Brain injuries caused by spherical bolts

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Object. Metallic particles contained in antihuman bombs increase the number of fatalities. The ballistics of these particles depend on the explosive that is used, the distance from the explosion, the shape of the particle projected, and the biomechanics of the injured tissue. The authors present their experience with penetrating spherical bolt injuries to the brain.

Methods. The authors retrospectively reviewed clinical and radiological data obtained in eight patients with penetrating spherical bolt injuries to the cranium: four had Glasgow Coma Scale (GCS) scores less than 8 (three died, one from an unrelated injury) and four had a GCS score of 15 (all survived). Two of the latter patients suffered unique anatomical injuries attributed to the distinctive ballistics of spherical bolts: in one patient the bolt penetrated the cavernous sinus causing minimal cranial nerve injury, and in the other patient the bolt lodged in the fourth ventricle causing acute hydrocephalus without other neurological deficits.

Conclusions. Penetrating spherical bolts to the brain may be lethal. Nevertheless, they have unique ballistics that cause highly delineated anatomical damage and minor neurological deficits.

KEY WORDS • spherical bolt • penetrating brain injury • ballistics

ARTICLES penetrating the body’s soft tissues cause a variety of injuries, the intensity of which is related to the particular type of tissue at a specific anatomical site of the injury (for example, noneloquent brain tissue versus the brainstem), the kinetic energy of the particle at the moment it hits the tissue, and the particle’s geometrical characteristics and ballistics within the tissue. Penetrating brain injuries have been described in several large series focused on war and civilian victims, in which general survival statistics as well as treatment options and outcomes have been investigated. Previous analyses of brain injuries caused by different types of particles had focused on the relative velocity of the particle and not on the influence of the shape of the particle (for example, bomb debris compared with an object with a more uniform shape such as a bullet). We describe the specific ballistics and pathophysiological mechanisms of penetrating injuries to the brain caused by small spherical bolts and present our experience with several unique injuries of this sort.

Clinical Material and Methods

Our hospital is a primary and tertiary referral center for patients with head injuries and serves a population of 500,000. We retrospectively reviewed the cases of all patients (Cases 1–8). All eight patients had sustained a single blunt injury or an isolated head injury in the other four patients (Cases 5–8). All eight patients had sustained a single blunt injury to the calvaria. The diameters of the bolts ranged between 9 and 14 mm and the bolts weighed approximately 10 g each (Fig. 1); they all appeared to be ball bearings. One patient had sustained three additional spherical bolt injuries to her neck, with no clinical or surgical consequences.

Noncranial Injuries

Eight patients (four male and four female individuals ranging in age from 15 to 62 years) fulfilled the inclusion criteria of this study. Four were admitted to our institution with a GCS score of 15 and four had GCS scores less than 8. All eight patients underwent CT scanning, which demonstrated a spherical bolt within the calvaria. The patients’ demographic data are summarized in Table 1. None of them had suffered from any severe or active systemic disease before the index injury. On their arrival at the emergency department, moderate to severe noncranial injuries were diagnosed in four of the patients (Cases 1–4) and some other mild injury or an isolated head injury in the other four patients (Cases 5–8). All eight patients had sustained a single bolt injury to the calvaria. The diameters of the bolts ranged between 9 and 14 mm and the bolts weighed approximately 10 g each (Fig. 1); they all appeared to be ball bearings. One patient had sustained three additional spherical bolt injuries to her neck, with no clinical or surgical consequences.

Noncranial Injuries

With the exception of one patient (Case 1) who exhibited severe hemodynamic and hypoxemic disturbances on admission, the patients were hemodynamicely stable with no hypoxia. Of the four patients who initially had a GCS score of 15, one had a broken arm, which was set; one had open

Abbreviations used in this paper: CT = computerized tomography; GCS = Glasgow Coma Scale; GOS = Glasgow Outcome Scale.
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TABLE 1
Characteristics of eight patients with brain injuries caused by spherical bolts*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>GCS Score</th>
<th>Pupils on Admission</th>
<th>Hypotension/Hypoxia on Admission</th>
<th>Noncranial Injuries</th>
<th>GOS Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20, M</td>
<td>3</td>
<td>DUR</td>
<td>PP</td>
<td>bilat pneumothorax; asystole on admission</td>
<td>1†</td>
</tr>
<tr>
<td>2</td>
<td>38, F</td>
<td>4</td>
<td>DUR</td>
<td>N/N</td>
<td>particles in rt thigh, pelvis, chest,LEs</td>
<td>1‡</td>
</tr>
<tr>
<td>3</td>
<td>17, F</td>
<td>5</td>
<td>N</td>
<td>N/N</td>
<td>open fractures in lt leg</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>15, F</td>
<td>5</td>
<td>A, more so on lt than on rt</td>
<td>N/N</td>
<td>injury to lt eye; particles in neck</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>21, F</td>
<td>15</td>
<td>N</td>
<td>N/N</td>
<td>none</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>35, M</td>
<td>15</td>
<td>N</td>
<td>N/N</td>
<td>simple closed arm fracture</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>62, M</td>
<td>15</td>
<td>rt, absent; lt, normal</td>
<td>N/N</td>
<td>particle in rt thigh subcutaneous tissue</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>17, M</td>
<td>3</td>
<td>DUR</td>
<td>N/N</td>
<td>particles in both UE's</td>
<td>1†</td>
</tr>
</tbody>
</table>

* A = anisocoria; DUR = dilated unreactive pupil; LE = lower extremity; N = normal; P = present; UE = upper extremity.
† Died 1 day after injury.
‡ Died 5 days after injury.

Neurological Consequences of Penetrating Head Injury

Four patients were admitted with a GCS score of 15. Three had equal and responsive pupils, and the fourth had an old opacification of the right eye. Two patients (Cases 3 and 6) were asymptomatic. One patient (Case 5) presented with diplopia, whereas the remaining patient (Case 7) became irritable. The specific injuries in this group, including the entry sites and trajectories, are summarized in Table 2. All injuries were unilateral. Three patients underwent neurosurgical procedures. The first patient (Case 3) underwent local debridement of the entry site with evacuation of superficial intraparenchymal blood. The bolt was not extracted because of its deep location. The second patient (Case 7) had acute hydrocephalus due to the fact that the bolt lodged within the fourth ventricle (Fig. 2). A ventriculostomy was placed in this patient and the bolt was carefully removed by a suboccipital craniectomy and slight elevation of the tonsils and vermis. No injury to the floor of the fourth ventricle was evident. The entry site in this patient was debrided as well. The bolt in the third patient (Case 6) was extracted from the skull. In one patient (Case 5) a bolt was left within the right parietal lobe.

In four patients the GCS score was less than 8 on admission. The main findings on CT scans obtained in these patients are summarized in Table 2. One patient (Case 1), who presented with a GCS score of 3 with wide and unreactive pupils and severe hemodynamic and respiratory disturbances, did not undergo any neurosurgical procedure and died the following day, most probably as a result of combined neurological and noncranial injuries. An intracranial pressure monitor probe was inserted into another patient (Case 2), who presented with a GCS score of 4 and had dilated and unreactive pupils (Fig. 3). In this patient intracranial pressure ranged between 70 and 100 mm Hg and cerebral perfusion pressure was less than 30 mm Hg. This patient was declared brain dead 5 days later. The third patient (Case 4) underwent several neurosurgical procedures, including massive debridement with closure of left middle cerebral artery distributing branches (Fig. 4). During the following weeks, a local abscess and meningitis were noted and the patient eventually recovered to the point at which she could be treated in a rehabilitation center. The fourth patient (Case 8), who presented with a GCS score of 3, with wide and unreactive pupils, was declared brain dead a few hours after admission and did not undergo any neurosurgical procedure.

Patient Outcomes

All four patients who presented with a GCS score of 15 survived. In one patient (Case 7) a ventriculoperitoneal

FIG. 1. Photograph showing a spherical bolt originally used as a ball bearing.
Shunt was inserted to treat communicating hydrocephalus; that man had a GOS score of 4. Another patient (Case 5) still suffers from paresis of the left trochlear nerve and hypesthesia in the territory of the left ophthalmic division of the trigeminal nerve. This woman’s left-sided abducens nerve paresis has resolved. She suffers from partial right upper quadrantopsia, most probably secondary to some left temporal lobe injury. Two patients (Cases 3 and 6) have no neurologic deficits.

Three of the four patients who presented with a GCS score less than 8 died. One death was secondary to severe chest and brain injuries (Case 1), whereas the others were secondary to lethal brain injury (Cases 2 and 8). The fourth patient (Case 4) has partially recovered: she suffers from right hemiparesis, left eye blindness, and right temporal hemianopia. She is able to walk with assistance and understands speech, but suffers from speech disturbances (that is, motor dysphasia) and can speak only in short sentences.

**Discussion**

Projectiles added to bombs have been described previously and are intended to intensify the extent of morbidity and mortality. Nails, various bolts, and any metallic debris have been used, as well as ball bearings. We describe a series of eight patients who suffered penetrating head trauma caused by spherical bolts, all of which were ball bearings.

**Bioengineering and Ballistics of Penetrating Projectiles to the Body**

Many studies have focused on ballistics and the importance of penetrating projectiles to the body. The ballistics of a projectile are subdivided into a few phases. The first, “internal ballistics,” focuses on the source of the projectile—rifle, bomb, or other—and the dynamics of the source. The second phase, “external ballistics,” focuses on the traveling stage between the source and the target. This phase takes into consideration the flight itself, the collision, and the penetration of interfering objects until the projectile reaches the target. Basically, during the external phase, the projectile demonstrates a yaw motion (a slight alternating deviation of the projectile’s axis relative to the flight axis). Any collision will change the motion’s speed, angle, and yaw, as well as the projectile’s shape, thus affecting its ballistics. The terminal and final phase of ballistics is known as “terminal ballistics” and includes the physical interaction between the projectile and the tissue it penetrates. As we are dealing with projectiles released from bombs in a non-laboratory scenario, internal as well as external ballistics are mostly unpredictable, and influenced easily by explosive characteristics, distance from the victim, and the path projectile shrapnel travels until it reaches the target body. Specific projectiles may influence the external ballistics, however. Nonaerodynamic projectiles such as spherical ones will lose more kinetic energy than nails. Thus at the point of penetration, the projectile’s velocity is comparatively reduced. In addition, nonspherical projectiles such as spherical projectiles will lose more energy as they penetrate the first layers of the body such as the skin and skull.

**Terminal Ballistics**

During the terminal phase, the projectile causes tissue injury by creating temporary and permanent cavities. A permanent cavity is caused by a direct crush of tissue, whereas a temporary cavity is caused by compression of surrounding tissue. Terminal ballistics are influenced by multiple factors. Some factors are related to the projectile itself, whereas others relate to the injured tissue. Projectile-related factors include its mass (M; a heavier particle possessing higher inertia is better able to maintain its velocity and is, therefore, potentially more damaging for a greater distance than a lighter one with the same striking velocity) and striking velocity (V; damage is dependent on the amount of kinetic energy of the projectile just before it penetrates the tissue). The striking velocity is more important than the mass in determining the amount of energy available to be imparted to the tissue because the kinetic energy is equal to 0.5 MV². High-velocity injuries have traditionally been assumed to cause more damage than low-velocity ones, an assumption that is still under dispute.

The amount of energy lost into the tissues depends on the area perpendicular to the traveling axis presented by the projectile at any point during its course. These aspects are influenced by the shape, deformation and breakup, and stability of the projectile.

**Shape.** In one study, spheres and chunky shell fragments of the same weight were fired into a gelatin model at vari-

### Table 2

**Flight path of particle within the calvaria and description of brain injury**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Entry Site</th>
<th>Lodging Site</th>
<th>Transventricular Injury</th>
<th>Comments on Injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>rt occipital</td>
<td>rt frontal</td>
<td>no</td>
<td>massive rt hemispherical damage</td>
</tr>
<tr>
<td>2</td>
<td>lt frontal</td>
<td>rt parietal</td>
<td>yes</td>
<td>massive bhemispherical damage</td>
</tr>
<tr>
<td>3</td>
<td>rt frontal</td>
<td>rt frontal</td>
<td>no</td>
<td>intraparenchymal hemorrhage; small SDH</td>
</tr>
<tr>
<td>4</td>
<td>lt supraorbital</td>
<td>lt occipital (out of skull)</td>
<td>no</td>
<td>massive lt hemispherical damage</td>
</tr>
<tr>
<td>5</td>
<td>rt maxilla</td>
<td>lt parietal</td>
<td>no</td>
<td>transverses lt cavernous sinus; mild rt temporal contusion secondary to bone fragment</td>
</tr>
<tr>
<td>6</td>
<td>lt frontal</td>
<td>lt frontal calvaria, no skull/brain penetration</td>
<td>no</td>
<td>stuck in skull; small EDH, SDH, &amp; SAH</td>
</tr>
<tr>
<td>7</td>
<td>rt posterior fossa</td>
<td>4th ventricle</td>
<td>no</td>
<td>mild acute hydrocephalus</td>
</tr>
<tr>
<td>8</td>
<td>rt frontal</td>
<td>4th ventricle</td>
<td>no</td>
<td>massive SAH, rt temporal &amp; occipital acute SDH, bilat uncal herniation</td>
</tr>
</tbody>
</table>

* EDH = epidural hematoma; SAH = subarachnoid hemorrhage; SDH = subdural hematoma.
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Fig. 2. Case 7. Computerized tomography scan revealing a spherical bolt lodged within the fourth ventricle.

Fig. 3. Case 2. A: A CT scan revealing massive bihemispherical destruction with intraventricular hemorrhage. B: A corresponding CT scan demonstrating that the damage was caused by the bolt crossing from the left to the right side.

ous velocities. In all tests, chunky fragments lost a high percentage of their energy close to the entry site and penetrated the gelatin a shorter distance. Spherical particles, on the other hand, lost a much lower percentage of kinetic energy compared with chunky shell fragments at equal distances and penetrated the gelatin a significantly longer distance. In another study, the permanent cavity created by spherical particles was constant and unified, with the cross-section diameter identical to the diameter of the projectile, whereas the temporary cavity was large immediately after penetration but declined in size afterward.

Deformation and Breakup. Any projectile that breaks up or causes bone debris produces secondary projectiles that cause damage by their ballistics. Penetrating projectiles to the brain have to pass through the skull, thus causing secondary bone fragments.

Stability. A stable projectile is one traveling “nose on,” so that its axis is always pointing along the motion axis. Shell fragments are inherently unstable; they travel in a tumble motion, changing the area perpendicular to the flight axis and thus changing the sizes of permanent and temporary cavities—enlarging them, decreasing them, and so forth. Unlike irregularly shaped projectiles, such as chunky projectiles or even bullets, spherical projectiles display no tumbling action; the energy transferred to surrounding tissue is predictable and is a function of distance and velocity, steadily decreasing after penetration.

Factors Related to Injured Tissue. Projectiles that penetrate air-containing tissue cause smaller temporary cavities, whereas projectiles that penetrate solid nonelastic tissues such as brain tissue cause larger temporary cavities.

In summarizing the bioengineering data about various projectiles, it seems that irregularly shaped projectiles produce irregular cavities and cause especially extensive damage. Spherical particles have unique ballistics. They are nonaerodynamic, losing speed during the external phase and losing more energy during skin and skull penetration. These projectiles create a permanent cavity that remains constant in size and a temporary cavity that steadily decreases in size. Having lost much of their kinetic energy on penetrating the skull, the length of the distal temporary cavity is short and the permanent cavity may be short as well. These specific ballistic characteristics yield a kind of “stab wound” injury.

Brain Injuries Caused by Spherical Bolts

We present eight cases of brain injuries caused by spherical bolts. Generally, brain injuries may not correlate with the extent of tissue damage. In one patient (Case 5), the bolt penetrated the cavernous sinus, resulting in some cranial nerve injury—palsies involving the ophthalmic division of the trigeminal nerve as well as the abducens and trochlear nerves. This patient easily could have died had the carotid artery been injured. In another patient (Case 3), a temporal or parietal lesion similar to the one in his frontal lobe could have caused comparatively more clinical damage. This lack of correlation between the amount of tissue injury and the clinical state is true for any injured tissue in the body but much more so for the brain. Although this relationship is totally dependent on the specific tissue and its physiological role and has nothing to do with the ballistics of projectiles, spherical bolts cause less damage in a given anatomical site than particles with nonspherical shapes. Had the particles been irregularly shaped in the same injury sites, an injury to the cavernous sinus would have had a greater chance of injuring the carotid artery, and a projectile lodged in the fourth ventricular could have injured the brainstem.

Basic prognostic factors seem applicable to our study group despite its small size. Three of our deceased patients presented with GCS scores of 3 or 4 and dilated and unreactive pupils; one of these patients had sustained a bilateral transventricular brain injury. A fourth severely injured patient sustained a unilateral injury; she underwent massive debridement and decompression, which allowed the brain
to recover. This patient survived despite receiving a massive unilateral injury and an almost complete left hemispherectomy; we contend that her survival was not related to the specific characteristics of the bolt injury.

Indications for surgery in our group were the same as those accepted for any penetrating brain injury.3,15 Non-symptomatic intracerebral bolts were not removed unless surgery was otherwise indicated (massive debridement in the patient in Case 4 and removal of an intraventricular bolt causing hydrocephalus in the patient in Case 7). The presence of metallic projectiles and bone fragments did not mandate removal because they are not associated with a higher rate of infection and their removal does not reduce the incidence of seizures.3 Patients in a moribund state were not surgically treated.

Our patient population is inherently biased because we did not include patients who were killed at the scene: there were 47 recorded deaths in the four bombing events; the differential diagnosis of the cause of death in people who died at the scene did not include brain injury due to a penetrating spherical bolt or any other fatal injury. Moreover, four of our eight patients presented with a GCS score of 15, possibly misrepresenting the severity of injury among the injured in mass casualty events.

Conclusions

This small group of eight patients demonstrates the versatile potential of penetrating spherical bolts to the brain. The unique feature of this kind of particle, compared with other penetrating particles, is the stab wound-like quality of the injury, which could result in a precision injury with less surrounding damage to the brain tissue or, alternatively, massive brain destruction with severe consequences.

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