REVIEW

The radiological management of bomb blast injury

S.S. Hare,*, I. Goddard, P. Ward, A. Naraghi, E.A. Dick

Departments of aRadiology, bAccident and Emergency, St Mary’s Hospital, London, UK, and cDepartment of Radiology, Royal London Hospital, London, UK

Received 27 April 2006; received in revised form 31 August 2006; accepted 7 September 2006

A need to understand the nature and patterns of bomb blast injury, particularly in confined spaces, has come to the fore with the current worldwide threat from terrorism. The purpose of this review article is to familiarize the radiologist with the imaging they might expect to see in a mass casualty terrorist event, illustrated by examples from two of the main institutions receiving patients from the London Underground tube blasts of 7 July 2005. We present examples of injuries that are typical in blast victims, as well as highlighting some blast sequelae that might also be found in other causes of multiple trauma. This should enable the radiologist to seek out typical injuries, including those that may not be initially clinically apparent. Terror-related injuries are often more severe than those seen in other trauma cases, and multi-system trauma at distant anatomical sites should be anticipated. We highlight the value of using a standardized imaging protocol to find clinically undetected traumatic effects and include a discussion on management of multiple human and non-human flying fragments. This review also discusses the role of radiology in the management and planning for a mass casualty terrorist incident and the optimal deployment of radiographic services during such an event.

© 2006 The Royal College of Radiologists. Published by Elsevier Ltd. All rights reserved.

Introduction

Bomb explosions have the potential to inflict multi-system, life-threatening injuries on many people simultaneously. The pattern of injury produced can be complex, unpredictable and diagnostically challenging. Such injuries, which were previously usually seen in a military setting, are now becoming more familiar in the civilian world. The simultaneous arrival of multiple critically ill casualties, as well as many with non-critical injuries, can overwhelm a medical facility. Therefore mass casualty terrorist incident planning needs to encompass this, and ensure that radiology services do not become a bottleneck to patient flow.1

Classification of bomb blast injuries (see Table 1)

Bomb blast injuries have been classified into four categories.2,3 Patients may be affected by one or more categories.

Primary injuries

Primary blast injuries are due to the initial very high pressure blast wave impacting especially at air–liquid interfaces on both solid and air-filled structures (barotrauma). The primary shock wave spreads radially at the speed of sound. In air it dissipates rapidly in proportion to the cube of the distance from the blast centre whereas in water it is transmitted more powerfully, more rapidly and over a longer distance. The degree of tissue injury is directly related to the magnitude and duration of the peak pressure as well as the proximity of the victim to the blast.

* Guarantor and correspondent: S.S. Hare, Radiology Department, St Mary’s Hospital, Praed St., Paddington, London W2 1NY, UK. Tel.: +44 077 6989 1220/020 8455 1588; fax: +44 020 7886 7626.
E-mail address: samanjit@btinternet.com (S.S. Hare).
Several systems are prone to primary blast injury: the inner ear and eardrum, the limbs and earlobes (both traumatically amputated), the lungs (so-called blast lung injury), and rarely, the gastrointestinal tract. Of those with a primary blast lung injury, many die immediately due to a massive cerebral or coronary air embolism. A small group of those with primary blast lung survive but may later die due to progressive pulmonary insufficiency. Proximity to a blast is probably more important than the strength of the blast. Close proximity that does not result in immediate death can result in traumatic amputation of limbs and ear lobes, hence these are indicators that the victim was close to the blast centre. Those who are at a distance greater than 6 metres from the bomb will probably not experience substantial blast injury. Position of the victim in relation to the bomb, including angle and height of the victim in relation to the centre of the explosive device, are also important in determining extent of injury.

Secondary, tertiary and quaternary injuries

Secondary blast injuries are caused by flying debris and bomb fragments causing penetrating trauma. Tertiary injuries occur when individuals are thrown by a major "blast wind", a longer phase of negative pressure causing blunt and penetrating trauma. Quaternary injuries include all other injuries and illnesses, e.g., burns, smoke inhalation, and the exacerbation of existing conditions.

Overall, it is secondary and tertiary effects that predominate amongst bomb survivors as many die from primary blast effects at the scene. Injuries in survivors may be due to a combination of effects; for example, traumatic limb amputation arises due to primary and tertiary effects. The primary blast shearing wave runs along bone and causes a comminuted limb fracture, the limb subsequently flails in the tertiary blast wind, which completes amputation of the residual intact soft tissue structures.

The clinical presentation depends on whether the blast tracks through air or water and whether it is open air or within an enclosed space. Detonations in confined spaces, such as those targeted on the London Underground, produce higher morbidity and mortality than explosions in open spaces and include more serious and complex forms of multiple trauma in individual victims as well as a higher incidence of primary blast injuries and blast lung. Leibovici et al. found open air blasts cause mortality of 7.8% compared with 49% in a closed environment. In an enclosed space (which may include a bus with no open windows) the blast wave is amplified due to additive effects of reverberations and reflections from the surrounding walls. As a result, unpredictable life-threatening multiple trauma injury patterns are seen if the victim survives.

Patterns of injury—what should the radiologist expect?

Bomb blast victims may present with some of the features that may be found in any multi-trauma situation, such as haemorrhagic shock, intra-abdominal solid organ contusions, or open fractures. Other features are more specific to bomb

<table>
<thead>
<tr>
<th>Table 1 Classification of bomb blast injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injury type</td>
</tr>
<tr>
<td>Primary (blast wave)</td>
</tr>
<tr>
<td>Secondary</td>
</tr>
<tr>
<td>Tertiary (blast wind)</td>
</tr>
<tr>
<td>Quaternary</td>
</tr>
</tbody>
</table>

2 S.S. Hare et al.
blast injury such as blast lung, and the presence of multiple shrapnel fragments. Both types of injury need to be actively sought out and the radiologist needs to be aware of constellations of injury patterns. Injuries may be due to multiple causes (i.e., primary, secondary or tertiary blast injury) and may occur at multiple anatomical sites in up to two-thirds of explosion victims according to one study by Peleg et al. 13 This review of more than 1000 patients exposed to explosion or gunshot injury found that explosion patients are at greater risk of injury to three or more body regions, in particular affecting the head, extremities and chest. 13

It is important to remember that there is usually a much higher proportion of critically ill patients in a bomb blast event than in another multi-trauma event. Of all patients who were admitted at one hospital in Madrid after the 2004 bombings, one third were deemed to be in a critical condition. 5,6 The Israeli trauma registry shows that one third of terror victims have severe trauma, and that in children, 25% of terror-related injuries are critical compared with 3% of non-terror related injuries. 14 The review by Peleg et al. of explosion/blast victims revealed almost half had an Injury Severity Score of over 25. 13 Frykberg reviewed primarily indoor terrorist bombings worldwide from 1969 to 1995 and found the number of critically ill varied between 9 and 22% of all victims. Set against this high proportion of critically ill casualties is the fact that in survivors the overwhelming predominance is of relatively minor non life-threatening injuries. 8,13

Of those immediately killed after terrorist bombings, head injury, primary blast lung, abdominal injury, and other thoracic injuries are most commonly found. 8 Of those who survive, injuries to the abdomen and chest, as well as traumatic limb amputations, are prognostic markers of severity and should be recognized as having a substantial and significant mortality of up to 20%. 8

Head and facial injuries

Severe head trauma is one of the leading causes of fatalities in blast victims. 8 Various studies report an excess of head injuries in explosion victim survivors affecting between 12 and 55% of survivors, but these may often be radiology negative concussive brain injuries rather than contusions 5,13,15, amongst the patients seen at our institutions, only three had abnormal brain computed tomography (CT) examinations.

Facial injury and fractures are common, due to both flying debris and direct blunt trauma (Fig. 1). 5,6 A disrupted maxillary sinus is commonly seen as a focal point in facial fractures from blast injury (Fig. 1). Eye injuries, including globe perforation, are also seen frequently as a result of secondary missiles accelerated by the blast wind 5,6; 18% of the Madrid cohort had eye lesions. Closed globe orbital lesions without intracranial extension may result in infection and an unproven but theoretical risk of sympathetic ophthalmia, which was the rationale behind the prophylactic enucleation of some victims (Fig. 2). 16,17

Thorax

Blast lung injury is a major cause of immediate death and morbidity in critically ill patients. Blast lung injury can occur without external chest wall injury and is due to the very high pressure primary blast wave pushing the chest wall towards the spine, causing transient high intrathoracic pressure. This leads to tearing of alveolar septae, rupture of alveolar spaces and subsequent alveolar haemorrhage and oedema. Blast lung injury is characterized clinically by hypoxia, respiratory distress and haemoptysis all of which progress over the first few hours after the blast. Radiologically there are pulmonary infiltrates, more commonly bilateral and diffuse with a typical “butterfly” distribution. 3,18 There is a high prevalence of blast lung injury in the critically ill survivor group. After the 2004 Madrid bombings, Peral Gutierrez et al. found

Figure 1  A 46-year-old woman who sustained severe blunt and penetrating trauma to the face as well as a patellar fracture and lower limb soft tissue injury. Axial CT image reveals a comminuted fracture of the anterior and medial walls of the left maxillary sinus. The sinus is filled with blood and fluid. A foreign body (arrow) is seen embedded in the soft tissues inferior to the left orbit.
63% of critically injured patients were affected. In a review of 916 blast victims from 31 separate bombs, Avidan et al. found that although only 10% of all patients had blast lung, up to three-quarters of those admitted to the Intensive Therapy Unit were affected, and it was particularly common in those present at a closed-environment explosion. Mortality in patients with blast lung injury varies between 3 and 40%, and is frequently due to associated injuries. Some authorities believe that blast lung can have a delayed or latent component (between 24–48 h after the blast) similar to acute adult respiratory distress, but others dispute this and state that if significant respiratory decompensation is going to occur, it should do so within 2 hours of the blast. Hence prolonged observation of asymptomatic patients is not necessary. Blast lung injury is often associated with ruptured tympanic membranes, burns, limb fractures and amputation, vascular and solid abdominal organ injury. The primary blast wave can also cause pneumothorax, haemothorax and pneumomediastinum, as well as bronchopleural fistulae and air emboli. The thorax is also susceptible to penetrating secondary blast injury from primary fragments originating from the bomb (e.g., metal) or from...
Abdominal sonography for trauma has been recommended to triage patients in the emergency department and identify intra-abdominal fluid or solid organ haemorrhage.\(^8,21,22\) FAST was reported to be positive in up to 12% of patients in the mass casualty setting of the 1988 Armenian earthquake, although no FAST performed on our patients was positive.\(^8,21,22\)

**Axial skeleton**

Spinal fractures were seen in two of the London victims (Fig. 5) and may have been due to the primary blast wave or a tertiary blast injury. These have been noted in other series affecting between 2 and 5% of all blast victims.\(^5,6,13\)

**Limb fractures and traumatic amputation**

Traumatic lower limb amputation is a form of tertiary blast injury and usually only tends to occur in combination with other critical injuries. It is rare in survivors and has high mortality,\(^23\) usually as a result of severe hypovolaemic shock. It is more common in victims close to the blast and its presence should alert the radiologist to strongly suspect additional severe blast injury elsewhere.\(^10\)

Various complex comminuted fractures of the lower limb long bones occurred in the London bombings, likely due to the primary blast force or tertiary blast wind (Fig. 6). Such comminuted fractures require external fixation to minimize the risk of infection.\(^24\) Fractures of the lower limb were notably more common than those of the upper limb in our cohort of bomb blast patients, which contrasts with the findings of a large Israeli series (Peleg et al., 37 and 38% of the blast victim population had an upper or lower limb fracture) and may be due to the positioning of the bomb in relation to the victims.\(^13\)

**Flying fragments**

Many of the severe injuries seen in survivors of bomb blasts are due to penetrating injuries from flying fragments, including metal (shrapnel) and non-metallic fragments. Individuals far from the detonation site can be injured by objects accelerated by the blast wind phenomenon.\(^2\) Metal objects were not incorporated into the London bombs. Several patients had multiple (\\textgreater 10) separate fragments in either the lower limb or face. Flying fragments included glass (Figs. 1 and 2), metal (Fig. 2) and bone (Fig. 6). Several patients had multiple penetrating bony fragments.
originating from other blast victims, raising the problem of possible infection. To our knowledge, these are the first published radiological images of bony flying fragments originating from other individuals (Fig. 6). It can be very difficult to identify a small surface entry site for flying fragments, which can result in significant debris being completely missed at the patient’s initial presentation, highlighting the importance of routine screening radiography or the use of a CT scout in such patients.\textsuperscript{13,25} The role of radiology is not only to identify all of the possible flying fragments, based on both the penetrating surface wounds and their possible trajectory, but also to help surgeons decide which fragments need to be removed during thorough surgical debridement. (All foreign debris removed needs to be preserved for forensic purposes.) All bony fragments should be removed because of the high risk of infection associated with them\textsuperscript{26} but while all penetrating missile wounds should be thoroughly explored, not all other foreign material needs to be removed.\textsuperscript{27} The decision as to whether to leave fragments or pursue them depends on accessibility of the fragments, and risk of damage to the surrounding structures during surgery, compared with the risk of infection secondary to skin or clothing, which enters tissue cavities with flying fragments.\textsuperscript{25,27}

**Mass casualty planning: the role of the radiologist and use of radiography (see Fig. 7)**

The radiologist has a central role in attempting to reduce the mortality and morbidity in mass...
casualty situations and should be able to seek out and recognize the spectrum of injuries that can potentially be inflicted by explosive devices. In addition the provision of radiographic services affects forward patient flow in a mass casualty event. Hirshberg et al. suggest that most disaster plans underestimate the need for radiography and CT, and also emphasizes the importance of not hampering patient flow through the hospital by over-use of radiology.1

Suicide bombings result in numerous casualties over a short time period and can seriously challenge even the most experienced hospitals and staff.9 Hence detailed plans need to be in place prior to such an event. General principles of mass casualty events include the avoidance of both over-triage (i.e., sending too many non-critical patients to hospital, which may result in medical resources being overwhelmed) and under-triage (which may result in critical injuries being missed, unless patients are frequently re-evaluated).9 Most studies (predominantly from Israel and Spain) show that approximately 20% of casualties will have critical injuries requiring urgent care.7

Within the hospital setting, the mass casualty plan outlined below corresponds to that put in place in our institutions on 7 July 2005. After a mass casualty event there will be an initial chaotic period as new casualties continue to arrive at the hospital followed by a plateau/definitive phase once the last new patient has arrived and finally a “step-down”/end of mass casualty event.13,14 Only “minimal acceptable care” should be given during the chaotic initial phase to ensure a maximum number of patients survive,1,7 i.e. the use of major diagnostic tools such as CT and angiography should be minimized. Once in the definitive/plateau phase, optimal patient care can be provided and patients can be re-assessed. It can be difficult to predict when the initial chaotic period of continued patient in-flow ends: up-to-date accurate information on the number of victims may not be available or may not be adequately communicated to key hospital staff, as was our experience on 7 July. Hence the hospital’s mass casualty plan needs to be able to adapt to a variable number and type of casualties.14 It is very important for patients to flow through the hospital

---

**Figure 6** A 48-year-old man with multiple extremity injuries. This man also suffered severe blunt trauma to the abdomen requiring emergency splenectomy (not shown). Plain anteroposterior radiograph of the left leg reveals a distal comminuted fracture of the left femur with multiple loose bony fragments, some of which originated from other victims. This patient also had comminuted fractures of the tibia and fibula requiring surgical amputation.

---

**Figure 7**

![Image of mass casualty plan](image-url)
departments quickly (from Emergency to Radiology or Theatre), receiving "rapid but abbreviated" care to avoid delay in treatment of critical patients. The mass casualty plan is summarized in Fig. 7 and includes:

1. All elective and non-urgent patients are cleared from the hospital, in particular from the emergency department and from radiology. Both clinical and non-clinical staff are allocated to key areas of the radiology and emergency department.

2. The role of radiology involves bedside radiography and FAST in the emergency department, as well as plain radiography and fluoroscopy in the X-ray department and theatre and CT of some patients. A radiologist should be stationed in the major trauma bays to perform FAST to exclude free abdominal fluid or haemodynamically significant abdominal injury. Radiologists are also stationed in the emergency department, immediately reporting all plain radiographs and communicating with the supervising clinicians, with a similar set-up in CT. As for the entire hospital, plans for further back-up staff should be in place if there is a prolonged event.

3. All critically ill patients require a chest, cervical spine and pelvis view as routine, as well as plain films based on the site of penetrating wounds as these can cause complex internal injuries.

4. Unstable critically ill patients should be transferred straight to theatre for exploratory laparotomy/thoracotomy or other operative procedure to treat the cause of haemodynamic instability.

5. Stable but critically ill patients can be transferred to CT before the operating theatre or ITU. The scout view should cover the entire body (to look for shrapnel and undetected fractures) and be followed by CT of the head, and chest to pelvis.

6. Non-critical casualties frequently require radiographs (up to 70%). However, for non-critical patients radiography is often a major bottle-neck to forward patient flow.

Conclusion

All radiologists working in an urban setting need to be aware of the possible features of bomb blast injury, including both those in common with any severe trauma and those specific to the blast phenomenon. The patterns of injury relate to the unique sequence of events occurring during a blast, which are quite different to those from other causes of trauma. There should be a particularly high index of suspicion for the presence of blast lung, pneumothorax, penetrating flying fragments and multiple fractures in such patients.

In addition, the radiologist has an important role in managing the flow of casualties through a hospital during such a mass casualty terrorist event. In a world where terrorism is on the rise, this awareness will be vital in helping reduce the morbidity, and mortality for civilian blast victims.

Acknowledgements and dedication

We wish to thank all those who have allowed their imaging to be included. This manuscript is dedicated to the victims of the 7 July London Underground bomb attacks.

References

8. Frykberg E. Medical management of disasters and mass casualties from terrorist bombings: how can we cope? J Trauma 2002;53:201–12.