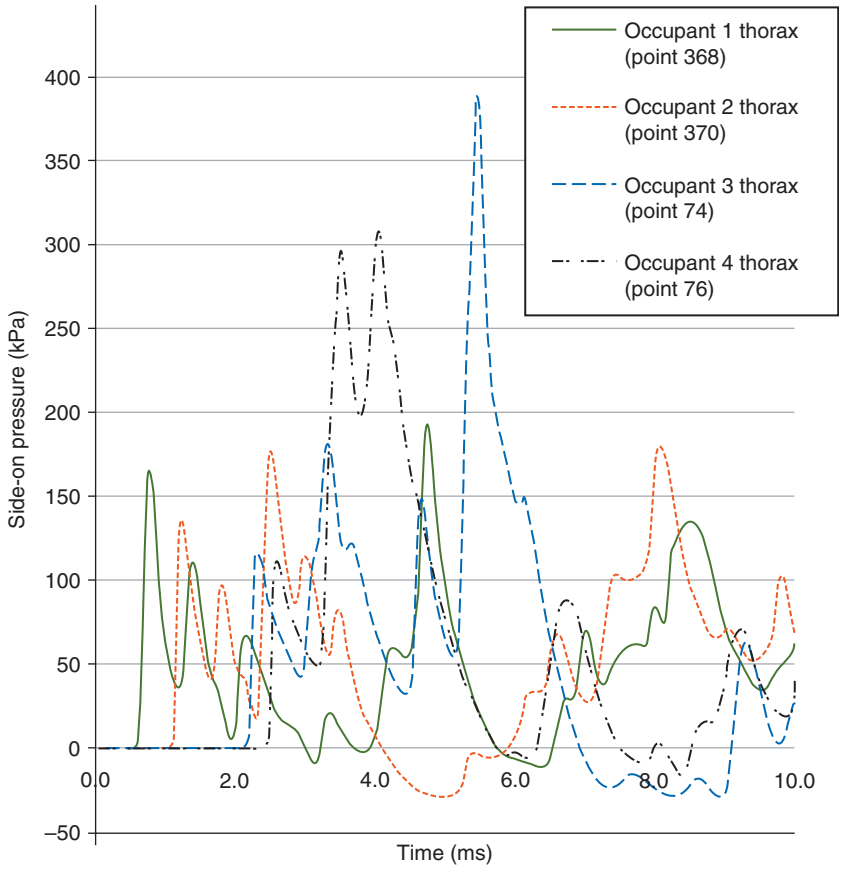

Figure 2 Complex Wave. Calculated thoracic pressures for four experimental occupants of a vehicle are exposed to a small explosive device. Strikingly different blast doses are demonstrated despite the close proximity of the occupants to each other. Courtesy of Professor Ian Horsfall, The Defence Academy, UK.

Table 1 Blast injury nomenclature

Primary Injury	Results from exposure to an explosive shock wave.
Secondary Injury	Fragmentation injury.
Tertiary Injury	Results from bodily displacement or building collapse.
Quaternary Injury	Includes burn injury and inhalation of toxic substances

Classically, primary blast injury is described as predominantly affecting gas-containing organs such the larynx, middle ear and bowel, in addition to the lungs. However, cerebral oedema and vascular endothelial injury occur, as can life-threatening liver or splenic lacerations, testicular rupture,[10] retroperitoneal bleeding and muscular compartment syndromes. Thus, exposure to a blast wave can cause a life-threatening primary blast injury syndrome, in which lung injury often predominates.

Incidence and presentation

PBLI is encountered globally as a result of military conflict, acts of terrorism and industrial accidents. Identifying patients with the condition can be challenging, as casualties will normally present with a mixed pattern of injury and a specific biomarker does not currently exist. During the most recent conflict in Afghanistan, PBLI was identified in 6-11% military casualties surviving to reach a field hospital.[2,11] This is despite the rudimentary nature of the opposition forces that lacked basic industrialised weaponry, and in particular lacked the thermobaric weaponry used extensively in the Chechen and Balkan conflicts.[12] The incidence of PBLI can reach almost 80% in blast exposed non-survivors,[13] in whom it is the only autopsy finding in 17%.[14] As discussed above, the incidence and severity of PBLI increases significantly with increasing proximity to the explosion (ground zero) and when injuries are sustained within an enclosed space such as a bus or underground train. In such circumstances in excess of 80% of survivors may suffer PBLI.[15] Some 94% of serious casualties in the Madrid train bombings suffered PBLI.[16]

PBLI is likely to become increasingly relevant in future conflicts for several reasons. The majority of military casualties are injured as a result of exposure to blast;[17] however, as the use of body armour and improved pre-hospital care become more widespread, blast-exposed victims will survive long enough to reach a field hospital. Computed tomography (CT) scanning is also now routinely undertaken as part of initial battlefield casualty management facilitating early diagnosis.

Pathophysiology

PBLI consists of an immediate autonomic response, followed by haemorrhage and parenchymal injury, which then culminates in an inflammatory phase. Other components of the primary blast injury syndrome affecting other organ systems may begin to materialise over the subsequent hours and days. Vago-vagal reflexes mediate a characteristic apnoea, bradycardia and hypotensive episode and a transient hypercoagulable state resulting in thrombus formation. This is mediated by stimulation of nociceptive peri-alveolar C-fibres.[18] The apnoea lasts for up to 15 s and is followed by a period of rapid shallow breathing.[19] This primary response has been postulated to play a significant role in non-survivors.[10] Animal experimentation has demonstrated a complete absence of this response when bilateral vagotomies are undertaken before blast exposure. Interestingly, vagotomies also attenuate blast induced neurological trauma.[20]

The exact mechanism leading to haemorrhage and parenchymal injury remains speculative. The longstanding consensus argues that the blast wave dissipates its kinetic energy within the lung through the generation of shear and stress waves.[21] Low velocity shear waves result from deformation of the thoracic wall. They are responsible for the surface haemorrhage seen on lung tissue facing the explosion. Shear waves cause random movement of tissues of differing densities around fixed points resulting in tearing of parenchymal tissue (inertial damage). This is known as the low-frequency response of the torso.[22] Supersonic stress waves (augmented sound waves) constitute the high-frequency response and result in more diffuse damage. The speed of transmission of these high amplitude waves through the lung does not allow energised gas to escape along the airways, resulting in the collection of a large number of air bubbles.[23] It is thought that rapid compression and expansion of these air bubbles within the alveoli leads to alveolar rupture (implosive injury) and hence to the hallmark of the disease, which is the formation of abnormal air-filled spaces such as pneumatoceles, lung laceration, pneumothoraces and venous air embolism. Rarely, pneumoperitoneum may occur. Arterial air embolism may also arise, evidenced by tongue blanching and livedo reticularis. As these stress waves converge towards the mediastinum, the sums of the additive pressures cause a stress-concentration effect in lung tissue leading to greater injury and the characteristic X-ray findings discussed below. This is augmented by the formation of more damaging tension waves (particles in the transmitting medium travel in the opposite direction to the wave propagation creating stretch), as the stress waves reflect back down the path they have just travelled. Fundamental to the proposed mechanism of injury resulting from exposure to stress waves is the phenomenon of spallation. Spallation is well recognised by material scientists and widely proposed as a significant injury mechanism in biological tissue. Spallation occurs as stress waves travel between materials of high acoustic impedance and materials of low acoustic impedance (e.g. lung parenchyma to air). It results in fragmentation of the high impedance material into the low impedance material. It is analogous to the last ball of a Newton's cradle flying up in response to the impact of the first ball. Microscopically, severe alveolar over-distension is ubiquitous.[24] Concomitantly, alveolar capillaries rupture and with the formation of alveolar-venous fistula result in localised haemorrhage. This can be significant and can cause immediate respiratory compromise or macroscopic bleeding into the large airways. This extravasated blood precipitates a free-radical mediated inflammatory process involving leucocyte accumulation, the generation of inducible nitric oxide (iNO) and oxidative damage resulting in perivascular oedema. Inhibiting this leucocyte response before exposure to blast prevents the formation of pulmonary oedema.[25] Measurement of exhaled NO may facilitate diagnosis and monitoring of the disease as it does in other disease states.[26 27] The inflammatory process continues to evolve over the subsequent 24 - 56 h. The extent of inflammation will, in part, depend on the overall burden of whole body injury driving a systemic inflammatory response.

Air embolism is thought to be predominantly responsible for immediate fatalities.[28] In casualties suffering long bone and/or pelvic injury, bone marrow embolism also occurs.[24 29]

Casualty identification and management

When receiving casualties from an explosive incident eliciting the following details will help identify those at risk of PBLI. Exposure within a confined space is of paramount importance and for open-air explosions the stand-off distance from ground-zero needs to be determined. In the latter case, the presence seemingly un-injured co-located fatalities should raise suspicion. Casualties with clinically significant PBLI will most likely be symptomatic by the time they reach a medical facility. However, mild injury may not become apparent for several h whilst the inflammatory response manifests itself.[2] Spontaneously breathing casualties will be short of breath, possibly with impaired gas exchange, and may have haemoptysis. Tachycardia, tachypnoea and cyanosis reflect increasing severity of the injury. Patients with severe injury will go on to develop ARDS. The classic chest x-ray appearance is of bilateral peri-hilar ("batswing") infiltrates, which have been generated as the pressure wave reflects back from the mediastinum. The incidence of this varies considerably between reported series and may reflect a casualty's proximity to an explosion and the degree of confinement in the environment of the blast. Diagnosing PBLI in isolation via imaging, however, is uncommon; PBLI is rarely classical in appearance, and the picture is often mixed with lung contusion (tertiary blast injury) and penetrating fragments (secondary blast injury). The opacification seen on plain film chest radiography is a representation of the initial consolidation of alveoli by haemorrhage. CT imaging clearly demonstrates the distribution and extent of alveolar haemorrhage, commonly seen around the mediastinum and is a more sensitive tool to demonstrate the lacerations, pneumatoceles and pneumothoraces resulting from PBLI. As is often the case in traumatised individuals, CT scanning may also demonstrate acute peri-traumatic pulmonary thrombus as an incidental finding, for which an explosive mechanism of injury is a recognised risk factor.[30] The clinical significance of these thrombi is not yet established. Alternative diagnoses at this stage of presentation include: pulmonary contusion (rib fractures and peripheral lung injury), tension pneumothorax, ARDS as a result of other causes (inhalation of toxic substances, gastric aspiration) and use of chemical weapons. These injuries may co-exist with PBLI.

Patients who are adequately breathing spontaneously 2 h after injury are unlikely to need mechanical ventilation because of PBLI alone.[15 31] Patients who are asymptomatic 6 h after exposure can be discharged from close medical observation.[32] Whilst tympanic membrane rupture may predict blast brain injury,[33] it is poorly correlated with PBLI, with a sensitivity of 29%.[34] Membrane rupture does however identify patients who would benefit from a period of observation.[35]

Casualties with PBLI require supportive care in a high dependency or intensive care environment. Some 80% will require mechanical ventilation.[31] Any pneumothoraces should ideally be drained before transfer to a CT scanner, though the increasing

speed and improving access to cross sectional imaging makes this less vital in patients with relative respiratory stability, but who may have other life threatening injuries. The combination of blast injury and haemorrhagic shock is particularly threatening to the patient and damage control resuscitation must be expedited in these casualties.[36] It must be borne in mind that large pneumothoraces can be missed on supine plain films. In view of the lack of evidence to suggest otherwise, ventilatory strategy should adhere to the low-volume open lung approach advocated for patients suffering from acute respiratory distress syndrome.[37] The use of high PEEP advocated by this ventilatory approach, is at odds with the requirement to limit PEEP in the context of any broncho-pleural fistulas and pneumatoceles and will need to be individually tailored. Some authors have recommended mechanical ventilation with a high inspired concentration of oxygen (80% or above) for the first 24 h in an attempt to dissolve gas emboli, with mortality benefits demonstrated in animal studies.[38] Alternative forms of ventilation such as high frequency oscillatory ventilation and airway pressure release ventilation have been used with success but are dependent on local expertise and availability.[39] All of these ventilator strategies require tolerating hypercapnia within the limits of a manageable arterial pH.

Future therapy may involve manipulation of the inflammatory response to blast injury. The antioxidant N-acetylcysteine amide has shown significant promise, by modulating neutrophil mediated pulmonary inflammation in rodent models of blast injury.[40] Empirical use of Tranexamic Acid has also been suggested but without an evidence base. Therapeutic hypothermia is also showing promise in mitigating blast lung injury in small scale, small animal models.[41] Nebulised activated Factor VII has its advocates based on small case series[42] but this is not supported by recent experimental examination.[43]

In the longer term, patients suffering isolated blast lung injury can expect to make an excellent recovery demonstrated by lack of symptoms, normal exercise tolerance and normal lung function tests.[44] This contrasts with the long-term risk of developing bowel adhesions[45] resulting from blast bowel injury or with permanent hearing deficit after tympanic rupture.

Conclusion

Primary blast injury including primary blast lung injury will be increasingly encountered by medical professionals making awareness important. It is of particular relevance to the anaesthetic and intensive care community, who will be predominantly concerned with caring for these casualties initially. Treatment remains supportive utilising current best practice and further research is required in order to identify specific treatment modalities.

Authors' contributions

Study design/planning: T.S., J.H.,
Study conduct: T.S., P.M.,
Data analysis: T.S.,
Writing paper: T.S., M.H., E.K., I.G.,
Revising paper: all authors

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Declaration of interest

None declared.

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