From Henry Shrapnel (1761–1842) to today’s neurosurgery: how antipersonnel weapons have laid the foundation of clinical and surgical management of head injury fractures and penetrating brain injuries

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Henry Shrapnel invented an antipersonnel weapon capable of defragmenting with the explosion of charge. Modern grenades or improvised explosive devices may be seen as an evolution of Shrapnel’s ammunition. Starting by analyzing the ballistics of these weapons, it is possible to understand the historical evolution of the management of skull fractures and penetrating brain injuries (PBIs).

A circular crack line with a splinter at the center, depressed in bone, was a characteristic feature of fractures due to Shrapnel’s bullet. Three longitudinal fissures, one medial and two lateral, may be present due to tangential blows. Craniectomy and/or fracture reduction were almost always necessary in these cases.

The first document describing medical examination and therapeutic strategies for head-injured patients dates back to 1600 BC (the Edwin Smith Papyrus). Several doctors from the past century, such as Puppe, Matson, and Cushing, proposed different theories about skull fractures and the management of craniocerebral injuries, paving the way for diagnosing and treating these injuries.

Shrapnel fractures required wider craniotomies and in the past surgeons had to deal with more severe injuries. Based on past military experiences during what could be called the post-shrapnel age, guidelines for the management of PBIs were introduced in 2001. In these guidelines various concepts were reviewed, such as the importance of antibiotics and seizure prevention; included as well were prognostic factors such as hypotension, coagulopathy, respiratory distress, and Glasgow Coma Scale score. Furthermore, they highlight how it has not been possible to reach a common viewpoint on surgical management. Nevertheless, in contrast with the past, it is preferable to be less aggressive regarding retained fragments if there is no intracranial mass effect.

Although military situations were useful in building basic principles for PBI guidelines, civilian PBIs differ noticeably from military ones. Therefore, there is a need to review modern guidelines in order to apply them in every situation.

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ABBREVIATIONS GCS = Glasgow Coma Scale; IED = improvised explosive device; PBI = penetrating brain injury.


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nades) or may present a mechanical launcher that projects them at high speeds (rocket-propelled grenades [RPGs]). Furthermore, hand grenades may be characterized by fragmentation-producing splinters (defensive hand grenades), or by high explosive charge, due to the speed of chemical reaction during detonation (offensive hand grenades).^2^ However, since the 19th century, the use of improvised explosive devices (IEDs) has been increasingly widespread in war and domestic terrorism. The US Department of Defense defines IEDs as “devices placed or fabricated in an improvised manner incorporating destructive, lethal, noxious, pyrotechnic or incendiary chemicals, designed to destroy, disfigure, distract or harass and often incorporate military stores...”^3^ They usually consist of a container with a source of power (a battery), a charge, an initiator (detonator), and a switch.\(^4\)

Therefore, starting from the analysis of the ballistics of shrapnel bullets, we can understand how clinical and surgical management of skull fractures and penetrating brain injuries (PBIs) have evolved over the last century (Fig. 1).

The Ballistics of Shrapnel Missiles, Impact Forces, and Injuries Related to Modern Weapons

Many surgeons underestimated extracranial soft-tissue wounds produced by shrapnel bullets in the war setting, because they resemble normal confused-lacerated wounds. Although soft-tissue wounds were trivial and shrapnel bullets were animated by small forces, they may also conceal skull involvement. Indeed, typical fractures related to shrapnel bullets were characterized by a circular fracture line, because the spherical morphology of the pellet created a cone of depression that exceeded the elasticity index of the cranial bones. They presented with a splinter at the center; this splinter was approximately 1 cm in diameter, wider on the side of the inner skull, but usually not able to injure the dura mater. The splinter was generally depressed in the cranial cavity and embedded in such a way that lifting and eventually removing it was impossible without a limited craniectomy. Moreover, skull injuries produced by tangential blows of shrapnel missiles had to be considered. They were more severe because they could cause contusions and/or meningoencephalic lacerations and carry hair and skin fragments. Typically, this fracture type consists of three longitudinal fissures, one medial and two lateral, and less extensive secondary cracks. In these cases, with shrapnel-related wounds, craniectomy or fracture reduction was almost always performed. Wound dressing was usually associated with wound debridement to prevent meningoencephalitis or posttraumatic epilepsy.\(^5\)

Grenades and IEDs, instead, besides ballistics similar to shrapnel, may cause barotrauma-related injuries. Indeed, an explosive detonation (converting a solid into a hot gas) originates a blast wave of compressed high-pressure air moving at supersonic speeds. Other injuries include burns, toxin or dust inhalation, radiation exposure, and asphyxiation\(^6\) (Fig. 2).

Evolution of Theories

Concerning posttraumatic fractures, as related by Geserick et al., in 1903 Puppe pointed out his well-known principle: when two linear fractures on a solid surface intersect, it is possible to determine which one has been made first, because the more recent fracture ends at the line of the other one, which is already present.\(^7\) Since then, this theory has been largely used and applied to examine skull fractures, although it has been adapted to the development of new technologies and materials. Remarkably, there are constant parameters (referred to below as extrinsic factors), such as bullet caliber, direction, angle of entry, and velocity, that may differ and determine a variety of clinical scenarios.

Furthermore, according to Berryman,\(^8\) it is possible to assess a fracture by the following interconnected triad: fracture characteristics, intrinsic factors, and extrinsic factors. Intrinsic factors determine how the bone responds to trauma, which may be related to bone architecture, patient sex, and age. Different from intrinsic factors, extrinsic factors are represented by bullet velocity, mass, design, and cavitation. Therefore, given any two of these components, the characteristics of the third can be deduced.\(^7\) Depending on the missile’s ballistics, there may be different skull fractures, such as irregular, stellate, comminuted, and depressed fractures. The latter ones are the most prone to complications.

Nevertheless, the first document describing medical examination and therapeutic strategies for head-injured patients is the Edwin Smith Papyrus, written in Hieratic script in approximately 1600 BC. It tried to categorize wounds through sophisticated clinical examination, distinguishing between superficial ones and those penetrating the skull or dura mater. It described a wide variety of fractures and recognized the prognostic relevance of a torn dura mater, meningitis, or signs of basal skull fractures (bleeding from nostrils or ears). Due to limited therapeutic options, the injuries considered to be treatable were the ones without skull or dura mater penetration.\(^9\)
It took until the end of the 19th century and World War I, approximately 1 century after Henry Shrapnel's invention, to hear about the first efforts to standardize surgical procedures. At first, Cushing\(^1\) and subsequently Matson\(^1\) proposed a systematic classification of craniocerebral injury, becoming pioneers in managing head wounds (Tables 1 and 2).

Before Harvey Cushing, in World War I, head wounds were often bathed with various antiseptics and remained open to ensure drainage until they were closed many days later. Surgeons used to make a cruciate incision on the scalp and perform a small craniectomy. When Cushing introduced his new operative techniques, the mortality of penetrating missile wounds reduced from 50%–60% to 28.8%. He introduced four new essential surgical principles: en bloc craniectomy at the site of cranial penetration; detection and removal of bone fragments and damaged brain parenchyma along the missile track; incision of intact dura mater to remove blood clot and pulped brain; and distillation of dichloramine T (an antiseptic) into head wounds after debridement. Moreover, in his article in the *British Medical Journal*,\(^1\) he stressed the importance of a meticulous preoperative neurological examination and the necessity of completely shaving the head to prevent overlooking cranial wounds. Concerning surgical techniques, he replaced the cruciate scalp incision with a tripartite incision and introduced primary wound closure with galeal sutures. He also analyzed the importance of stereoscopic radiographs to localize indriven metal fragments, laying the ground for modern neuroimaging\(^12,13\) (Figs. 3 and 4).

### Discussion

Typical shrapnel fractures, beyond the ones due to tangential blows, were depressed, and a craniectomy, sometimes extended, was usually necessary for splinter removal. Moreover, bullets had superficial tangential forces,

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**TABLE 1. Cushing’s classification of craniocerebral injuries**

<table>
<thead>
<tr>
<th>Group</th>
<th>Type of Wound</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Scalp wounds w/ or w/o cerebral contusion</td>
</tr>
<tr>
<td>II</td>
<td>Wounds w/ local fractures but w/ intact dura, w/ or w/o cerebral injury</td>
</tr>
<tr>
<td>III</td>
<td>Wounds w/ depressed bone fragments puncturing dura, &amp; cerebral contusion</td>
</tr>
<tr>
<td>IV</td>
<td>Wounds w/ detached &amp; indriven bone fragments, brain usually extruding</td>
</tr>
<tr>
<td>V</td>
<td>Penetrating wounds w/ projectile lodged, brain usually extruding</td>
</tr>
<tr>
<td>VI</td>
<td>Wounds w/ bone fragments or projectile opening ventricle, brain usually extruding</td>
</tr>
<tr>
<td>VII</td>
<td>Wounds involving orbitonasal, auropetrosal region, brain exposed, meninges opened</td>
</tr>
<tr>
<td>VIII</td>
<td>Perforating wounds, cerebral injury severe</td>
</tr>
<tr>
<td>IX</td>
<td>Bursting fractures, extensive cerebral contusion</td>
</tr>
</tbody>
</table>

Based on Cushing H. Note on penetrating wounds of the brain. *BMJ.* 1918;1(2982):221-226.\(^1\)

**TABLE 2. Matson’s classification of craniocerebral injuries**

<table>
<thead>
<tr>
<th>Class</th>
<th>Type of Wound</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Scalp wound w/ no skull fracture</td>
</tr>
<tr>
<td>II</td>
<td>Wounds w/ skull fracture w/o dural penetration</td>
</tr>
<tr>
<td>III</td>
<td>Wound w/ skull fracture, dural &amp; associated brain parenchymal penetration: a) gutter type w/ no retained missile; b) penetrating variety w/ retained missile in the brain parenchyma; &amp; c) perforating type w/ no retained missile</td>
</tr>
<tr>
<td>IV</td>
<td>Class III wounds w/ the following complicating factors: a) ventricular penetration; b) fracture of the orbit or sinus; c) injury to the dural sinus; &amp; d) intracerebral hematoma</td>
</tr>
</tbody>
</table>

causing laceration of skin, subcutaneous fibrofatty tissue, galea aponeurotica, loose areolar connective tissue, and periosteum. Whether the injury is penetrating or closed, subgaleal hematomas were usually present. Like subdural hematomas, these hemorrhagic collections in the subgaleal space spread more diffusely over the skull because of a relative lack of impedance in this space. In contrast, subperiosteal hematomas, such as epidural hematomas intracranially, tend to be more confined and have a lenticular shape. Hence, except in children, they do not cross suture lines, because of the tight skull attachments of the periosteum.14,15

Therefore, surgeons had to adapt to perform wider craniectomy and treat more severe soft-tissue injuries. Although before Shrapnel’s invention and Cushing’s observations the goal was to remove as many bony and bullet fragments as possible, surgeons preferred not to trephine. Indeed, the use of a drill implied high mortality or neurological sequelae, due to the lack of surgical experience.16

Military conflicts in which cranium-penetrating missiles are being used are still occurring worldwide, and shrapnel injuries are a significant cause of death. The mortality related to military high-velocity missiles is high, despite appropriate treatment. These missiles travel at a speed greater than 3000 ft/sec and result in a cavitation injury more extensive than the missile track, due to cavitation and shock waves.17

In general, skull-penetrating wounds are often accompanied by intracranial hemorrhage, depressed bone fractures, and cerebral edema, and they may cause intracranial hypertension and malignant cerebral edema. As in the last century, pharmacological and surgical management are still a source of discussion.

Immediate relief for a patient with a craniocerebral missile injury must consider the setting (battlefield, rural, or urban environment) and resources available at the nearest medical facility. In a battlefield scenario, treatment of these injuries begins with basic first aid, consisting of the application of shell dressing by paramedics, as performed in the past. Afterward, the patient is transported to the nearest aid station, often located close to the defensive position, where a doctor evaluates him. Before the introduction of the idea of the triage system, with the involvement of more soldiers or civilians, the clinical outcome of head-injured patients was worse due to the absence of prehospital guidelines of the Advanced Trauma Life Support (ATLS) protocol: to control the airway, provide oxygen as needed, control bleeding, obtain vital signs, and intravenous access as soon as possible.18 Battlefield-related injuries are usually from shrapnel, and soldiers exhibit extremely damaging cerebral injuries. Thus, the idea of triage is different from a civilian setting because it aims to identify who has a higher probability to survive for rapid transport. In 2001, specific guidelines for care of patients with PBI were introduced. They resumed old concepts, such as the influence of ballistics on PBI (projectile’s fragmentation potential deserved a particular mention) and highlighted prognostic factors.19

Since World War I, an aspect that has been constant is the risk of head infections among patients with PBI, particularly meningoencephalitis. Whitaker reported that during World War I, before the antibiotic era, there was an infection rate of 58.8% among cranium gunshot wounds.20 Only since 1946 has the use of antibiotics been considered a preventive factor for infections in penetrating head injuries.20 This is demonstrated by the fact that when penicillin was administered, the infection rate dropped to 5.7% from 13%.19 The incidence of infections related to penetrating head injuries ranges from 5% to 23%, including intracranial and extracranial infections such as skull osteomyelitis, empyema, meningitis, cerebritis, and cerebral abscess.21 Risk factors for intracranial infections are deep penetrating injuries, CSF leaks, air sinus wounds, and retained bone fragments.22 Consequently, civilian PBIs cause fewer intracranial infections (incidence between 1% and 5%) than war PBIs. The wide variety of microorganisms that may cause these infections supports the use of broad-spectrum antibiotics. Proper antibiotic prophylaxis must have good cerebral penetration.19

Another important aspect related to the management of PBIs is the prevention of seizures. Indeed, head-penetrating injuries seem to provoke seizures more commonly than closed ones. Analyses of patients wounded in World War I, World War II, the Vietnam War, and the Korean
conflict revealed that the incidence of seizures had remained the same, despite improvements in patient transport, neurosurgery techniques, and medical support. That is the reason why the importance of using proper antiepileptic medications (such as phenytoin, carbamazepine, valproate, or phenobarbital) in the first week after PBI to prevent early posttraumatic seizures is stressed, because beyond 7 days they do not prevent the onset of new ones.

Furthermore, another effect of cerebral penetration is cerebral edema and consequently an increase of intracranial pressure, which could be treated medically and surgically in different ways. In the past, the simple, noninvasive method that could be performed on the battlefield (of elevating the head to 30° above parallel) alone would have helped intracranial pressure decrease while waiting for transportation.

Focusing on prognostic factors, even a single episode of hypotension (defined as a systolic blood pressure of < 90 mm Hg), for instance, for a severely brain-injured patient, is associated with worse outcomes. Indeed, these patients benefit from administering hypertonic saline resuscitation, synthetic colloid solutions, and albumin.

Moreover, coagulopathy (detected by blood examinations) and respiratory distress are associated with increased post-PBI mortality. Although out-of-hospital intubation seems to be a factor in adverse clinical outcomes, a wide array of supraglottic devices may be viable alternatives to prehospital intubation.

According to the guidelines for management of PBI, higher mortality and bad clinical outcome seem to correlate to a low Glasgow Coma Scale (GCS) score. Therefore, several flow charts considering GCS score as a parameter have been proposed, such as the one by Tsuei et al. that accounts for GCS score and pupillary response.

Although regarding clinical management of PBI has been possible to develop shared recommendations, surgical approaches and surgical priorities are still debated. The foundation of current surgical management of PBI is based on the first known battlefield situations. The mortality rate resulting from head wounds in World War I decreased from 55% to 28% after Cushing introduced the techniques of en bloc craniectomy, surgical debridement, and primary closure of open wounds with watertight sutures.

Craniectomy is usually preferred to craniotomy to remove devitalized tissue. Complete removal of intracranial bone fragments or metal missile splinters from PBIs has been controversial. There may be two types of surgical behaviors: one that tends to preserve brain tissue as much as possible, and the other that tends to remove any foreign body, including bone. Victor Horsley, for instance, in the footsteps of Harvey Cushing, recommended the removal of bone fragments to relieve local signs and prevent epilepsy: the general cutoff considered for this practice was 1 cm for a fracture line. The rationale behind this aggressive debridement was the idea of preventing complications related to retained fragments, such as brain edema, infections, and seizures. Nevertheless, Rish et al. suggested that some soldiers who suffered head wounds during the Vietnam War still had fragments on CT scans after several neurosurgical operations aiming at their complete removal. Therefore, repeated cranial surgeries exposed individuals to more perioperative risks without a certain result.

Another example is represented by the 32 patients reported by Taha et al.: their wounds were stitched up in a single layer and were treated with intravenous 3-day methicillin. None of them died, and only one presented with an intracranial abscess (the only reported infection). Obviously, there were selection criteria that eliminated patients at high risk of carrying a substantial amount of necrotic brain tissue—such as having an initial GCS score of 10, undergoing treatment within 6 hours from trauma, having a length of wound less than 2 cm with no exit, having a missile trajectory far from the sylvian fissure, and not presenting with intracranial hematoma. Regarding epilepsy, there does not seem to be a correlation between intracranial fragments and seizures after PBI, as suggested by Salazar et al. in 1985 in a study on veterans of the Vietnam War.

Besides, depressed skull fractures such as those caused by spherical bullets over the superior sagittal sinus and the confluence of sinuses cause cerebral venous outflow obstruction and intracranial hypertension, requiring emergency surgery. Given these circumstances, it has been assumed that debridement of fragments and devitalized tissue is mandatory only if they cause cerebral mass effect.

Conclusions

Throughout the past few centuries, starting from the use of Shrapnel’s projectiles, different theories regarding craniocerebral injuries were developed, up to the creation of modern guidelines for patients affected by PBIs. Military situations helped build basic principles in the management of PBIs. Nevertheless, civilian PBIs differ noticeably from military ones. The former usually consist of accidents with firearms or other implements, resulting in intentional injuries such as suicide attempts. In a civilian setting, the nature of the weapons involved is different, and injuries result in low-velocity gunshot wounds. In addition, wounded patients may be transported to hospitals, benefit from modern diagnostic and therapeutic tools, and the concept of a triage system is completely different from that of the battlefield. Therefore, there is the need to review these guidelines with an entire literature based on civilian PBI, to apply them to the more common situations such as the civilian ones.

References


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Conception and design: Venanzi, Pavanello. Acquisition of data: Venanzi. Analysis and interpretation of data: Venanzi. Drafting the article: Venanzi. Critically revising the article: Pavanello. Reviewed submitted version of manuscript: Piatelli, Pavanello. Administrative/technical/material support: Venanzi, Pavanello.

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