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PAPER

CRIMINALISTICS

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Primary and Secondary Skeletal Blast Trauma*,†

ABSTRACT: This study examines primary (resulting from blast wave) and secondary (resulting from disintegrated, penetrating fragments) blast trauma to the skeleton. Eleven pigs were exposed to semi-controlled blast events of varying explosive type, charge size, and distance, including some cases with shrapnel. Skeletal trauma was found to be extensive, presenting as complex, comminuted fractures with numerous small, displaced bone splinters and fragments. Traumatic amputation of the limbs and cranium was also observed. Fractures were concentrated in areas nearer the blast, but there was generally no identifiable point of impact. Fractures were more random in appearance and widespread than those typically associated with gunshot or blunt force injury events. These patterns appear to be uniquely associated with blast trauma and may therefore assist forensic anthropologists and other forensic examiners in the interpretation of skeletal trauma by enabling them to differentiate between blast trauma and trauma resulting from some other cause.

KEYWORDS: forensic science, forensic anthropology, blast trauma, skeletal fractures, terrorism, explosive devices

Terrorism is defined by the *Federal Code of Regulations* as "the unlawful use of force or violence against persons or property to intimidate or coerce a Government, the civilian population, or any segment thereof, in furtherance of political or social objectives" (1). Worldwide, the prevalence of terrorist attacks employing the use of explosive devices has dramatically altered the proverbial battlefield by targeting civilians and producing various mass casualty injuries not typically treated in general population medical centers. The cumulative effect of terrorist bombings against US targets such as the World Trade Center attack on September 11, 2001, the Oklahoma City bombing, the bombings of the embassies in Dar es Salaam and Nairobi, and the numerous insurgency attacks in Iraq and Afghanistan has served to shift counterterrorism focus from wide-scale weapons of mass destruction to conventional explosive attacks. According to the National Counterterrorism Center (NCTC), in 2008, 11,800 terrorist attacks were committed against noncombatants resulting in over 54,000 deaths, injuries, and kidnappings (2). Bombings alone accounted for more than one-third of terrorist attacks with explosives, vehicle bombs, and improvised explosive devices resulting in a majority of injuries (2).

Terrorist explosive devices are utilized to produce maximum damage, drawing wide-scale attention while having minimal costs associated (3). The initiation of an explosive device leads to the rapid change of a small amount of solid or liquid material into a large volume of gas. An explosive in a given configuration, when initiated, will have associated peak overpressure and impulse, which can be measured at given distances from the seat of the explosion. This is referred to as the blast wave or the positive phase of the blast wave. This blast wave originates from the detonation wave, which travels through the explosive material at speeds often as high as 6–8 km/sec (4). As this shock wave meets the atmosphere, air is displaced at a high rate of speed as this blast wave moves through the atmosphere. After the blast wave has moved beyond a given point, a local vacuum exists which air in the atmosphere rushes back in to fill. This is the negative phase of the blast wave. It is not as powerful as the positive phase, but it lasts relatively longer. Injury and death typically occur because of the positive phase of the blast wave or via direct physical contact with items projected by blast forces. When studying blast trauma, consideration must be given to the type and size of the explosive charge, the proximity to the blast site, and the physical make-up of the area surrounding the event.

Blast traumas were first described during World War I and fall into several categories (5–7). Primary blast injuries result from barometric changes and affect hollow organs such as eardrums, lungs, and bowels (4, 8). Examples of primary barotraumas include but are not limited to ruptured eardrums, blast lung, and intestinal perforation. Blast overpressures of 2–5 psi can rupture eardrums while blast overpressures ≥80 psi have been shown to be lethal in more than 50% of cases (4, 8). Secondary blast injuries include any penetrating trauma resulting from fragments or shrapnel. In some cases, objects such as ball bearings may be incorporated into explosive devices to increase the damage caused by penetrating trauma (9). Although not a topic of this article, tertiary blast injuries result if large objects fall onto an individual or if an individual is thrown into objects. Tertiary blast injuries are associated with blunt and penetrating trauma in addition to crush injuries. Other miscellaneous injuries are associated with burns and smoke/dust inhalation.

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Forensic anthropologists have become increasingly involved in criminal, humanitarian, and conflict-related investigations that involve human skeletal remains, not only to assist with the identification of individuals, but also to interpret skeletal trauma associated with explosive weapons. In recent wars and terror events, most injuries of the skeletal system have been caused by exploding ordnance (10). Explosive weapons are designed to be destructive through the sudden pressure change caused by the blast or by spreading shrapnel that acts as small projectiles, both of which may result in skeletal fractures and dismemberment. While there is an abundance of literature on blast trauma, particularly in medical and orthopedic journals, the focus of these studies is generally mortality from and treatment for blast injuries (e.g., [3–8, 10–18]). Moreover, most of these studies are case reviews, with very few controlled, empirical studies having been conducted (e.g., [11]). Within the anthropological literature, studies of skeletal trauma emphasize blunt, sharp, and gunshot trauma, with little mention of skeletal trauma resulting from blasts, though Kimmerle and Baraybar (19) provide a good summary for explosive-related injuries.

To correctly interpret the skeletal fracture patterns resulting from blasts, it is important to understand the mechanisms of skeletal blast trauma and to document known blast trauma patterns. Various factors can affect the morphology of blast wounds including type and amount of explosive, type and amount of shrapnel, location of the explosion, the presence of structures or intermediate targets, location of the victim relative to the blast, and the physiology of the victim (19) as well as the size and shape of fragments (11). We hypothesize, however, that blast trauma, when carefully examined and interpreted, can be distinguished from other mechanisms of skeletal trauma. This project aims to examine primary (resulting from blast wave) and secondary (resulting from disintegrated, penetrating fragments) blast trauma to bone in semi-controlled environments and document skeletal fracture and dismemberment patterns. The issues of particular concern are whether primary blast forces can be distinguished from other types of blunt force trauma and whether secondary blast trauma can be distinguished from other projectile trauma such as gunshot wounds.

Materials and Methods

Euthanized pigs (*Sus scrofa*) procured from a local farmer were used as test specimens. Specimens were exposed to blast events of varying explosive type, charge size, and distance carried out over four separate series of tests. Parameters for each set of tests are described in detail later and summarized in Table 1. Specimen and test preparation were carried out with the assistance and supervision of explosives experts. To avoid confusion with bone fragmentation, the authors will use the term “shrapnel” to refer to the explosive effect of projecting pieces of metal from the explosive main charge when such metal pieces originate from the container of an explosive charge or from added metallic material such as ball bearings, nuts, bolts, and nails.

TABLE 1—*Blast parameters for each test specimen.*

Specimen	Explosive Type and Amount	Distance	PSI
1	1 ft^2 PETN, 120 ft detonation cord, 0.5 lb C4	Contact	*
2	2 lbs C4 in pipe bomb	Contact	*
3	500 g C4 sphere	Contact	2500 at 0.5 ft
4	1000 g C4 sphere	Contact	2700 at 0.6 ft
5	1500 g C4 sphere	Contact	3100 at 0.6 ft
6	4000 g C4 sphere	5 ft	254
7	4000 g C4 sphere	1 ft	2900
8	4000 g C4 sphere	2 ft	1100
9	4000 g C4 in vest, ½″ ball bearings	Contact	*
10	4000 g C4 in vest, ½″ ball bearings	1 ft	*
11	4000 g C4 in vest, ½″ ball bearings	2 ft	*

*Overpressure table data are generally only available in spherical and hemispherical charge configurations. Additionally, overpressure data become difficult to measure or predict in such proximity to explosive charges.

The first series of blast tests were carried out in conjunction with the FBI’s Underwater Search and Evidence Response Team (USERT) Underwater Post-Blast Training Course. As part of the training, USERT planned to detonate explosive devices on two boats. Following the explosive events, forensic divers were to enter the water to recover boat fragments, bomb components, and remains.

Specimens 1 and 2 weighed *c.* 160 lbs each. Within the smaller of the two boats (an 18-ft Wellcraft), three types of explosives were used: pentaerythritol tetranitrate (PETN)-based detonating cord, PETN-based detasheet, and research department explosive (RDX, aka cyclonite)-based C4. Approximately 120 ft of 50-grain (10 g/m) high-explosive detonating cord (velocity 22–25,000 ft/sec) was wrapped around a cardboard frame. Approximately 1 ft^2 of detasheet was also secured to the cardboard. On the boat, 0.5 lb of C4 was placed under the cardboard, and the pig (specimen 1) was placed on top of the cardboard in the driver’s seat. Additionally, several more feet of detonating cord were wrapped around the specimen’s neck and forelimbs. On the larger boat (a 26-ft Fiberform), the pig (specimen 2) was placed on the floorboard near a pipe bomb filled with slightly more than 2 lbs of C4.

The second, third, and fourth series of tests were carried out on an explosives demo range on Marine Corps Base Quantico. A stand was constructed to orient the pigs in a vertical (“standing”) position. The stand consisted of two 4 × 4 posts inserted into the ground, with a third piece of wood positioned across the top of the 4 × 4 s. The pigs were secured to the top beam by wrapping their forelimbs and the beam with heavy-duty monofilament tape (Fig. 1). Detonating cord secured around the monofilament tape was wired to detonate at the same time as the C4 so that the specimen would be released from suspension at the same time as the blast occurred. The charges were initiated electrically.

The second round of tests was designed to investigate the effect of varying charge size of direct contact explosive events. Three test blasts were carried out using pigs that weighed *c.* 120–135 lbs each (specimens 3–5). Spherical C4 charges were taped in direct contact with the specimens (Fig. 1a). Specimen 3 was positioned with 500 g of C4 in the chest region, specimen 4 had 1000 g of C4 placed in the abdominal region, and specimen 5 had two charges of 750 g each of C4, one placed in the chest region and one in the abdominal region.

The third set of tests examined the effects of distance from the blast. The same charge size of 4000 g C4 was used for the three tests, varying the distance of the test specimen from the charge. The pigs, weighing *c.* 100 lbs each, were affixed to a suspended board, similar to specimens 3–5. The charge was suspended from a tripod of 2 × 4 s at a height equivalent to the approximate center of mass of the specimen and positioned at the appropriate distance (Fig. 1b). The first charge was positioned 5 ft from the specimen, the second was 1 ft away, and the third was 2 ft away (Table 1).

The fourth round of tests involved the inclusion of shrapnel associated with a simulated suicide bomb event. One larger (300 lb) specimen (specimen 9) was designated as the “bomber” specimen and was fitted with a body armor cover vest containing 4000 g C4 and 250 ½″ ball bearings. The remaining two specimens were

FIG. 1—*Specimen positioning for blast events. (a) Specimens 3–5; (b) specimens 6–8; (c) specimens 9–11.*

designated as "victim" specimens and weighed about 100 lbs each (so that victims could be osteologically segregated from the bomber). A triangular stand was constructed to accommodate all the three specimens into a single blast event (Fig. 1c). They were positioned at a distance of 1 ft (specimen 10) and 2 ft (specimen 11) from specimen 9. Corresponding blast pressure, where possible, was calculated and can be seen in Table 1.

Following the blast events, searches were conducted over an appropriate radius, and the recovered material was transferred to plastic bins (recoveries were not complete for all specimens). Photographs were taken of the overall dispersion as well as of the larger, bone-containing portions of the remains although analysis of the dispersion and recovery effort are beyond the scope of this study. To the extent possible, specimens were field processed, removing the internal organs and as much soft tissue as possible. The specimens were then transferred to the FBI Laboratory for additional processing and analysis. To remove the remaining soft tissue, the specimens were macerated in warm water using hot plates and stainless steel stock pots. The remains were then filtered through cheesecloth and ¼″ screen and dried under a ventilated hood.

Specimens were examined visually and microscopically to determine the physical matches of fragments to analyze fracture patterns. Physical matches were reaffixed using Duco cement or Instabond, occasionally with the assistance of clay or sand to stabilize the fragments while the glue dried. The extent and pattern of skeletal fracture and dismemberment were documented, along with any other pertinent observations. All specimens had preexisting projectile trauma to the head from euthanization, so cranial fractures were not analyzed. Several specimens were examined radiographically, but with the exception of possibly facilitating the location of projectiles, this technique proved much less useful for locating, identifying, and analyzing fractures and fracture patterns than visual analysis and was therefore not performed on all specimens.

Results

Postblast dismemberment and major fracture patterns observed during reconstruction are summarized in Table 2. The severity of skeletal trauma was found to directly relate to the amount of explosives utilized as well as the placement of the explosives in relation to the specimen, with severity increasing with charge size and proximity to the blast event. Several examples of commonly observed fractures can be seen in Fig. 2. Collectively, fractures caused by the blast wave exhibited trauma that is often associated with mixed forces including compression, shearing, and bending; these patterns appear to be more random in appearance than those typically associated with projectile or blunt force injury events. Extensive comminuted fractures with numerous small, displaced bone splinters and fragments were observed in long bones, scapulae, and os coxae. Transverse and oblique fractures were noted in the head, neck, and shaft of numerous ribs. Several specimens sustained butterfly fractures in rib bodies.

Fractures consistent with hyperextension were observed in the dorsal spines, laminae, articular facets, and transverse processes of the vertebrae. Several specimens sustained primary fractures to the calcanei. Specimens exposed to blasts that included shrapnel displayed even greater fracture severity, with extreme bone fragmentation and extensive splintering, especially of the long bones. Skeletal injuries were concentrated in areas nearer the blast, but there were no identifiable points of impact. Fracture patterns were more random in appearance than those typically associated with gunshot or blunt force injury events. Traumatic amputation of the limbs and cranium was observed in numerous specimens.

Overall, skeletal trauma from the blast events observed in this study tended to be extensive, presenting as complex, comminuted fractures with numerous small, displaced bone splinters and fragments. Usually, long bone shafts were the most severely fractured, with frequent splintering into small bone fragments (one tibia, shown in Fig. 2, was reconstructed from more than 25 splintered fragments). Like other mechanisms of perimortem trauma, we observed delamination and plastic deformation resulting from blast trauma. As has been noted in other studies (e.g., [12]), fractures running parallel to the collagen fiber arrangement tended to be linear, while those fractures that ran obliquely or vertically to it were irregular or jagged. This was most often observed on the ribs and vertebrae (see Fig. 2). No stellate fractures or other fractures indicative of a point of impact were noted. One exception was the observation of butterfly fractures of the ribs, which appear to have resulted from the ribs being bent against their curve in response to the blast wave applied to the ventral side, rather than from impact forces originating from the dorsal side.

Although it has been noted (10) that 60–70% of all wounds in modern warfare result from secondary blast injuries, we saw significant and severe skeletal fractures in specimens located <5 ft from the blast event. Leibovici et al. (4) suggest that injuries would have been more severe at the 5-ft distance (and likely farther) if they occurred in a confined space versus the open-air scenario examined here. The authors explain that this is because of the fact that when the blast energy is contained in a confined space, the pressure

TABLE 2—*Postblast observations and fracture patterns.*

Specimen	Postblast Observations	Major Fracture Patterns
1	No dismemberment Visible soft-tissue damage to forelimbs	Fragmentation/splintering of forelimb bones, especially midshafts Dorsal spines separated from vertebrae
2	Posterior/caudal portion (pelvis and lower legs) not recovered and seen on video footage to have been displaced across the lake Anterior portion recovered in two parts—isolated forelimb and forelimb with shoulder and head	Long bones of hind- and forelimbs severely fractured Numerous rib fractures, especially below tubercles Dorsal spine and transverse process vertebral fractures
3	Dismemberment of head/upper arm from lower portion Hind portion recovered in several parts	Hindlimb long bones intact Humeri severely fractured, especially shafts Warped "blown out" rib fractures Dorsal spine vertebral fractures
4	Decapitation	Upper limb intact Lower limb extensively fractured, especially shafts Lower ribs fractured at angle
5	Decapitation Wider east/west dispersal radius than specimens 3 and 4	Fractures of all long bones, especially at midshaft Numerous rib fractures especially toward sternal ends with jagged, splintered edges Dorsal spine and transverse process vertebral fractures
6	No dismemberment Very little displacement	All bones intact No fractures noted
7	Amputation of hind limbs at the femoral head/acetabulum	No fractures to forelimb Hindlimb extensively fractured Butterfly fractures of ribs Fractures of transverse process of vertebrae
8	Amputation of forelimbs	Splintering rib fractures at neck/tubercle Lower limb long bones severely fractured, especially midshaft Radius and ulna severely fractured, especially midshaft
9	Dismemberment of torso with lower end remaining near blast site Vertebrae embedded in soil under blast site	Severe cranial fragmentation No fractures to hindlimb All vertebrae fractured Ribs highly splintered Discoloration—possible burning
10	Amputation of limbs, displaced from blast site	Rib butterfly fractures neck and head Dorsal spine vertebral fractures Numerous shards and small unconstructable long bone fragments present
11	Amputation of limbs, displaced from blast site	Rib neck and midshaft fractures Dorsal spine and transverse process vertebral fractures Extreme overall fragmentation, especially long bone shafts Lots of small splintered bone shards

waves are reflected from doors, walls, and ceiling, exposing occupants to increased intensity and duration of the pressure.

Ball bearing injuries have been shown to be remarkably similar to gunshot traumas (13); however, fragmentation of the three specimens subjected to the blast event involving ball bearings was so severe that no discernable point of impact could be located. Traumatic amputation of the limbs and cranium was also observed. Limb amputations were at the joint in one case (specimen 7), but otherwise were through long bones, which fits well with models presented by Hull and Cooper (14), who explain this as resulting from a combination of shock wave-induced diaphyseal fracture followed by avulsion through the fracture site by dynamic forces acting on the limb.

As noted by Kimmerle and Baraybar (19), projectile trauma from gunshot wounds can often be distinguished from shrapnel trauma based on differences in size, shape, number, association, and distribution of wounds, with shrapnel wounds being more variable and irregular in size and shape and also more numerous. The lower impact force of shrapnel compared with ballistic projectiles also generally means that shrapnel fragments will seldom exit the victim and are often recovered. Peleg et al. (15) noted that the two types of injuries tend to differ on body region affected, distribution, and severity. Weil et al. (16) also indicate blast traumas involve a higher energy mechanism, leading to increased injury severity and more fractures compared with gunshot wounds.

Discussion and Conclusions

Primary blast mechanisms have been reported to produce traumatic amputations, decapitation, and skeletal fractures, while secondary blast mechanisms produce projectile defects, radiating, concentric, or comminuted fractures with an injury distribution depending on the location of the victim to the blast (19). The patterns observed in this study appear to be characteristic of blast trauma or at least differ enough in quality and extent to appear distinct from other types of well-documented skeletal trauma (such as gunshot, sharp force, and blunt force). These results may therefore assist forensic anthropologists and other forensic examiners in the interpretation of skeletal trauma by enabling them to differentiate between blast trauma and trauma resulting from some other cause. Although we believe that diagnosis of blast injuries is possible, it does require thorough analysis of the individual skeletal injuries and careful interpretation of the injury distribution over the entire skeleton. It is also important to consider the various factors affecting trauma including the bone type, injury location, and all available contextual and investigative information.

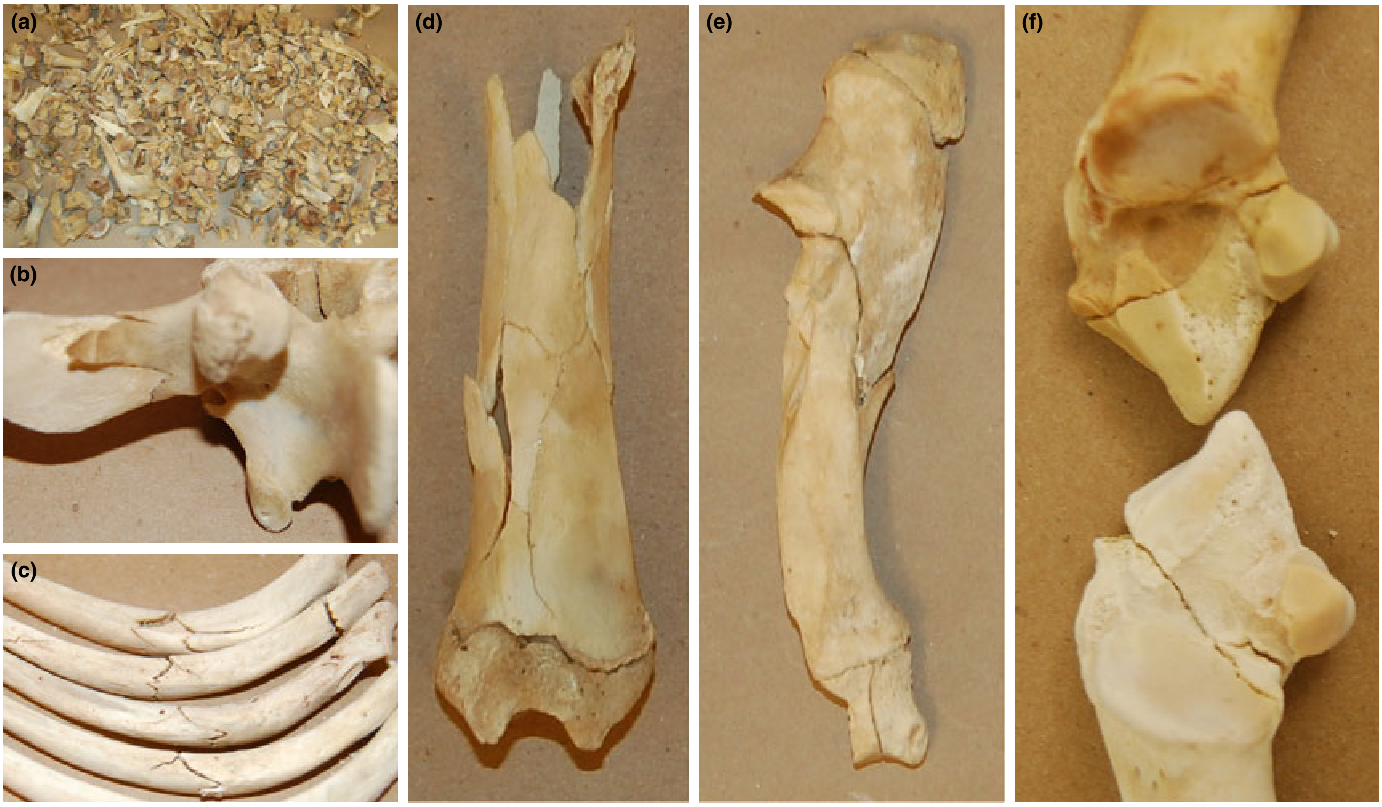

FIG. 2—*Examples of observed fragmentation and fractures.*

Although this semi-controlled study is among the first of its kind, it is fairly limited in scope. We examined only one primary explosive, only small blast distances and open-air settings, few events involving shrapnel, and only injuries of the postcranial skeleton. It is also possible that tertiary blast trauma from the specimens impacting the ground after the blast may have been a factor, but was considered limited. Similar studies should consider the investigation of cranial and soft-tissue injuries and the distribution and recovery of disintegrated parts. Additionally, few reported terrorist bombings have occurred in open-air settings (17), and several authors including Hadden et al. (18) have commented on the apparent protective effect of clothing, indicating the need for studies utilizing a wider variety of blast scenarios.

While we believe that relevant and useful findings are reported here, much more research is needed in the area of blast trauma, especially considering the increasing frequency with which anthropologists and other forensic and investigative professionals are likely to encounter skeletal trauma resulting from explosive events.

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