Although most trauma centers have experience with the imaging and management of gunshot wounds, in most regions blast wounds such as the ones encountered in terrorist attacks with the use of improvised explosive devices (IEDs) are infrequently encountered outside the battlefield. As global terrorism becomes a greater concern, it is important that radiologists, particularly those working in urban trauma centers, be aware of the mechanisms of injury and the spectrum of primary, secondary, tertiary, and quaternary blast injury patterns. Primary blast injuries are caused by barotrauma from the initial increased pressure of the explosive detonation and the rarefaction of the atmosphere immediately afterward. Secondary blast injuries are caused by debris carried by the blast wind and most often result in penetrating trauma from small shrapnel. Tertiary blast injuries are caused by the physical displacement of the victim and the wide variety of blunt or penetrating trauma sustained as a result of the patient impacting immovable objects such as surrounding cars, walls, or fences. Quaternary blast injuries include all other injuries, such as burns, crush injuries, and inhalational injuries. Radiography is considered the initial imaging modality for assessment of shrapnel and fractures. Computed tomography is the optimal test to assess penetrating chest, abdominal, and head trauma. The mechanism of blast injuries and the imaging experience of the victims of the Boston Marathon bombing are detailed, as well as musculoskeletal, neurologic, gastrointestinal, and pulmonary injury patterns from blast injuries.

© RSNA, 2016 • radiographics.rsna.org

Introduction

At 2:49 PM on April 15, 2013, two improvised explosive devices (IEDs) created from pressure cookers detonated near the finish line of the 117th Boston Marathon, immediately killing three bystanders and injuring hundreds (1,2). Patients began arriving at nearby hospitals within 18 minutes of the explosion. One hundred eighteen patients were treated at the nine nearby hospitals, with a total of 264 victims treated in 27 hospitals (1,3). Although most trauma center radiologists have experience with the imaging of gunshot wounds and stabbing injuries, trauma related to explosive injuries is not commonly encountered outside the battlefield setting. Unfortunately, terrorism is a growing global concern that knows no borders and does not discriminate.

The purpose of this article is to describe the mechanisms and types of blast-related injuries, as well as the role of radiology in their diagnosis and management. An algorithm used to image medically stable and unstable patients with blast injuries is detailed.
Figure 1. Diagram of a pressure cooker bomb. A pressure cooker bomb is an IED created by inserting explosive material into a pressure cooker and attaching a blasting cap into the cover of the cooker.

Although military-grade explosives such as C-4 and Semtex have been used by the Irish Republican Army, less-powerful explosives such as ammonium nitrate and fuel oil (1995 Oklahoma City bombing), triacetone triperoxide (TATP; 2005 London bombing), smokeless powder (1996 Atlanta bombing), urea nitrate (1993 World Trade Center bombing), GOMA-2 (2004 Madrid train bombing), and black powder (2013 Boston Marathon bombing) have also been used (5–7). As the term IED would imply, these devices are “improvised” from readily available materials. In the case of the Boston Marathon bombing, the IED was created from a pressure cooker, Christmas lights, black powder, nails, ball bearings, and remote control car parts (Fig 1) (8).

Physics of Explosives and Mechanisms of Injury

In an explosive detonation, a solid is converted rapidly to a hot gas (9). The expanding hot gases created by the explosive form a blast wave of compressed high-pressure air moving at supersonic speeds (9,10). The point of highest pressure is known as the peak overpressure (10). This point is followed by a “blast wind,” or “dynamic overpressure,” that can move in excess of 2000 km/h. After the blast wind is a drop in pressure resulting from the displaced air pushed outward by the blast wind and wave. The graphical pattern produced by changes in pressure with time known as the Friedlander waveform applies to blasts in open spaces (Fig 2). In confined spaces, the walls, floor, and ceiling reflect the blast wave and result in amplification of the blast energy by as much as fourfold to eightfold; windows and vents reduce the energy by venting some of the overpressure. The scale of injuries experienced by blast victims is dependent on their distance from the nucleus of the blast, with the magnitude of the pressure wave inversely related to the third power of the distance, as well as the amount of debris and shrapnel thrown.
by the explosive device. Injuries are caused by compression and shearing effects in tissues, debris carried by the blast wind, and blunt trauma caused by the victim being displaced and impacting immovable objects (11).

**Categorizing Injuries**
Injuries encountered in most IED detonations can be divided into primary, secondary, tertiary, and quaternary injuries (Fig 3) (2,10–15). Primary injuries are a result of the high-pressure blast wave and the subsequent drop in pressure after the blast wave. This combination causes compression and shearing of tissues as the wave passes through the body and results in injuries to gas-filled structures such as the ear, the lungs, and, rarely, the bowel, as well as traumatic brain injuries (11,13). After a blast, secondary injuries are the most commonly encountered and are blunt or penetrating injuries resulting from materials thrown out from the bomb casing (primary fragments) and debris from the environment being carried by the blast wind (secondary fragments) (13,16). Tertiary injuries occur as a result of victim displacement by the blast wind and include visceral injuries, fractures, and closed head injuries. Tertiary injuries also include injuries sustained as a result of structural collapse (as can occur in the bombing of a building), such as crush injuries (10,14). Quaternary injuries encompass burns, inhalation of toxins and dust, exposure to radiation, and asphyxiation; and these injuries are not usually radiographic diagnoses. Some injuries, such as fractures, traumatic amputations, and head injuries, can result from a combination of primary, secondary, and tertiary blast injuries.
Primary Blast Injuries

Primary blast injuries are those caused by baro-trauma from the initial increased pressure of the explosive detonation and the rarefaction of the atmosphere immediately afterward. These changes in pressure have their greatest effect on gas-filled organs such as the middle ear, the lungs, and, rarely, the bowel.

Pressures of as little as 5 psi (35 kPa) above ambient atmospheric pressure can result in rupture of the tympanic membrane (14,17,18); accordingly, injuries to the ear are among the most common in blast victims (19), many of whom will experience impaired hearing and tinnitus. Although this kind of injury will seldom be a radiologic diagnosis, tympanic membrane rupture should be kept in mind in regard to patients who are exposed to explosive blasts (Fig 4). The initial blast wave can also cause ossicular fractures and dislocations (20,21). Although less important in the acute phase of injury triage, these injuries can be diagnosed at dedicated thin-section CT of the temporal bone (22).

Pulmonary blast injuries have been found to occur in 47% of immediate fatalities and to be the cause of death in 11% of those who survive the immediate blast (23). Pulmonary blast injuries can occur at blast pressures as low as 40 psi (280 kPa) above ambient pressure and will be found in 50% of victims exposed to pressures of greater than 70–80 psi (490–560 kPa) (Fig 5) (24). The increased pressure and subsequent rarefaction as a result of the primary blast wave as it propagates through the chest result in disruption of interalveolar septa, with resultant alveolar hemorrhage and alveolar rupture. Traumatic alveolovenous fistulas can form, resulting in systemic air embolism (15,24–26). Injuries are greatest at the interface between the lung and the mediastinum, at the costophrenic angles, and at the lung periphery at the intercostal spaces (where the lungs are not shielded by the ribs). Alveolar rupture at the lung periphery can result in the formation of subpleural cysts and pneumothorax (Fig 6) (15,24). Lacerations can also be seen in severely affected lungs. Patients present with cough, dyspnea, and hypoxia as a result of ventilation-perfusion mismatch that is due to vascular shunting and impaired gas exchange. This clinical condition has been called “blast lung syndrome” (18,27). Chest radiography demonstrates patchy airspace opacities in areas of hemorrhage, often occurring in a perihilar “butterfly” pattern (24,26–30), and traumatic pneumatoceles can manifest as areas of lucency within the airspace opacity. Because blast victims typically undergo portable radiography in the supine position, attention should be paid to the periphery so as not to miss subtle pneumothoraces. CT can be used to further evaluate lacerations and contusions, localize foreign bodies, detect subtle pneumothorax, and direct interventions (24,30). CT can also be considered for patients with persistent clinical manifestations of blast lung syndrome but negative chest radiographs (28). It is interesting to note that rib fractures are more commonly related to secondary and tertiary mechanisms of injury (31).

Primary blast injuries to the bowel are encountered less often than blast lung injuries (15), occurring in 0.3%–0.6% of blast survivors and usually in combination with other injuries (27,32). Bowel injury is most likely to occur in patients subjected to underwater explosion. When the bowel encounters the blast wave, it is subject to compression in the positive-pressure phase, expansion in the negative-pressure phase, and shearing stresses. These pressure changes may cause contusion, intramural hematoma, and perforation. Shearing stresses may cause tearing of mesenteric vessels and separation of the layers of the bowel wall, resulting in bowel ischemia (18,27). Intramural hematoma can also result in delayed perforation secondary to necrosis of the smooth muscle of the bowel wall (15,32). Patients with primary blast injuries to the bowel present with symptoms such as nausea, vomiting, abdominal pain, hematemesis, melena, and peritonitis (15,27). Severe hemorrhage can result in hemodynamic instability. Radiographs of the abdomen may demonstrate intraperitoneal free air from bowel rupture, as well as projectiles from secondary blast injury. CT is more sensitive in detecting primary blast injuries.
Figure 6. Primary blast injuries to the lungs and bowel. (a) Axial contrast-enhanced CT image shows a right pneumothorax (straight arrow) and pneumomediastinum (curved arrow) caused by the overpressure wave produced by a gasoline explosion. (b) Axial CT image of the pelvis shows pneumoperitoneum caused by shrapnel (arrowheads), which caused perforation of small bowel loops. Shrapnel also caused a bone defect in the left iliac bone. (Fig 6b courtesy of Laurian Copel, MD, and Hillel S. Maresky, MD, Department of Radiology, Assaf Harofeh Medical Center, Tzrifin, Israel.)

to the bowel, demonstrating bowel wall thickening in areas of intramural hematoma and intraperitoneal fluid. Hyperattenuating sentinel clot can also be identified adjacent to sites of hemorrhage (27). CT is also more sensitive in the detection of pneumoperitoneum secondary to bowel rupture, which most commonly affects the ileocecal region and the colon (18,32,33). If there is penetrating trauma caused by secondary blast injury, it may be difficult to ascertain if the source is gas tracked into the abdomen from penetrating ballistic fragments, gas from ballistic fragment penetration of a hollow viscus, or gas from bowel perforation that is due to barotrauma from primary blast injuries.

Secondary Blast Injuries
Secondary blast injuries are caused by debris carried by the blast wind and most often result in penetrating injury from small shrapnel. The shrapnel can also cause blunt trauma similar to that encountered in motor vehicle accidents, gunshot wounds, stabings, and assaults (18,34,35). Terrorist bombs are typically packed with debris such as screws, nails, washers, ball bearings, rocks, and glass, in an effort to increase the lethality of the device (Fig 7). In the case of suicide bombers, bone fragments and shrapnel may also act as projectiles, causing penetrating injuries (10,36). These projectiles disperse out from the center of the blast at speeds similar to those of bullets and can cause penetrating injuries at distances of hundreds or even thousands of meters from the blast site (Fig 8) (18). This distance is in contrast to primary blast injuries, which usually occur within tens of meters from the blast site. Consequently, secondary injuries are the most
commonly encountered form of injury in blast victims (16). Secondary blast injuries have no predilection for a particular body region and can range from devastating penetrating brain injuries to bomb fragments embedding in soft tissues with little clinical consequence (34).

Radiography and CT are the two imaging modalities that are used for the assessment of secondary blast injuries (Figs 9–11). Orthogonal view radiographs can be used to localize bomb fragments and sites of fractures of the extremities and to identify debris in the thorax or abdomen. CT may disclose pulmonary lacerations, pneumothoraces, penetrating injuries to the abdominal viscera, and vascular injuries (10,32,34,36,37).

**Tertiary Blast Injuries**

Tertiary blast injuries are caused by the physical displacement of the victim and the wide variety of blunt or penetrating trauma sustained as a result of the person impacting immovable objects such as surrounding cars, walls, or fences (Fig 12) (32,38,39). Splenic laceration and rupture, liver injuries, brain injuries, and orthopedic injuries have all been reported (18,38,40,41). These injuries are not well described in the radiologic literature but would be expected to have imaging appearances similar to those of injuries sustained in falls and when pedestrians are struck by moving vehicles.

**Combination Injuries**

Injuries to the head can result from multiple mechanisms, and it may be difficult to ascertain which mechanism is responsible for which injury. Primary blast injuries to the head can take the form of (a) a direct blast wave transmission...
Figures 9–11. (9) Tympanic membrane perforation. This perforation was a rare instance in which the injury was a secondary blast injury (not primary). Axial noncontrast CT image shows a ball bearing (arrow) located in the expected location of the right tympanic membrane. (10) Secondary blast injuries. Frontal radiographs of the pelvis (a) and left knee (b) show multiple soft-tissue ball bearings and nails. Note the nondisplaced fracture of the left lateral tibial plateau (arrow in b). (11) Secondary blast injuries to the lower extremities. (a) Frontal radiograph of the left leg shows multiple ball bearings and nails lodged in the soft tissues. (b) Lateral radiograph of the right leg of a different patient shows an open comminuted fracture of the distal tibial and fibular shaft caused by a large piece of shrapnel (arrow).

Vascular injuries can also be a feature of blunt and penetrating trauma (46,51,52). In patients with closed head injuries, areas of intraparenchymal, subdural, epidural, and subarachnoid blood can all be identified and can be caused by either (a) the patient being impacted by debris (secondary mechanism) or (b) the patient impacting other objects (tertiary mechanism) (Figs 13, 14) (53). Open head injuries can be due to penetrating trauma (secondary mechanism) from debris thrown by the blast, resulting in disruption of brain parenchyma and resultant bleeding into both intraaxial and extraaxial spaces (46,49). Facial

to the brain parenchyma via foramina such as the optic canal and the superior orbital fissure or (b) a rapid deformation of the skull plates and severe global head acceleration resulting in shearing injury and axonal disruption (27,42–45). The blast wave itself has been reported to cause cerebral edema (46). Distortion of the chest resulting from the primary blast wave can exert pressure on the cardiac chambers, resulting in surges of blood into the brain; and vascular injuries such as vasospasm and pseudoaneurysm formation have been identified in blast victims (43–45,47–50).
Fractures around the air-filled facial sinuses can be a result of pressure changes from the primary blast wave or trauma sustained as a result of debris thrown from the blast or the patient impacting other objects (27,31,36). All of these injuries can be identified alone or in combination at CT, and a low threshold for performing CT angiography should be maintained for any patient who has sustained injury as a result of the primary blast wave or who demonstrates subarachnoid or intraparenchymal blood, especially if there are fractures that extend through vascular foramina. Magnetic resonance (MR) imaging typically is not immediately performed in blast injury patients because of the risk of movement of metallic shrapnel in the magnetic field.

Musculoskeletal injuries are the most common injuries encountered in blast victims, the most severe manifestation being traumatic amputation, which occurs in 1%–3% of victims (Figs 15–17) (54). Traumatic amputations occur as a result of multiple injury mechanisms. Coupling of energy from the blast wave into the shaft of long bones has been shown to produce fractures that have a predilection for the proximal third of the humerus and forearm, as well as the distal...
third of the femur and proximal third of the tibia (Figs 15–17) (10,55). The subsequent blast wind then separates the limb from the body at the site of fracture, resulting in transosseous amputation. Debris carried by the blast wind can also result in limb amputation as a direct result of blunt and penetrating trauma (15,36). Traumatic blast limb amputation carries a high mortality, and a high level of suspicion for additional injuries should be maintained for any patient with traumatic amputation (15,35,36,53,56). Imaging of orthopedic injuries can initially be undertaken with radiographs, which identify fractures as well as radiopaque debris carried into the soft tissues by the blast wind. CT is more sensitive in the detection of debris such as glass (57). CT is also useful in assessing for concomitant injuries and the position of debris in relation to neurovascular structures, and CT angiography is helpful for the assessment of vascular injuries (54).

Figure 14. Craniectomy performed for increased intracranial pressure. Frontal radiograph (a) and coronal CT image through the temporal region (wide window width) (b) show bilateral frontal craniectomies performed because of increased intracranial pressure in a patient who had suffered severe traumatic brain injury from an IED blast in the Middle East.

Radiologic Experience of the Boston Marathon Bombing

The Boston Marathon bombing was perpetrated on Patriots’ Day, a local (but not federal) holiday. Consequently, local hospitals were operating on a normal schedule and were fully staffed (58). The timing of the blasts at 2:49 PM was just before shift changeover between 3 and 5 PM at Massachusetts General Hospital and Brigham and Women’s Hospital (58,59), which fortuitously ensured that there was nearly a double complement of radiology staff available even before calling in additional staff members. Because of the proximity of the blast site to the hospitals, the first patients were imaged within 30 minutes after the bomb blast (2,60).

Because of the low power of the bombs in comparison with military explosives, the mortality was low, and the injuries were predominantly penetrating injuries to the lower extremities. IED-related mounted (in a vehicle) fatalities are mainly caused by head and chest injuries, but lower extremity traumatic injuries are the leading cause of death in dismounted (outside a vehicle) fatalities. No deep penetrating injuries to the abdomen or chest occurred as a result of the Boston Marathon bombing. The low power of these IEDs resulted in a predominance of secondary blast injuries, with ball bearings, nails, screws, and pieces of the pressure cooker housing acting as shrapnel (2,60,61). Of the 43 patients who underwent radiography in the emergency departments of three local hospitals, 32 had retained shrapnel in quantities ranging from one to 41 fragments per individual, with a total of 189 fragments (2). Of these fragments, 138 were embedded in the lower extremities, eight in the upper extremities, 25 in the pelvis, two each in the chest and the abdomen (which did not penetrate the pleural or peritoneal spaces), and 14 in the head and neck (2). This distribution was likely a function of the bombs being placed at ground level. Fractures were identified in 11 patients, involving the lower extremities, hand, orbit, nose, and lumbar spine. A tibial fracture, a nasal bone fracture, and isolated transverse process fractures in the lumbar spine were believed to be tertiary injuries,
Figures 15–17. (15) Traumatic lower extremity amputation from an IED blast in the Middle East. (a, b) Two radiographs show extensive muscle loss in the right leg, for which the patient underwent emergent amputation above the knee. The patient had soft-tissue loss, ongoing hemorrhage, calcaneal fracture, and hypotensive shock. (c) CT angiogram shows proximal right popliteal artery occlusion (arrow). (16) Radiography of limbs after traumatic amputation. (a) Radiograph of amputated bones and soft tissues was obtained to evaluate for shrapnel fragments. (b) Radiograph of the amputated distal portion of the lower extremity and pieces of bone was obtained to document removal of the shrapnel from the remaining limb. (17) Traumatic limb amputation from IED blast injuries in the Middle East. (a) Radiograph of the right foot shows traumatic amputation of the mid foot, distal to the talus and calcaneus. (b) Radiograph shows fractures of the femur and tibia. There is traumatic amputation of the right leg. Multiple shrapnel fragments are located in the soft tissues adjacent to the amputation site.
with the remainder caused as secondary injuries from blast wind–related flying shrapnel (2).

**Imaging Algorithm**
Radiography is considered the initial imaging modality best suited to perform a rapid initial assessment for the presence of fractures and penetrating shrapnel fragments in the evaluation of a patient for blast injuries. A preliminary survey involves radiography of the chest, abdomen, and any additional body parts for which there is a suspicion of injury. The chest radiograph is a supine image to evaluate for acute pathologic conditions, such as pneumothorax and hemothorax. Radiographs in at least two projections allow assessment of the anatomic location of the shrapnel.

For a patient in the immediate vicinity of a blast, in a mounted IED attack, or with evidence of severe trauma on the basis of radiographs, focused assessment of sonography in trauma (FAST), or clinical assessment, CT is a powerful tool for assessing injuries and determining treatment and prognosis. CT is considered the most appropriate imaging modality for medically stable patients when imaging is considered for head, chest, or abdominal injuries (Fig 18). In a retrospective chart review at the U.S. Air Force Theater Hospital at Balad Air Base in Iraq, 90% of patients involved in explosive blast injuries required CT examinations, 93% of which were initial trauma whole-body CT (“pan-scan”) (62). Furthermore, if there is a suspicion of vascular injury, then CT angiography can be performed. CT angiography has been found to show occult vascular injury in a considerable proportion (17%) of
military trauma patients undergoing whole-body CT (Fig 19) (63). Medically unstable patients suspected of having a torso injury can be best evaluated with FAST performed in the trauma bay and with portable torso radiography of the chest and abdomen (Fig 20). FAST can include assessment for pericardial effusion and is usually performed by surgeons or emergency medicine physicians.

Initial evaluation with MR imaging should be avoided in blast injury patients until the presence of metallic shrapnel has been excluded because of the risk of thermal injury or movement of metallic shrapnel in the high magnetic fields. The role of MR imaging in later stages of evaluation is not clear and is undergoing more investigation (64).

**Conclusion**

The extensive use of radiologic investigations in victims of the Boston marathon bombing reaffirms the role of radiology in the evaluation of foreign bodies and skeletal trauma in medically stable patients. The most common radiographically apparent findings at initial assessment include shrapnel and fractures. Evaluation with radiography and CT plays an integral role in the diagnostic assessment of the blast injuries and in the optimal management of medically stable patients.

**Acknowledgment**—Susanne Loomis, MS (Massachusetts General Hospital, Boston, Mass), provided the artwork for the illustrations in Figures 1 and 3.

**Disclosures of Conflicts of Interest**—M.H.L. Activities related to the present article: disclosed no relevant relationships. Activities not related to the present article: institutional grant and personal fees from GE Healthcare; personal fees from Millennium Pharmaceuticals. Other activities: disclosed no relevant relationships.

**References**


This journal-based SA-CME activity has been approved for AMA PRA Category 1 Credit™. See www.rsna.org/education/search/RG.