An historical context of modern principles in the management of intracranial injury from projectiles

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The contemporary management of projectile head injuries owes much to the lessons neurosurgeons have distilled from their experiences in war. Through early investigation and an increasingly detailed account of wartime clinical experience, neurosurgeons—including the field’s early giants—began to gain a greater understanding not only of intracranial missile pathophysiology but also of appropriate management. In this paper, the authors trace the development of the principles of managing intracranial projectile injury from the Crimean War in the 19th century through the Vietnam War to provide a context that frames a summary of today’s core management principles.

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One of neurosurgery’s great legacies has been the development of cogent principles of management of projectile head injuries. The development of our contemporary thinking coevolved with the evolution of the field of neurosurgery itself; this reciprocally dynamic relationship was strengthened in the great wars of the 20th century, and from the earliest days involved some of the true titans of the discipline. Military conflict has sharpened our understanding of the pathophysiology and treatment of injuries from projectiles, specifically bullets and shrapnel from explosive blasts. Innovations in firearms created new types of brain injuries from which we are able to glean much about how the brain responds to trauma. Before reviewing the history of missile trauma management in neurosurgery, it is important to note that although penetrating trauma of the head has been present since antiquity, projectile injury that results from penetrating bullets or metal fragments from blasts only became a reality after the Renaissance. The pathophysiology of a penetrating head wound from an instrument such as a sword or javelin is markedly different from that of a high-speed projectile such as a bullet, particularly because of the cavitation surrounding the projectile. Furthermore, only in recent history have modern, high-speed projectiles been in use, markedly changing both the nature of head injury and its management. It was not until the early 20th century when a concerted effort by the new specialty of neurosurgery—involving accumulated case series and experimental studies—started to shed light on the best management approaches. Although it is difficult to perform rigorous, scientific studies on penetrating head wounds, given the inherent variability of each case, neurosurgeons were able to generate coherent guidelines, which for the most part serve as the foundation for management today. The goal of this paper, therefore, is to trace the modern development of penetrating brain injury protocols with respect to high-speed penetrating injury. We shall trace early developments briefly and focus primarily on the innovations of the World Wars and more recent conflicts. Finally, we conclude with a review of the current standard of care in the management of high-speed projectile wounds, with the demonstration that military neurosurgery has contributed significantly to our present standards of treatment in both wartime and civilian arenas.

Before World War I

Antiquity and the Middle Ages

The management of head injuries from penetrating missiles has been an important factor on the battlefield since antiquity. Although the management of head trauma in ancient times and in the Middles Ages is not entirely within the scope of this article, Dagi reviews the important contributions that were made in the premodern era. The innovation of gunpowder and guns heralded an era of radical surgical treatment, specifically because of the prevailing belief that penetrating gunshot wounds

Abbreviation used in this paper: ICP = intracranial pressure.
had some additional poisonous or magical property when compared with penetrating wounds from other weapons. From Hippocrates and Theodoric before the advent of gunpowder, to Paré and Macleod afterward, Dagi\(^2\) traces important questions on the management of penetrating head injuries, including the need for trephination, the types of ointments or dressings used, and the decision to leave a wound open for suppuration. Importantly, the line of inquiry that these questions raised was to be answered only later with the advent of the World Wars and the birth of neurosurgery as a separate field.

**Nineteenth Century**

During the mid-19th century as the Industrial Revolution became manifest, advances in technology entered the military realm, where more powerful weaponry was being developed. A significant development was the Minié ball, a newly designed bullet to be fired from a musket that had rifling grooves for spin-stabilization of the bullet and thus more accuracy and a much higher penetrating force. Furthermore, the design allowed the rifle to be used as a primary weapon in battle because of its accuracy and shorter and easier reloading. These advancements were used in both the Crimean and American Civil Wars, and led to the publication of important case notes from these wars. These works were an early indication of the important advances that occurred in the 20th century.

George H.B. Macleod, a surgeon in the Crimean War, wrote a seminal work in military surgical history, *Notes on the Surgery of the War in Crimea; With Remarks on the Treatment of Gunshot Wounds*.\(^52\) He began by echoing an important theme of this review, “That military surgery does not differ from the surgery of civil life, is an assertion which is true in letter, but not in spirit. As a science, surgery, wherever practised, is one and indivisible; but as an art, it varies according to the peculiar nature of the injuries with which it has to deal, and with the circumstances in which it falls to be exercised.”\(^52\) Military surgery provides an important avenue for learning about the management of injuries and afflictions prevalent in a war setting.

In his surgical notes on gunshot wounds, Macleod first outlined some of the important perioperative issues of his time. For example, he emphasized the use of chloroform as an anesthetic, the need for control of hemorrhage and shock, the use of antisepsis for the prevention of gangrene, and the importance of facilities for prevention of environmental complications such as frostbite.\(^52\) Tetanus was also a serious problem, and it should be noted that even in modern practice, tetanus prophylaxis is a staple of penetrating missile injury management.

The most important contribution from Macleod’s notes is his chapter on injuries of the head. He reviewed 630 cases of gunshot wounds to the head from April 1, 1855, until the end of the Crimean War. Sixty-seven of these cases had penetration of the cranium and these patients died; 19 cases in which the skull was perforated were also unequivocally fatal. His discussion emphasized important points in the management of penetrating head injuries, such as the rationale for the decision to operate and the extent of debridement of bone fragments. On the former point, within the contemporaneous literature, there was significant disagreement as to indications for trephination, but there was strong evidence of universally poor outcomes from trephination and operative intervention. Nevertheless, Macleod\(^52\) believed that the primary operative indications were: (1) in cases of fracture with great depression—cases in which the bone is forced deep-ly into the brain, especially if it is turned so that a point or an edge is driven into the cerebral mass; or (2) unless we clearly make out the impaction of spiculae, balls, or other foreign bodies in the brain, which cannot be removed through the wound by means of the forceps.

Secondary operative indications were evidence of compressive symptoms or in cases in which a fragment is irritating the brain and requires surgical intervention to retrieve it. On his second point of debridement, he argued strongly for the removal of “loose portions of bone,” and “If the dead piece [of bone] can be removed without violence, I believe it should always be done as soon as it is found to be loose.”\(^52\) Despite advocating these surgical interventions, Macleod recognized the futility in many of these cases: “Perhaps the best line of conduct is to let the man die in peace. I have never known a case of perforating gun-shot wound of the head recover. Some such are, however, on record.”\(^52\)

The American Civil War surgeons on both the Union and Confederate sides saw similar destruction caused by improved weaponry. S. Weir Mitchell served as a Union Army physician in Philadelphia and helped manage a number of wounded, particularly from the battle of Gettysburg. Although beyond the scope of this article, Mitchell\(^60,61\) described in detail the presentation, management, and follow-up of missile injuries to nerves and the spinal cord. On the Confederate side, a surgeon named Felix Formento\(^30\) documented his experience with gunshot injuries to the head and echoed sentiments similar to Macleod. Both Formento and Macleod cited German surgeon, Georg Stromeyer who published a small series on gunshot injuries from his experiences in the Schleswig Wars.\(^29\) These early authors were some of the first to experience in person the severity of penetrating missile injury in war and their early concerns would be revisited in the 20th century.

**The Turn of the 20th Century**

Largely as a result of two World Wars and rapid innovation in technology, the last part of the 19th century and the first half of the 20th century saw some of the most prolific advancements in the medical/surgical management of projectile injury. Although the ability to manage projectile injury likely benefitted from general medical improvements as well as from specific improvements in neurosurgical care, it is clear that neurosurgeons were critical to this advancement.

Sir Victor Horsley, one of the pioneers of neurosurgery, contributed a great deal to our understanding of the mechanisms of injury from gunshot wounds.\(^29\) In the 1890s, he performed original experiments using clay and animal models to explore the forces from bullets.\(^37\) In his clay model of the brain, he fired bullets of different caliber at a range of velocities into clay of various states
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of hydration. He demonstrated that velocity and cavity formation were an important factor in tissue damage from projectiles.\textsuperscript{47} Further laboratory work with Kramer on experimental dogs with transcranial gunshot wounds led Horsley to propose that respiratory depression was a significant mechanism of death.\textsuperscript{50} In his article in the journal Nature, Horsley stated, “The medulla oblongata is thus subjected to pressure from two sources: (1) the hydrodynamic displacement of the brain en masse; (2) the direct crushing effect due to the movement of the cerebrospinal fluid in the ventricles.”\textsuperscript{46} Using his experimental canine model, he continued to describe how respiratory arrest occurs immediately and it is possible to provide artificial respiration that can result in recovery from fatal respiratory arrest.\textsuperscript{46,50} Almost instantly after the respiratory failure, however, fatal hemorrhage was of serious concern.\textsuperscript{7} Horsley’s perspective was also shaped by his own experiences with head injury from the First World War. In a lecture given on February 8, 1915, he discussed a case of a fragmented bullet in a patient who came under his care 10 days after the injury.\textsuperscript{46} Horsley performed extensive debridement of the infected wound, and the patient made a good recovery. In the same lecture, he touched upon important aspects of management including the effects of ICP, evacuation of hematomas, and infection.\textsuperscript{46}

These important early experiments demonstrated a scientific approach by a neurosurgeon to understand the pathophysiology of penetrating brain injuries from high-speed projectiles as well as a critical appraisal of clinical experience, which would come to be increasingly important as neurosurgeons assessed their outcomes in the years ahead. Furthermore, Horsley’s work foreshadowed important questions that still dominate the discussion of penetrating brain injury, including: 1) mechanism of injury, 2) timing of resuscitation and surgery, 3) critical care management, 4) extent of surgical intervention, and 5) postoperative rehabilitation, including seizure prophylaxis.

World War I

As the First World War commenced in 1914, Horsley sought active service and was finally appointed to work in Egypt from 1915 to early 1916.\textsuperscript{39} Eventually, Horsley volunteered to go to Mesopotamia, but unfortunately he soon died on July 16, 1916, without having been able to gather and publish his experiences in the war.\textsuperscript{7} Nevertheless, World War I would prove to be a fertile ground for early neurosurgical experience in the management of penetrating head trauma.

In 1916, Colonel Gray, a surgeon with the British Expeditionary Force, published his series of 392 cases of head wounds requiring trephination, with a mortality incidence of 58 cases (14.8%).\textsuperscript{33} The treatment his team gave included complete and early debridement of wounds with meticulous aseptic technique. He firmly believed that regardless of whether the operation was performed in the forward area or later at a base hospital, it was necessary to perform a single thorough operation to avoid future complications. Of note, Gray excluded “hopeless” cases as well as those with severe wounds with “explosive intracranial effects.”\textsuperscript{33} Other surgeons at the time also published their results with various mortality rates, although the accepted standard appeared to hover around 50 to 60%.\textsuperscript{20,38}

In addition to the other surgeons, Harvey Cushing became active in the war effort as a strong supporter of improving the medical facilities and treatments for soldiers injured in battle.\textsuperscript{7,38} It would be fair to say that, through his involvement in the evolution of the management of missile injuries to the head, Cushing crystallized the pivotal role that a handful of neurosurgeons played in this area. Cushing’s first exposure to the war came when he left Boston in 1915 for a 3-month tour to bring a “Harvard Unit” to the frontlines. After leaving on the Canopic on March 18, 1915, he arrived at Gibraltar on March 28, after which he arrived in Paris by train. There, Cushing began to see the poor state of medical preparedness in the Ambulance Américaine at Paris. Gravely concerned about America’s own state of affairs, he began to tour the region and various fronts, operating on patients and gathering information. In his biography on Cushing, Fulton detailed Cushing’s travels, including a description of Cushing’s first use of a magnet and nail to extract a metal shell fragment from the base of the brain.\textsuperscript{38} After traveling for some time, Cushing eventually began his return trip on the St. Paul on May 8, 1915, immediately after the sinking of the RMS Lusitania by a German U-boat. One can only imagine how passing the wreckage of this ship on May 9, in combination with his recent tour in France, would energize Cushing to redouble his wartime efforts.

After his European travel in 1915, Cushing recognized the need for early, definitive surgery in patients with head wounds in addition to improving the entire military triage and medical system.\textsuperscript{39} Motivated by the need for advanced neurosurgical care and a reorganization of the Allied Forces’ medical system, Cushing eventually returned to Europe as the head of Base Hospital No. 5 at Camiers, followed later by an important stint at Casualty Clearing Station No. 46, where he received numerous casualties from the battle of Passchendaele. These casualties would serve as the foundation of his published military operative experience.\textsuperscript{7,38}

Perhaps Cushing’s greatest contribution to the management of soldiers with head wounds was his meticulousness in observing and cataloging the injuries with basic statistics on patient outcomes. In 1918, Cushing published 2 important series—one on penetrating wounds of the brain and another larger work on all cranial wounds from his experiences at Casualty Clearing Station No. 46.\textsuperscript{19,20} He wrote, “It would be desirable if we could all come to record our cases from the same standard… Only by the establishment of some accepted standard will it be possible to compare the efficacy of operative methods advocated by different individuals.”\textsuperscript{20} At the time, a mortality rate of 50% had been accepted for wounds penetrating the dura. Cushing published his series of 133 cases of penetrating wounds out of a total of 219 cases of surgically managed head wounds. From this 3-month series, he reported a decline in deaths from 54.5% for the first month, to 40.9% for the second month, and 28.8% for the last month. He attributed this remarkable improvement to his method of treatment that included en bloc removal of any involved.
bone, aggressive suction debridement of any devitalized brain tissue (as opposed to finger exploration), extraction of bone fragments with minimal disruption of dura and the wound, and use of antisepsis. In his larger work, he detailed 9 grades of head wounds and noted that either early or delayed infection contributed significantly to the mortality risk of his patients with penetrating wounds. Additionally, the issue of antisepsis during World War I was under heated debate, as various solutions were used ranging from dichloramine-T (advocated by Cushing) to Carrell-Dakin solution or iodine-based solutions.38 Many had argued for and practiced a technique of a moderate debridement followed by aggressive instillation of an antiseptic agent such as Carrell-Dakin solution.62 Eventually Cushing himself stopped using any antisepsis after realizing that early, aggressive debridement with proper surgical technique could achieve similar outcomes, which were still poor given the extremely difficult problem of infection.38

Horrax,45 in 1919, published similar results with an operative mortality rate of 44.7% (34 of 76 patients) in cases of penetrating head injuries. His patient series was notable for an emphasis on leaving the dura open to allow the inevitable infection to escape. He also emphasized the importance of sterile dressings for fungating cerebral tissue from these open wounds so as to keep them in place in as sterile a fashion as possible. It is important to note that in the series reported by Cushing and Horrax, additional perioperative procedures of appropriate shaving, positioning, and overall aseptic technique were also considered to be important.

Cushing’s publication of his patient series would serve as an important precedent for the management of World War II cases by individual surgeons. Furthermore, the discussion of antisepsis would be revisited, particularly after the development of effective antibiotics, including penicillin. The lasting contributions from World War I in the management of penetrating head wounds are primarily the need for early, definitive neurosurgical treatment and the attention to detail created by accurate publications of case series and methods. Finally, with the establishment of neurosurgery as a separate field and with the practical neurosurgical training many young surgeons received in the War itself, one of the lesser-appreciated legacies of the War was the development of a handful of skilled neurosurgeons who could begin to train residents throughout the US.49 This trend would continue through World War II and play a role in supplying adequate neurosurgical personnel within the military. From the ravages of a terrible war, then, the coalescing field of neurosurgery was starting to make sense of the battlefield management of missile injuries to the head.

**World War II**

By the start of the Second World War, neurosurgery had evolved into its own specialty, and medicine in general had developed significantly in its own right. Advances in anesthesia, critical care, and infectious disease were leading to major improvements in outcomes from all types of disease. Penetrating head trauma was no exception, and World War II served as a seismic period in the continued advancement of neurosurgery in this arena. Many surgeons at this time recounted their series of patients and created the first sizeable body of literature on the outcomes of patients after management, including detailed analysis of complications such as infection, seizures, and neurological morbidity. This fundamental body of literature in and of itself stands as a significant contribution to the field of neurosurgical trauma. In fact, when considering the contributions of the military to neurosurgery, World War II was ostensibly the reason for the creation of the Journal of Neurosurgery. The first editorial note states, “Since the outbreak of war in 1939, there has been less interchange between British and American neurosurgeons than before,” which served as the rationale for creating an English journal to improve communication of ideas.29 The editorial board recognized the need for establishing case series of wound management: “With the war in its most active phase, we would direct attention to the need for prompt recording of wartime experiences.” The editorial concluded with a condolecence to Major Kenneth Eden, “We cannot close without expressing deep sympathy to our British colleagues in the untimely death while on active service of Major Kenneth Eden, whose posthumous paper entitled, ‘Mobile neurosurgery in warfare. Experiences in the Eighth Army’s campaign in Cyrenaica, Tripolitania, and Tunisia,’ had just been published in the Lancet (Dec. 4, 1943).”25 It is striking to note that the luminaries of neurosurgery in the first half of the 20th century from Horsley and Cushing in World War I to others such as Matson and Cairns in World War II were vigorously active in military medicine. In the following section, we highlight some of the important themes and lessons learned from this conflict.

**The Central Role of Case Series**

One of the first and lasting contributions to neurosurgery from the World Wars came in the form of case series that recounted the experiences and outcomes of a particular surgeon and his team. Cushing had established this precedent with his large case series from World War I, and this trend continued into World War II.19 Here we recount some of the large patient series reported and the growing consensus in the management of penetrating head wounds. One of the first reported series came from Major Ascroft who reported on 500 cases of head wounds, with 292 having evidence of a pierced dura.4 His reported mortality rate was 44 deaths out of his 292 patients (15%). He also noted that 55% of those who survived penetrating head wounds were able to return to some form of duty. He was a firm believer in the specialization of units in the treatment of head wounds “to study intensively special kinds of injury and to make their results known.”4 He also recorded his system of rapid triage (<5 minutes) of hundreds of injuries that would arrive at the base hospital. In the event of hundreds of patients arriving per day, Ascroft reaffirmed the importance of maintaining high pre- and perioperative standards including appropriate transfusions, antibiotics/antiseptics, scalp shaving, and positioning. He noted that his team performed more than 100 operations in 12 days after a particularly bloody battle.
an experience that convinced them “that time is saved by not skimping the preliminaries;” he continued, “Careless placing of the patient on the table, niggardly shaving, and indifferent arrangement of the drapes all make for slipshod or slow and wearisome operating.”

Ascroft also presented these results at a regular meeting of the Boston Society of Psychiatry and Neurology, where a lively discussion was noted among some of the eminent leaders of neurosurgery at that time including Gilbert Horrax, Donald Munro, and Sir Geoffrey Jefferson. The consensus from that discussion was that sulfadiazine, suction, and diathermy were important technological innovations that significantly improved outcomes, particularly when compared with World War I data. Interestingly, Gilbert Horrax noted how the conditions of the desert in Africa actually improved outcomes due to cleaner wounds than those encountered in the muddy trenches of Flanders, where he treated patients in the First World War.

There were a number of other important case series that were published that led to a significant corpus of work on penetrating missile injuries of the head. Shearburn and Mulford, in their records of the 14-month Italian campaign, recorded an operative mortality rate of 12.3% (15 of 122 cases), although their improved rate might be due to classification differences, whereby all wounds that penetrated the dura were included, not only the more serious gunshot wounds with indriven fragments of bones or bullets. Cairns summarized the British mobile neurosurgical results in the British Medical Journal, in which he compared his units’ caseloads with Cushing’s World War I experience and also noted improvements in mortality risk and infection. His conclusion corroborated the findings of others—namely, the importance of adequate debridement and use of antimicrobials, particularly penicillin. Haynes’ series of 342 cases of penetrating wounds from Northern Africa, Sicily, and Western Europe reinforced the organizational structure requisite to care for so many wounded with a dedicated team of operative personnel that allowed them to operate on as many as 12 patients within a 24-hour period. Infection was also reduced significantly due to antimicrobial use in his patient series. Slemmon also advocated for a forward mobile unit and outlined its success in Italy.

**Debridement**

Although it had been claimed by many that adequate debridement was critical to the improvement of the patient after a head injury, Campbell’s results in 100 patients from the battle of Salerno in World War II shed light on the importance of removing bone fragments after penetrating wounds to the head. Out of 94 patients that had indriven bone fragments from penetrating head wounds, 45 had all fragments of bone removed at primary debridement and 49 did not. There were 0 deaths in the first category, but 5 deaths in the second, all due to infectious complications. The first group had only 11 total infections, the majority of which were superficial, while the incomplete debridement group had 30 infections, the majority of which were deep. These results confirmed the importance of care in initial debridement, thus leading the author to write, “Should either surgeon or proper facilities be lacking, further evacuation is preferable to poor debridement.” Of note, metallic foreign bodies were removed when accessible, provided that removal did not injure any other neural structures. Nevertheless, it was generally believed that metallic fragments had significantly lower infectious potential than indriven fragments of bone. As A. John Popp has described in his historical studies, this method of debridement that was promulgated by Campbell was actually used by some battlefield surgeons in World War I and had been also advocated by Theodoric in the Middle Ages.

Also of interest was Campbell’s dislike of the tripod incision, which had been used frequently by Cushing in World War I. Campbell noted that the tripod incision often had apical necrosis and infection and he preferred generous curvilinear flaps with the wound defect in the center to avoid a closure under tension. In their series of 156 patients, Gaynor and Gurwitz also disapproved of the tripod incision, and recommended that all indriven bone fragments must be removed. Finally, Ascroft’s large series also demonstrated the importance of adequate debridement, which reduced the risk of infection.

**Early Versus Delayed Surgery**

Once it had become essentially standard of care for definitive debridement, the debate turned toward timing of surgery, particularly given the logistics of evacuation to nearby forward hospitals without specialized neurosurgeons or to further base hospitals with specialized care. Since the First World War, Cushing stated that definitive neurosurgical management was more important than a minimal delay of a few hours. By the start of the Second World War, Brigadier Hugh Cairns had been in charge of the British neurosurgical effort and developed mobile, forward-area neurosurgical units that could be attached to a Casualty Clearing Station or hospital to provide specialized care more rapidly in the field. The first mobile unit was commanded by Peter Ascroft in North Africa. Ascroft, in his series, was one of the first to break down mortality rates according to location of the primary operation, comparing rates of forward-area neurosurgery with those from a base hospital. The mortality rate due to penetrating injuries in forward areas versus base hospitals was 17% and 16%, respectively. He believed that while delay was not preferred, it was tolerable if it did not result in a significant increase in death. Furthermore, he firmly argued that there should only be 3 reasons for keeping patients with head injuries in forward areas: 1) severe shock, 2) immediate surgery required due to active intracranial bleeding or extracranial injuries, and 3) no reasonable chance of reaching a specialized center within 48–72 hours. Although the data from Ascroft were important, only later did the mobile neurosurgical unit come into its full potential when Major Kenneth Eden (who, as noted earlier, did not survive the war) modified a large motor coach into a mobile operating theater. Eden showed the possibility of a specialized advanced neurosurgical unit that could be closer to the field and achieve good outcomes in patients. He noted a mortality rate of 23.6% (24 of 102 open brain wounds) in his
series of patients. Once again, however, Eden echoed previous experience that “the initial operation should be the final and complete one.” In fact, 4 of 9 cases of open brain wounds became infected if the patient did not achieve an adequate primary operation and required a second, specialized operation. Nevertheless, his infection rates were reduced from the previous benchmark of about 25% to 5%, with approximately 90% of wounds healing by primary intention. Eden also emphasized the variability inherent in mortality figures amongst different surgeons because there were drastic differences not only in which patients underwent surgery, but also in which patients were even triaged to evacuation from the front lines. Finally, Schwartz and Roulhac’s experience in North Africa echoed the consensus that timing of treatment is less important than adequacy of initial treatment. Delayed debridement had been successful in 8 cases from their series when surgery was performed between 36 hours and 4 days after injury. Furthermore, it was recommended that debridement be complete, with particular attention to bone fragments that can serve as the nidus for infection.

In contrast to those who documented near-equal mortality rates between early and delayed surgery, Finlayson and Gaynor and Gurwitz in forward hospitals highlighted the importance of timing in addition to adequacy of wound debridement. Grunnagle advocated early surgery, stating that 6 hours represented the optimum time interval for surgery, although antimicrobials allow for delayed operation. It should be noted that most authors, including those who believed in the possibility of delayed definitive surgery, realized the need for urgent decompression in the presence of massive intracranial bleeding or severely increased ICP.

Hematomas

One of the important early questions in the management of head trauma from projectiles was the treatment of hematomas. Major Donald Matson and Captain Julius Wolkin wrote about an early series of 11 patients treated for penetrating head wounds who suffered from hematoma distant from the site of the wound. He concluded that when a bullet or fragment traverses the brain and lodges approximately 2–3 cm below the surface distant from the entry site, then it is useful to explore that area for hematoma evacuation and debridement, especially because it is more accessible than deep fragments. Furthermore, in cases in which the projectile had an exit wound, he advocated for early operative management of the exit site first. These advances were made possible by the use of radiography, antimicrobials, and improved transfusion technologies.

Penicillin

The widespread use of antibiotics in neurosurgery was made possible by the large supplies provided by the military, despite an otherwise general shortage. In the middle of the war, Hugh Cairns contributed significantly to the use of penicillin in the treatment of head wounds. Cairns noted the importance of adequate debridement as the first step to limit infection, but then gave some preliminary guidelines with respect to the use of penicillin in wounds, including the application of calcium penicillin powder for wounds up to 72 hours or, for wounds delayed longer, instillation over days of penicillin solution. He also acknowledged the use of intraventricular and intracisternal penicillin for overt ventriculitis, but only after filtration of the penicillin through a Seitz filter to prevent contamination with penicillin-resistant organisms. Finally, at this time, additional therapy with sulfadiazine was common to cover additional organisms. Abbott, who published his series from the Southwest Pacific Theater, also wrote about his intracranial use of penicillin, including intrathecal and intraventricular administration. He would administer sulfadiazine and penicillin immediately to all patients, and then would administer between 25,000 and 50,000 units in saline intracranially after debridement, followed by 10,000 units for scalp closure and irrigation. He noted no toxic effects specifically from intraventricular administration. Rowe and Turner echoed these findings in their observations.

Although the intracranial administration of penicillin was deemed safe by these previous large patient series, only later did Walker et al. emphasize the convulsive potential of penicillin when applied in large doses intrathecally (40,000 units), which occurred regardless of the vehicle of the antibiotic. Further case reports by Erickson et al. confirmed the harmful effects of intrathecal penicillin. In terms of the actual bacteriological makeup of wounds, Campbell noted that Staphylococcus was the causative organism for most infections, although Ecker’s bacteriological study emphasized the selection of gram-negative organisms after use of sulfadiazine and systemic penicillin. The important lessons learned from World War II regarding infection were the importance of debridement, the preference of systemic versus intrathecal penicillin, and the emergence of organisms other than staphylococci as new primary concerns of delayed infection/abscess.

Dural Closure

Consistent with the debate between the World War I approach of suppuration from an open wound versus the new approach advocated by Campbell for antimicrobials and closure, there was a significant discussion on the importance of dural closure in the management of these wounds. Ascroft, who dealt with wounds earlier in World War II, advocated against primary dural closure and instead believed in the importance of allowing any pus or infection to leave through an open tract. On the other hand, Campbell stated that it is difficult to know if a primary dural closure is actually keeping an infection out of the intracranial cavity or not, but he did point out that in 3 cases his fascial graft closure helped contain infection to the extracranial wound. Ecker, Finlayson, Grunnagle, and Gaynor and Gurwitz all recommended primary dural closure, with a fascial graft if necessary. Shearburn and Mulford were the first to quantify their dural closures and noted the results in 122 patients: 56 with cadaveric dura, 53 with autologous tissue, 9 with muscle and suture grafts, and 4 with dura left open.
The debate over dural closure might also have reflected a growing difference in opinion between American and British neurosurgeons, which Groff noted in his series from Burma. Of note, Small and Turner did not reach a conclusion that dural closure was a significant means to prevent infection in their large series of 1200 patients.

**Drain Placement**

Although most authors do not detail the specifics of leaving a drain in initial surgery, there are a few who raised this important point, particularly given the antibiotic advancements since World War I. Previously, drainage was necessary for the inevitable infection that would result from these large head wounds. With the increased use of sulfonamides and penicillin, improvements in decreasing infection were clearly noted and thus drainage was no longer a requirement. Additionally, because adequate debridement with antimicrobials and antisepsis could yield a clean, healing wound, the drain itself came under scrutiny as a source of future infection. Shearbourn and Mulfords documented drain placement with 79 patients receiving a drain and 43 without, although it is not clear whether systematically chose some patients for drain placement, for example patients with signs/symptoms suggesting higher likelihood of infection. In their series, Schwartz and Roullace did not prefer to leave a drain because this could serve as a source of infection. Interestingly, Grunnagles strongly condemned the use of a drain and believed that it should be used with sulfonamides for < 24 hours only if absolutely necessary in cases of gross infection.

**Transventricular and Extensive Missile Injuries**

Major Walter Haynes reported his series of 342 penetrating brain wounds from the African and European campaigns, with a particular focus on penetrating brain injuries that were difficult to manage. In his description of 100 transventricular wounds, a type of wound that had carried significant mortality and morbidity risk in Cushings series, Haynes noted a postoperative mortality rate of 34% and an overall mortality rate of 49%. He also documented 159 cases of extensively damaged brain injuries that included penetrating injuries that often were transventricular and destroyed an entire lobe or a significant portion of one. In this series of extensive brain injuries, the postoperative mortality rate was 23.6% with an overall mortality rate of 40.8%. In particular, he emphasized the importance of antimicrobials, including penicillin, and the necessity of dealing with vascular injuries associated with penetrating missiles.

**Postinjury Sequelae**

Complications of penetrating brain injuries during World War II included infection, seizures, and permanent loss of neurological function. Cairns described these in some detail for his large series. After infection became better controlled as a result of the introduction of improved techniques and antibiotics, the most important postinjury complication was seizures. In Russells series of 200 patients, 32 (16%) developed convulsions; 6 of this group were severe and they all had remaining physical function or ability to perform work after recovery. The common interval for fits was 6 to 9 months after injury. Russell and Whitty published a much larger set of articles on this important subject in 1952, wherein they described the World War II incidence of seizures in 820 patients who were treated for penetrating brain injury. They noted that there was an incidence reported in the literature between 44 and 66%, although there were differences in selection criteria for those who qualified for posttraumatic seizures. Their results were similar, with 43% of 820 patients suffering from at least 1 seizure during a 5-year follow-up. These numbers are difficult to compare with the World War I experience given the remarkably different method of management, especially with regard to open healing versus primary dural closure. Russell also noted that a follow-up of 10 years might be more appropriate as some patients had seizure onset after the 5-year mark noted in previous studies. Of his 820 patients, 277 were studied with enough detail to provide information about timing of onset of seizures after injury; 73% had their first seizure within 12 months of injury, 18% between 1 and 2 years, and 9% between 2 and 5 years after injury. His review stands as an important work in summarizing the nature of posttraumatic epilepsy after World War I and World War II and looks ahead to the growing issue of the management of posttraumatic epilepsy later in the century.

**Lessons From World War II**

Although many authors have contributed to the literature for this period, Abbott, who was operating in the Southwest Pacific Theater, recounted the general principles of penetrating brain injury management. These principles included early resuscitative measures including administration of fluids, plasma, and antibiotics, early evacuation and early definitive care, administration of plasma and antibiotics, and roentgenograms before surgical management. The surgical aims were debridement of scalp, exposure of injury via craniotomy/craniectomy, adequate intracranial debridement, and careful multilayered closure of dura and scalp. He emphasized the importance of debridement, a watertight dural closure to help limit infection, and the use of antimicrobials. Finlayson, who also had a large experience in the Southwest Pacific Theater, echoed these principles of treatment in his patient series. At the close of the century’s last World War, then, neurosurgeons had codified generally accepted principles in the rational management of projectile injuries to the head. Perhaps one area of weakness of these early surgeons’ series was the lack of significant long-term follow-up and functional/neuropsychiatric outcomes. Only 1 serious report by George Malby focused on later outcomes of 200 cases of penetrating cranial injuries. In addition to noting standard infection and posttraumatic epilepsy statistics, he recorded residual neurological signs/symptoms and disposition from return to duty to retirement.

**Korean War**

The Korean War brought with it the consolidation of
the lessons learned in World War II. These experiences were laid out in a significant work by the US Army Medical Service, titled *The Neurological Surgery of Trauma*, whose purpose was “aimed at an improvement of neurosurgical management of casualties with penetrating wounds of the head.” Early in the Korean War, neurosurgical patients were not receiving definitive neurosurgical care early enough, and this created significant complications from retained bone fragments and cerebritis. Whereas World War II saw the creation of mobile neurosurgical units, this system really came into its own in the Korean War. The first mobile neurosurgical unit was established at Kumson, Korea, in October 1951, from which point an elegant system of triage and evacuation was set up. This 2-tiered system would take casualties by helicopter from the field to the mobile neurosurgical unit, followed by evacuation via airplane to the main Tokyo Army Hospital within a few days, where appropriate neurosurgical follow-up could be administered. With this new system in place, from 1950 to 1951, 879 patients with penetrating wounds of the brain were brought to an Army neurosurgical station, and 84 of these patients died, with a resulting mortality rate of 9.6%. The incidence of meningocerebritis dropped to approximately 1%. It cannot be overestimated how important the contribution of organization of medical personnel and equipment was to the Korean War and ultimately to our understanding of early, definitive neurosurgery as a means to improve outcomes in patients with penetrating head injuries.

In addition to laying the groundwork for standards in both operating and in the organization of military medical/surgical units, the Korean War represents an important time for pushing the boundaries in some of the more difficult aspects of surgical care in patients with penetrating head injury. For example, frank cerebritis had been previously managed conservatively, and because of the slow adaptation of aggressive, early neurosurgical care in the Korean War, patients with fungating cerebritis were examined and treated. Meirowsky and Harsh proposed a significant advance in the surgical treatment of these lesions in patients who had developed this cerebral fungus after inadequate primary debridement and closure. Their patient series from the Korean War demonstrated that aggressive initial resection, antibiotic-based irrigation, appropriate open wound care for hours to days, and multilayered closure could tremendously improve outcomes in these cases. In terms of studying infections, Wannamaker and Pulaski performed bacteriological studies on patients injured in Korea, and based on their series of 58 soldiers, they determined that retained bone fragments, improper closure of dura, and delay of surgery beyond 48 hours contributed significantly to an increased risk of infection. Furthermore, the growing use of penicillin and streptomycin were leading to antibiotic-resistant strains and resulting infections.

As the debate on dural closure shifted toward proper debridement, use of antibiotics, and early primary dural repair with the option of grafts, the Korean War experience confirmed these findings. In their series on 540 patients with penetrating head injury, Wallace and Meirowsky provided a detailed report including surgical “technic,” demonstrating that watertight dural repair with grafts, if necessary, have the following advantages: “prevention of centripetal infection, prevention of cerebrospinal fluid fistula, facilitation of cranioplasty, and avoidance of cortical meningeal scar formation.”

Surgical advances also occurred in the management of hematomas following injury, as Barnett and Meirowsky reported in their series from October 1951 to October 1952 in Korea. Of 316 penetrating head wounds, including wounds from fragments of blast injuries, 146 (46.2%) were accompanied by intracranial hematomas. Of note, these patients were the beneficiaries of the faster evacuation system in which neurosurgical care could be provided at the evacuation level, usually within 8 hours. The authors compared the incidence of hematomas treated within 8 hours of injury (46.2%), with incidence rates in previous literature, including 27% of patients treated within 12–36 hours, and 7% of patients treated within 24–72 hours. The evidence related to early treatment of hematomas possibly reflects a bias in which those patients with hematomas suffer poor outcomes and do not survive to obtain later neurosurgical care. Therefore, it is imperative to provide the earliest, definitive neurosurgical treatment possible, including hematoma evacuation.

Given the complexity of wound management in the World Wars, special effort to examine details of wound management was secondary to the overall description of cases. As neurosurgery improved technically, and as mortality rates decreased, wounds of the sinuses and transventricular wounds could be studied more specifically. Meirowsky, in his patient series from the Korean War, noted a mortality rate of 11.6% in 112 patients with dural sinus injury. He described the incidence of these sinus injuries by location and also described their surgical management, which includes the standard penetrating head injury protocol plus ligation of transected sinuses and debridement with primary closure, if possible, of lacerated sinuses. Additionally, Wannamaker described advancements in the management of transventricular wounds of the brain, which included debridement of clots and fragments of bone/missiles from the ventricle, and watertight dural closure.

**Postoperative Sequelae**

In Lewin and Gibson’s series from the British side of the Korean War, they provided a complete case series that described results very similar to the American experience. In addition, they noted the incidence of postoperative sequelae, including a seizure rate of 36%, but this rate was in the context of very limited follow-up (< 1 year). In 1 review there were 134 Korean War veterans with penetrating injuries, and of these, 54 (40.3%) had developed posttraumatic seizures. This rate is compared with that from World War II veterans from the patient series of Walker and Jablon, which demonstrated a 56.7% rate for penetrating head wounds. These initial series emphasized not only the high incidence of posttraumatic epilepsy, but also the limitations in our understanding at the time of its development and management.
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posed. Preoperative roentgenograms were necessary and gave “information about the bony defect, number and location of in driven bone fragments, and location of metallic fragments.” The anesthetic used primarily at the time was thiopental sodium. The surgical technique included sterile dressing of the wound, wide excision of the skin edge, and narrower excision of all exposed layers and periosteum. After thorough inspection, a wide excision of any exposed musculature was undertaken. Once the area was debrided in this fashion, new sterile instruments were used for an extension of the scalp wound with a curvilinear or S-shaped incision. A radius of approximately 4 cm of intact bone surrounding the fracture site was ex-
posed with the removal of periosteum. En bloc resection of the site of fracture/depression was recommended using bur holes and rongeurs as necessary. Before opening the dura, irrigation and hemostasis was performed. There had been some debate in the literature regarding the use of forcible irrigation, but the authors believed that it was “an important and irreplaceable part of the entire process of debridement.”75 Excision of damaged or necrotic dural edges was followed by placement of “stay” sutures. Cortical debridement included resection of any damaged tissue, irrigation of the injury track, inspection, and most importantly removal of clots and “REMOVAL of ALL BONE FRAGMENTS.”79 Metallic fragments were to be removed if easily accessible. Hemostasis was obtained and the dura was closed in a watertight fashion with a graft including fascia, pericranium, or “gelfilm.” The scalp was closed in standard multilayered fashion with No. 0 silk sutures and covered with a sterile dressing.75

In all, the Korean War experience was instrumental in the consolidation and dissemination of knowledge gleaned from the World Wars. Organization of a successful model of evacuation had been implemented successfully and the general practice of sound techniques in neurosurgery for penetrating head injury allowed for a demonstrable improvement in mortality rates and outcomes. Trauma and neurosurgery would have to wait for other advances in medicine, such as advanced neuroimaging and improved pharmaceuticals, to allow further improvements in the coming decades.

Vietnam War

In terms of the management of penetrating brain injury, the Vietnam War was essentially an extension of work from the 1940s and 1950s. Hammon76 recounted his series of 2187 patients with head injuries and described this successful implementation of the evacuation and early neurosurgery model. Of the patients who underwent surgery in his series, 95% were evacuated by helicopter and treated early with establishment of an airway, resuscitative fluids, and a sterile head dressing. Patients were brought to the operating room as soon as possible with the acquisition of radiographs if stable. The operative technique was exactly as outlined previously for the Korean War, with a curvilinear incision, extensive debride-
ment, followed by a watertight dural closure with graft if necessary. Postoperative antibiotics and phenytoin were administered in all cases. If there remained bone fragments on postoperative radiographs, repeat debridement would be performed. Of note, he divided his wounds into gunshot wounds versus fragments, which coincided with the growing firepower in both guns and explosives. Fur-
thermore, his series showed that death was not directly related to the brain injury but rather to other soft-tissue injuries sustained or postoperative complications. The US Army’s operative mortality rate was 9.74% overall with an 8.88% mortality rate due directly to cerebral causes. When one removes the number of deaths from patients who were brought in comatose, the mortality rate drops to 3.33%.36

In addition, some of the management points from World War II and the Korean War were evaluated more carefully during the Vietnam conflict. Carey et al.18 performed a bacteriological study of 45 penetrating brain wounds and found that 44 had contaminated skin wounds within 2–4 hours after injury, but that only 5 had intracranial infection. Approximately 45% had contaminated bone fragments that had been driven into the brain parenchyma. Although the skin contamination contained a variety of bacterial organisms, the bone fragments were consistently contaminated with staphylococci. Hammon77 studied 42 patients with retained intracranial bone frag-
ments who were brought to Walter Reed Army Medical Center; of these, 40 patients required further debridement, with 8 in-hospital deaths. The surviving patients under-
went courses of debridement and antibiotics. With regard to the safety of secondary operations, both the series by Hammon77 and further work by Meirowsky56 argued that early secondary reoperation for debridement were critical. In terms of brain abscess, an important complication following injury, a patient series from the Vietnam War45 demonstrated a high mortality (54%) and morbidity (82%) rate, although the overall incidence of this serious compi-
lcation was only 3% from a study population of 1221. These findings supported previous treatment strategies of removing all in driven bone fragments to prevent recur-
rent infection or cerebral abscess.

Further advances from the Vietnam War included pri-
mary prevention to avoid brain injuries in the first place. For example, the use of improved helmets became more commonplace, and although they did not always protect against bullet wounds, they were effective against frag-
ments from blasts.56 Even in operative technique, others had argued for a craniotomy technique over a cranieto-
my technique in certain selected cases for debridement.46

The publication in 1965 by the US Army Medical Service of the volume, Neurological Surgery of Trauma,75 stood as a landmark “textbook” on the care of patients with head injuries from penetrating fragments or bullets. In particular, detailed images and text focused on surgical techniques. Here we present a summary of the standard of care at that time. Preoperative care included airway maintenance and any immediate resuscitation with trans-
fusions and antibiotics. Before surgery, it was important to provide adequate initial wound care with a wide area of shaving and dry dressings that were not applied too tightly, because often brain tissue itself was or could become exposed. Preoperative roentgenograms were necessary and gave “information about the bony defect, number and location of in driven bone fragments, and location of metallic fragments.” The anesthetic used primarily at the time was thiopental sodium. The surgical technique included sterile dressing of the wound, wide excision of the skin edge, and narrower excision of all exposed layers and periosteum. After thorough inspection, a wide excision of any exposed musculature was undertaken. Once the area was debrided in this fashion, new sterile instruments were used for an extension of the scalp wound with a curvilinear or S-shaped incision. A radius of approximately 4 cm of intact bone surrounding the fracture site was exposed with the removal of periosteum. En bloc resection of the site of fracture/depression was recommended using bur holes and rongeurs as necessary. Before opening the dura, irrigation and hemostasis was performed. There had been some debate in the literature regarding the use of forcible irrigation, but the authors believed that it was “an important and irreplaceable part of the entire process of debridement.”75 Excision of damaged or necrotic dural edges was followed by placement of “stay” sutures. Cortical debridement included resection of any damaged tissue, irrigation of the injury track, inspection, and most importantly removal of clots and “REMOVAL of ALL BONE FRAGMENTS.”79 Metallic fragments were to be removed if easily accessible. Hemostasis was obtained and the dura was closed in a watertight fashion with a graft including fascia, pericranium, or “gelfilm.” The scalp was closed in standard multilayered fashion with No. 0 silk sutures and covered with a sterile dressing.75
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Pathophysiology and Mechanism of Injury

Significant work has been conducted to examine the pathophysiology of bullet injuries in the cranium in both the military and civilian setting. The two main mechanisms of wounding from projectile injury are from crushing and distortion of tissue. When the tissue is crushed by the physical contact of the projectile, it creates a permanent cavity. This cavity is affected not only by the size of the bullet, but also by the yaw and any deformation of the projectile. For example, if a bullet’s yaw angle changes through its tissue track such that it angles up or down, then it makes more contact with tissue, thereby creating a larger permanent cavity and more crush injury. Also, if the point of the bullet is a hollow-point or soft-point, then the bullet will deform upon contact and create a larger cross-sectional area of damaged tissue. In fact, military ammunition is required to have full metal casings (jackets) that prevent deformation while civilian ammunition is not, which allows for more deformation and a larger permanent cavity. Furthermore, fragmentation of the bullet itself or of other rigid structures such as bone can create secondary missiles that expand the resulting cavity.

In addition to injury induced by direct contact of a projectile and tissue, the rapid deceleration of a bullet in tissue exerts a large radial-expanding force that creates a temporary cavity. The changes in the yaw angle also contribute to the size of the temporary cavity in a manner analogous to a diver’s splash. If a diver enters the water completely in-line with his or her long axis, there is minimal splash, but if the angle changes upon entry, then a large splash and resulting wave is created. It should be noted that the yaw angle in flight remains relatively low, which allows normal long-axis entry into tissue, but as the yaw angle changes in tissue, there can be devastating consequences. Finally, although the significance of temporary cavity formation in injury is debatable, it can play a large role in the injury of sensitive tissues such as the brain and liver, which have near-water density. The bullet also creates a sonic wave, but this has been demonstrated to be of such short duration (approximately 2 microseconds) that it has minimal lasting damage on tissue.

Based on these models, the mechanism of death has been studied as well. After Horsley hypothesized the importance of apnea due to the missile-induced damage, further studies on an experimental model of bullet injury in cats showed the importance of airway and breathing support to reverse respiratory arrest from missiles. In fact, a clinical study in the civilian world on 480 patients in Chicago who suffered from cranial gunshot wounds illustrated that apnea and respiratory depression in addition to Glasgow Coma Scale score were important prognostic indicators in such patients.

Current Treatment

The goals of modern civilian neurosurgical care are not tremendously different from the lessons learned in the military. These include early evacuation, definitive neurosurgical treatment, and appropriate resuscitative measures (Table 1). Modern neurosurgical studies of head wounds have emphasized the civilian literature, in part because of the lack of major military operations until very recently in Iraq, Iran, and Afghanistan, and also because the majority of current victims of penetrating brain injuries are in the civilian world. In fact, modern military warfare has

<table>
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<th>Clinical Issue</th>
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<td>resuscitation</td>
<td>standard trauma resuscitative measures ideally at a designated trauma center, fluid resuscitation with crystalloid-based fluid preferred; GCS score after resuscitation highly predictive of outcome</td>
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<tr>
<td>ICP monitoring</td>
<td>ICP monitoring is often used and can accurately predict negative outcomes</td>
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<tr>
<td>craniotomy</td>
<td>aggressive, decompressive hemicraniectomy can improve intracranial hypertension</td>
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<tr>
<td>debridement</td>
<td>despite previous extensive debridentments, modern studies demonstrate effectiveness of modern neuroimaging to identify symptomatic bone/missile fragments, and the effectiveness of a less extensive debridentment than previously advocated, especially in civilian gunshot wounds; removal of indriven fragments when accessible is recommended; standard antibiotic protocols are used until debridentment is complete</td>
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<tr>
<td>closure</td>
<td>watertight dural closure with graft if necessary has been confirmed to improve outcomes since World War II and the Korean War; this includes repair of CSF leaks, particularly to protect against infection</td>
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<tr>
<td>seizure</td>
<td>although not studied extensively in penetrating missile injury, phenytoin for 1 week after injury can reduce incidence of seizures</td>
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* GCS = Glasgow Coma Scale.
made blast injury a more important contributor to brain injuries.6 Unfortunately, however, there is significant variability in the treatment of gunshot wounds in the civilian sector as discovered in a national survey of neurosurgical care administered by Kaufman and colleagues.38 According to a review by Carey,43 although antibiotics and tetanus prophylaxis appear to be well-established adjunctive therapies to surgery, there is still debate as to the effectiveness of improving outcomes by using seizure prophylaxis, intracerebral pressure monitoring, or barbiturate coma induction. Furthermore, both hypotension and hypoxia can reduce adequate tissue oxygenation and lead to poorer outcomes, based on work by Byrnes and colleagues7 who studied gunshot wounds among civilians in Northern Ireland. These suggest the importance of appropriate resuscitative measures even preoperatively to prevent hypotension and hypoxia.

In terms of surgical technique, there is some debate as to the necessity of aggressive debridement. Although Hammon36,37 echoed the need for aggressive debridement based on his large series from the Vietnam War, other studies since that time have shown the benefits of a more limited debridement.8 In particular, Brandvold et al.8 studied 113 patients in Israel during the Lebanese conflict from 1982 to 1985. With the advent of CT imaging, a less aggressive surgical debridement was studied in which patients underwent initial simple debridement with no specific effort to remove indriven bone or metal fragments identified on CT unless easily accessible by gentle irrigation. Outcomes were similar to Vietnam-era patient series and most interestingly, long-term incidence of postoperative seizures or infection due to retained fragments was low.8 A similar conclusion was obtained from a large series of patients suffering from low-velocity penetrating head injuries in the Iran-Iraq conflict.2 Here, surgeons with modern neuroradiological technology were able to identify patients who needed surgery due to compression from hematoma, symptomatic bone/metal fragments, or evidence of deep infection. By not operating or performing limited operations on those without need as identified on imaging, the patients were spared from postoperative complications of seizures and infection with similar mortality outcomes.2

Conclusions
The modern management of penetrating head injuries relies heavily on the experiences of neurosurgery during wartime. In particular, during the global wartime conflagrations of the 20th century, neurosurgeons active in the military were able to provide detailed accounts of their cases and techniques, which not only fueled the debates on the management of trauma in neurosurgery, but also advanced it toward modern principles. Although technological advancements in medicine—such as antimicrobials and modern neuroimaging—played a significant role in improving outcomes, neurosurgeons were leaders in the development of an aggressive system of evacuation from the frontlines and of the need for specialized neurosurgical care of these patients. Although some of the modern military contributions to the management of penetrating head injuries will be discussed elsewhere in this issue, it is important to appreciate the foundation laid by a close relationship between the military and neurosurgery, particularly in the first half of the 20th century. Moreover, we should be careful to not overlook the human lessons created by reflecting upon the military neurosurgeons who contributed to our understanding of projectile injury management through their service; the neurosurgeons who answered the call to their country’s service surely provide a compelling example of service. As new mechanisms of trauma such as blast injury occur in modern conflicts, once again there is an opportunity for neurosurgery to extend the boundaries of its field. Some things, however, will surely not change; nearly a century onward, neurosurgery’s care of the wounded soldier is still one of its hallowed services to society, and the lessons learned in this process will continue to inspire us as we care for men and women in uniform and in civilian life.

Perhaps Macleod32 summarized it best: “Finally, if in war the surgeon sees much which is terrible, much which taxes his feelings of humanity, and his regret at the feebleness of his art, he has also the comforting conviction that nowhere is his beneficent mission so felt, nowhere is the saving power of his profession so fully exercised.”

Disclosure
The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: all authors. Drafting the article: all authors. Critically revising the article: all authors. Reviewed final version of the manuscript and approved it for submission: ER Laws.

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