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Introduction: Military neurosurgery, past and present

Paul Klimo Jr., M.D., M.P.H.,[1] and Brian T. Ragel, M.D.[2]

[1]88th Medical Group, Wright-Patterson Air Force Base, Ohio; and [2]Department of Neurological Surgery, Oregon Health & Science University, Portland, Oregon

ἰητρὸς γὰρ ἀνὴρ πολλῶν ἀντάξιος ἄλλων
ἰούς τ᾽ ἐκτάμνειν ἐπί τ᾽ ἤπια φάρμακα πάσσειν.
For a physician has the worth of many other warriors, both for
the excision of arrows and for the administration of soothing drugs.
Homer, *Iliad* XI.514–515

Ever since armed conflict has been used as a means to settle disputes among men, there have been those who have been tasked to mend the wounds that ravage a soldier's body from the weapons of war. The Iliad portrays the pivotal 10th year of the legendary Trojan War, during which a schism in the Greek leadership prolongs the extended siege of the city of Troy. In the midst of this martial epic come the lines quoted above, quietly attesting to the value of the military physician, even under the crude conditions of the Greek Dark Age. They are uttered by Idomeneus, one of the foremost Greeks, when he is enjoining one of his comrades, Nestor, to rescue the injured Greek physician Machaon and take him back from the line to treat his wounds. He is afraid that Machaon will be captured by the Trojans, a loss far greater than that of any other single warrior.

Duty to country has helped shape the careers of many neurosurgeons, including iconic US figures such as Harvey Cushing and Donald Matson. This issue of *Neurosurgical Focus* celebrates the rich history of military neurosurgery from the wars of yesterday to the conflicts of today. We have been humbled by the tremendous response to this topic. The 25 articles within this issue will provide the reader with both a broad and an in-depth look at the many facets of military neurosurgery. We have attempted to group articles based on their predominant topic. We also encourage our audience to read other recently published articles.[1–4]

The first 8 articles relate to the current conflicts in Afghanistan and Iraq. The lead article, written by Randy Bell and colleagues from the National Naval Medical Center and Walter Reed Army Medical Center, discusses what is arguably one of the most important contributions by military neurosurgeons from these 2 conflicts: the rapid and aggressive use of decompressive craniectomies. This is followed by articles on decompressive craniectomy techniques by Ragel and colleagues and cranioplasty outcomes by Stephens and colleagues. After reading these articles, the reader will come away with an appreciation of the often complex nature of wartime penetrating and closed-head injuries and the remarkable recovery that many injured soldiers make with time.

Klimo and colleagues then review the military and civilian literature on penetrating spinal injuries, an injury that has received relatively little exposure in neurosurgical publications. This topic continues to generate the same controversies as it did more than 60 years ago during World War II. The paper concludes with treatment recommendations that were agreed on by members of all 3 services (Air Force, Army, and Navy) of the US Armed Forces.

The diagnosis and management of cerebrovascular trauma has been another hallmark of the current Iraq and Afghanistan conflicts, affecting roughly 30% of all soldiers with penetrating head injuries. Articles by Bell and Vadivelu review and discuss our current understanding and management strategies of wartime cerebrovascular trauma.

Eisenburg and Ragel detail the neurosurgical experience in the military conflict that has currently taken center stage (with the drawdown in Iraq), Operation Enduring Freedom in Afghanistan. The first article is written by our colleagues in the German Army about their time in southern Afghanistan (Kandahar), whereas the second documents the US Air Force's experience in central Afghanistan (Bagram).

There is a shift in topic focus with the next 2 papers. Given the shortage of military neurosurgeons, the military has led the way in educating nonneurosurgeons (for example, trauma surgeons and otolaryngologists) on life-saving neurosurgical maneuvers, something that would be very difficult to implement in the civilian world. Our nonneurosurgical colleagues are often stationed in remote locations (forward operating bases) that are very close to, if not in the immediate vicinity of, combat activity. The articles by Teff and Mauer show how such education is being undertaken and provide examples in which such training has led to life-saving operations for both local nationals and soldiers.

The recent conflicts in Iraq and Afghanistan have also forced military medicine to integrate the remarkable advancements in aeromedical evacuation into military medical operations. This has resulted in a truly global-reach system that can literally transport neurologically critically ill patients from the country of conflict to fully equipped medical centers in Europe and the US in a matter of hours. The challenges faced by the men and women of aeromedical evacuation are detailed in the articles by Fang and Reno.

This issue of *Neurosurgical Focus* has given us the opportunity to introduce nonmilitary neurosurgeons to military neurosurgical services from around the world. The reader will learn about military neurosurgical history and capabilities in France, Germany, Bulgaria, and Turkey.

Despite military neurosurgeons' caring for those who are wounded on the battlefield, the majority of their time is committed to caring for those who are at home—active-duty members and their family members—and are afflicted with neurosurgical diseases not unlike the general population. However, the delivery of medical services within the military results in several unique issues for the neurosurgeon, one of them being "return to duty" for active-duty members who undergo spinal operations for degenerative disease. Furthermore, the military medical system allows neurosurgeons, at times, to offer patients services that are in some respects more difficult to acquire in the civilian setting, such as artificial cervical and lumbar discs. These are the topics discussed in papers by Tumialán and Cardoso. Training of neurosurgeons also occurs in the military, and the article by Neal discusses an approach to assessing the acquisition of neurosurgical skills in residents with a particular surgical procedure that can easily be applied to all neurosurgical training programs, both military and civilian.

This issue of *Neurosurgical Focus* would not be complete without several historical articles. These articles pay tribute to underrecognized pioneers of the field (Loyal Davis) and describe the evolution of battlefield management of penetrating head injury and peripheral nerve injury during particular conflicts in history. We felt it was appropriate to conclude this issue with an article by Kellner and colleagues that discusses the emerging technologies of the future—brain-computer interfaces.

In conclusion, we are personally honored to have served in the US military. Although military neurosurgeons continue to strive for better treatments and outcomes, their humanitarianism is eclipsed by the bravery of their soldier patients as well as the wives, husbands, and children who had the strength to "keep the home fires burning" while their loved one was deployed in the service of this great nation.

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Early decompressive craniectomy for severe penetrating and closed head injury during wartime

Randy S. Bell, M.D.,[1,2] Corey M. Mossop, M.D.,[1,4] Michael S. Dirks, M.D.,[1,4] Frederick L. Stephens, M.D.,[1,4] Lisa Mulligan, M.D.,[1,2] Robert Ecker, M.D.,[2] Christopher J. Neal, M.D.,[1,2] Anand Kumar, M.D.,[2] Teodoro Tigno, M.D.,[3] and Rocco A. Armonda, M.D.[1–4]

[1]Uniformed Services University of Health Sciences; [2]Department of Neurosurgery, National Naval Medical Center, Bethesda, Maryland; [3]Department of Neurosurgery, Walter Reed Army Medical Center; and [4]National Capital Consortium Neurosurgery Program, Washington, DC

Object. Decompressive craniectomy has defined this era of damage-control wartime neurosurgery. Injuries that in previous conflicts were treated in an expectant manner are now aggressively decompressed at the far-forward Combat Support Hospital and transferred to Walter Reed Army Medical Center (WRAMC) and National Naval Medical Center (NNMC) in Bethesda for definitive care. The purpose of this paper is to examine the baseline characteristics of those injured warriors who received decompressive craniectomies. The importance of this procedure will be emphasized and guidance provided to current and future neurosurgeons deployed in theater.

Methods. The authors retrospectively searched a database for all soldiers injured in Operations Iraqi Freedom and Enduring Freedom between April 2003 and October 2008 at WRAMC and NNMC. Criteria for inclusion in this study included either a closed or penetrating head injury suffered during combat operations in either Iraq or Afghanistan with subsequent neurosurgical evaluation at NNMC or WRAMC. Exclusion criteria included all cases in which primary demographic data could not be verified. Primary outcome data included the type and mechanism of injury, Glasgow Coma Scale (GCS) score and injury severity score (ISS) at admission, and Glasgow Outcome Scale (GOS) score at discharge, 6 months, and 1–2 years.

Results. Four hundred eight patients presented with head injury during the study period. In this population, a total of 188 decompressive craniectomies were performed (154 for penetrating head injury, 22 for closed head injury, and 12 for unknown injury mechanism). Patients who underwent decompressive craniectomies in the combat theater had significantly lower initial GCS scores (7.7 ± 4.2 vs 10.8 ± 4.0, $p < 0.05$) and higher ISSs (32.5 ± 9.4 vs 26.8 ± 11.8, $p < 0.05$) than those who did not. When comparing the GOS scores at hospital discharge, 6 months, and 1–2 years after discharge, those receiving decompressive craniectomies had significantly lower scores (3.0 ± 0.9 vs 3.7 ± 0.9, 3.5 ± 1.2 vs 4.0 ± 1.0, and 3.7 ± 1.2 vs 4.4 ± 0.9, respectively) than those who did not undergo decompressive craniectomies. That said, intragroup analysis indicated consistent improvement for those with craniectomy with time, allowing them, on average, to participate in and improve from rehabilitation ($p < 0.05$). Overall, 83% of those for whom follow-up data are available achieved a 1-year GOS score of greater than 3.

Conclusions. This study of the provision of early decompressive craniectomy in a military population that sustained severe penetrating and closed head injuries represents one of the largest to date in both the civilian and military literature. The findings suggest that patients who undergo decompressive craniectomy had worse injuries than those receiving craniotomy and, while not achieving the same outcomes as those with a lesser injury, did improve with time. The authors recommend hemicraniectomy for damage control to protect patients from the effects of brain swelling during the long overseas transport to their definitive care, and it should be conducted with foresight concerning future complications and reconstructive surgical procedures. *(DOI: 10.3171/2010.2.FOCUS1022)*

Key Words • **decompressive craniectomy** • **penetrating head injury** • **blast injury** • **Glasgow Outcome Scale**

Brain injuries from military-grade weaponry differ significantly from those received in civilian settings. Not only are the destructive forces involved considerably higher (blast, high-caliber missile), but additional factors, including the effect of protective equipment (helmet, body armor), systemic injury burden, available resources in a war zone, and the intricacies of field and overseas transport, make diagnosis, treatment, and outcomes difficult and unpredictable. It is because of these variances that the approach to patients with brain injuries must, in many circumstances, diverge from that undertaken in civilian traumatic brain injury populations.

Abbreviations used in this paper: GCS = Glasgow Coma Scale; GOS = Glasgow Outcome Scale; ICP = intracranial pressure; ICU = intensive care unit; ISS = injury severity score; NNMC = National Naval Medical Center; OEF = Operation Enduring Freedom; OIF = Operation Iraqi Freedom; WRAMC = Walter Reed Army Medical Center.

TABLE 1: Injuries in military patients who underwent decompressive craniectomy stratified by mechanism and submechanism, as well as the extent of injury classified with reference to the most recent GOS score*

	PHI	CHI	Unknown	
mechanism of injury†	154	22	12	
	Blast	GSW	MVA/Blunt/Other	
submechanism†	130	39	19	
	Unilat Hemisphere	Bilat Hemispheres	Transventricular	Unknown
extent of PHI†	94	38	4	18
mean GOS score	3.7 ± 1.0	3.1 ± 1.3	3.5 ± 0.6	
p value		0.002		

* MVA = motor vehicle accident; CHI = closed head injury; GSW = gunshot wound; PHI = penetrating head injury.

† Values represent number of patients.

During the first 5 years of OIF and OEF, the vast majority of patients with severe closed and penetrating head injuries presented to the WRAMC in Washington, DC, and the NNMC in Bethesda, Maryland, for definitive care. This unique population has afforded an in-depth and timely study of the current approach to patients with severe closed and penetrating head injury during wartime. The purpose of this paper is therefore to evaluate the circumstances leading to and outcomes after decompressive hemicraniectomy. The importance of this procedure will be emphasized and guidelines provided for current and future neurosurgeons deployed in a war zone.

Methods

This study was approved by the institutional review boards at NNMC and WRAMC. We conducted a retrospective review of all soldiers, sailors, airmen, and marines injured in Operations Iraqi and Enduring Freedom between April 2003 and October 2008 by searching the databases at WRAMC and NNMC. During the specified period, 513 consultations were performed by the neurosurgery service in the aforementioned population; of these, 408 patients met the inclusion criteria for this study. Criteria for inclusion included either a closed or penetrating head injury suffered during combat operations in either Iraq or Afghanistan in a patient who subsequently received a neurosurgical evaluation at NNMC or WRAMC. Exclusion criteria included all patients for whom primary demographic data could not be verified.

Abstracted data included age at the time of initial injury, sex, type of injury (closed head injury or penetrating head injury), mechanism of injury (explosive blast injury, motor vehicle accident, and so on), initial GCS score, and admission ISS (numerical summation score categorizing the extent of trauma by body system) associated with one's initial injury. Also measured was the amount of time spent in the ICU, GCS and GOS scores at discharge, and GOS score at 6 months and 1–2 years following discharge.

Direct comparisons were then performed to determine the differences between those patients undergoing decompressive craniectomy and those who did not. The relationships between the 2 groups with respect to age at the time of initial injury, initial GCS score, and ISS score in those who did and did not undergo the decompressive craniectomy were examined. We also examined the impact conferred by decompressive craniectomy upon ICU time, discharge GCS/GOS score, and GOS score at 6 months and 1–2 years after discharge.

Statistical Analysis

The Statistical Package for the Social Sciences (version 14) was used to perform all inferential statistical analyses. Data were analyzed and results expressed as mean ± SD for all descriptive variables. Percentages for descriptive variables were calculated and expressed as a function of the total number of patients in the study. Comparability between subpopulations in this study were analyzed for all data including age at the time of initial injury, initial GCS score/ISS, ICU time, discharge GCS/GOS score, and GOS score at 6 months and 1–2 years after discharge using chi-square tests for categorical variables and ANOVA for continuous variables.

Results

During the specified 5-year period examined, 513 consultations were performed by the neurosurgery service concerning all wartime-related neurotrauma. Four hundred eight patients met the inclusion criteria for this study (male/female ratio 401:7; 228 with penetrating brain injury, 139 with closed head injury, and 41 not specified). Of these 408 patients meeting the inclusion criteria for this study, 188 presented having had decompressive craniectomies performed while in the combat theater for severe penetrating and closed head injuries (154 with penetrating head injury, 22 with closed head injury, and 12 unknown mechanism) (Table 1). Blast was the predominant mechanism of injury (Table 1).

Several trends emerged when examining for differences in this population compared with those who did not receive decompressive craniectomies (Table 2). While there were no significant differences in the age (26.2 ± 7.4 vs 27.5 ± 7.5 years, $p > 0.05$) or evacuation times (6.7 ± 7.3 vs 8.1 ± 10.6 days, $p > 0.05$) between those who did and did not receive decompressive craniectomies, respectively, there were significant differences in all other parameters studied. Patients undergoing decompressive

TABLE 2: Summary of statistical comparisons between patients with and without decompressive craniectomy*

Variable	Craniectomy	No Craniectomy	p Value
mean age (yrs)	26.1 ± 7.4	27.5 ± 7.5	>0.05
presenting score			
GCS	7.7 ± 4.2	10.08 ± 4.0	<0.05
ISS	32.5 ± 9.4	26.8 ± 11.8	<0.05
ICU stay (days)	19.4 ± 31.5	7.3 ± 10.4	<0.05
discharge score			
GCS	13.2 ± 3.1	14.7 ± 2.25	<0.05
GOS*	3.0 ± 0.9	3.7 ± 0.9	<0.05
6-mo GOS score*	3.5 ± 1.2	4.0 ± 1.0	<0.05
1-yr GOS score*	3.7 ± 1.2	4.4 ± 0.9	<0.05

* With the exception of p values, numbers reflect the mean ± SD.

craniectomies in the combat theater had significantly lower initial GCS score (7.7 ± 4.2 vs 10.8 ± 4.0, respectively, $p < 0.05$) and higher ISS (32.5 ± 9.4 vs 26.8 ± 11.8, $p < 0.05$) scores, on average, than those who did not receive decompressive craniectomies. Also, those receiving craniectomy had significantly increased ICU times (19.4 ± 31.5 vs 7.3 ± 10.4 days, respectively, $p < 0.05$) than those who did not.

Intergroup and intragroup analysis was performed to determine the effect of decompressive craniectomy on outcomes at discharge, 6 months, and 1–2 years. Significant differences in discharge mean GCS score (13.2 ± 3.1 vs 14.7 ± 2.3, respectively, $p < 0.05$), mean discharge GOS score (3.0 ± 0.9 vs 3.7 ± 0.9, respectively), mean GOS score at 6 months (3.5 ± 1.2 vs 4.0 ± 1.0, respectively,) and mean GOS score at 1–2 years (3.7 ± 1.2 vs 4.4 ± 0.9, respectively) were seen when comparing patients who underwent craniectomy and those who did not, respectively (Table 2). Within each group, improvements were noted for all patients comparing each time point respectively (that is, craniectomy: discharge GOS vs 6-month GOS score; discharge GOS score vs 1–2-year GOS score; and 6-month GOS score vs 1–2-year GOS score and so on; $p < 0.05$), indicating that regardless of treatment, clinical improvement was seen.

Observational analysis was also performed to determine the effect of the extent of injury on those with penetrating head trauma in whom the injury pattern was known or could be ascertained. Ninety-four patients presented with unilateral hemispheric injury (mean GOS score 3.7 ± 1.0) and 38 patients presented with bilateral hemispheric injury (mean GOS score 3.1 ± 1.3; $p < 0.002$). Within the bilateral hemispheric injury group, 4 patients presented with documented fragment traversal through the lateral ventricle en route to the contralateral hemisphere. The mean GOS score in this group at 1 year was 3.5 ± 0.6, but the population was too small for additional, meaningful statistical analysis. Overall, 84% of patients for whom follow-up data are available achieved a GOS score greater than 3 at 1–2 years.

Discussion

Historical approaches to the most severely injured patients during wartime have consisted mainly of conservative or expectant approaches largely secondary to resource, technique, and technological limitations. The current conflicts have seen a considerable paradigm shift, adopting an aggressive approach consisting of rapid, far-forward cranial decompression with watertight dural closure followed by rapid overseas evacuation to continental US hospitals. It is this approach, accompanied by the subsequent aggressive critical care management, that has resulted in meaningful survival in a population previously characterized by death and disability.[7]

Evolution of the Approach to Severe Traumatic Brain Injury and the Emergence of Decompressive Craniectomy

The modern approach to patients with severe head injury during wartime was pioneered by Dr. Harvey Cushing during Word War I.[9] His initial approach, characterized by aggressive cranial debridement carried through the Vietnam era.[10,11,15] A subsequent shift to local debridement and closure occurred during the Israeli/Lebanon conflict following analysis by Brandvold et al.[8] that indicated that aggressive cerebral debridement may have resulted in worse outcomes. It is important to remember that each of these conflicts occurred in the era predating routine, far-forward use of CT scanning.

The current conflict has seen the application of modern medical technique and technology in a way not previously available. Highly trained corpsmen and medics, often under direct enemy fire, rapidly resuscitate (through intubation, initiation of intravenous fluids) injured warriors within minutes of their injury. These patients are then rapidly evacuated to a Combat Support Hospital where CT scanning and neurosurgical evaluation are possible. Cranial decompression, in these circumstances, often occurs within the first 2–3 hours accompanied by ICP monitoring or ventricular drainage. Preliminary analysis of this approach was performed by our group in 2006.[4] At that time, just over 2 years into OIF, it became apparent that the most severely brain-injured patients were receiving appropriate decompression and that, at discharge from the hospital, the decompression was independently associated with improvement.

This extensive use of decompressive craniectomy following the most severe closed and penetrating head injury in these conflicts likely resulted from the necessities of medical evacuation transport. Following their resuscitation at the Combat Support Hospital, patients are placed on Combat Casualty Air Transport planes with critical care capabilities, but without direct neurosurgical supervision. These flights navigate half the globe, often during the time when cerebral swelling and increased ICP occur. It is therefore important to note that many of these operations might not have been performed if the added element of immediate air-transport to higher levels of care were not necessary. That said, 13 of the 188 patients who underwent decompressive craniectomy did so after arrival in the continental US. Seven of these patients received either craniotomy or bur hole evacuation of hematoma in

Fig. 1. A CT scan of an adequately sized decompressive craniectomy. Though not seen in this example, the temporal lobe was also adequately decompressed by lower bone removal.

Fig. 2. A CT scan example of a bifrontal craniotomy following a penetrating facial and frontal injury with anterior cranial fossa disruption. The *anterior white arrow* indicates the retained fragment, and the *posterior white arrow* shows the position of the tip of the external ventricular drain.

theater prior to transport. This highlights the unpredictable and often delayed nature of intractable ICP abnormalities in this population.

Effect of Early Decompressive Craniectomy: Outcomes

The results from our initial study have held true based on this longer-term study. As expected, for most parameters, individuals undergoing decompressive craniectomy differed from those who did not. This is reflected by the fact that both centrally (presenting GCS score) and systemically (ISS), those receiving decompressive craniectomy were worse off than those who did not. The difference in GOS scores was present at all time points; however, it must be stressed that, on average, those who required a decompressive craniectomy were able to participate in rehabilitation at discharge. Additional and subsequent improvement was seen in both groups at all time points.

Some important observational analyses were also conducted concerning the extent of injury. As expected, those with bilateral hemispheric injury fared worse than those with unilateral injury. What is interesting is that those with bilateral injury still, on average, were functionally able to participate in rehabilitation at 6–12 months (GOS score > 3). Four of the patients with bilateral injury had penetrating fragment tracks that traversed the ventricle. In all cases, these patients recovered meaningful survival, achieving functional rehabilitation status (Table 1).

While decompressive craniectomy has experienced resurgence in the civilian world in recent years, most of the reports have concerned closed head injury or stroke.[1,12,14,16] It is therefore difficult to make direct comparisons between the current experience and previously published data. To our knowledge, this is the only report representing the study of outcomes in the setting of early cranial decompression for penetrating head injury.

Overall, these wartime patients, and the circumstances surrounding their injuries, differ substantially from their civilian counterparts. Penetrating fragment injury accompanied by blast overpressure was the predominant injury mechanism (Table 1). With respect to civilian penetrating head injury, most are missile (bullet) injuries, and the vast majority (approximately 90%) seen in the civilian environment result in death prior to emergency room admission or very early in their hospital stay.[3] The improved survival in this military population is likely the result, in part, of immediate battlefield resuscitation (that is, within minutes of injury). The contribution of protective cranial and body armor in a group of largely healthy people must also not be understated. What must also be remembered is that this study represents only the patients who survived their original injury to reach the hospital; it does not include the denominator of all patients who were injured on the battlefield (killed in action) or died of wounds at the combat support hospital. Overall, application of the data discussed in this paper to the civilian experience must be done with considerable care.

Technical Considerations: Recommendations Concerning Patient Selection, Operative Plan, and Reconstruction

Prior to the performance of a decompressive craniectomy in this environment, several points should be considered. Planning for future surgeries and the inevitable complications that accompany any severe head injury is

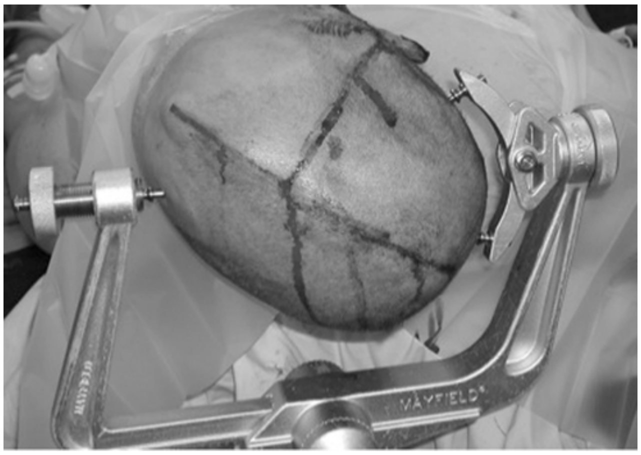

Fig. 3. Photograph showing the planned "Kempe" incision. The inferior limb is carried just to the cartilage at the anterior aspect of the pinna. The posterior aspect of the midline limb of the incision is carried as low as is required for exposure.

not only prudent, but can mean the difference between a good or poor recovery. The following recommendations are based on the problems encountered during definitive management of patients in this setting.

Early Decision Making. Surgical planning starts with patient selection. The patients who received early decompressive craniectomy in this study excluded those in whom the fragment track penetrated the zona fatalis (midline skull base, thalamus, brainstem).[13] Translateral ventricular lesions, if accompanied by a good presenting GCS score, should not necessarily exclude possible decompression in this population (Table 1). Attempts to ascertain ICP (ICP monitor or external ventricular drain) should be initiated prior to decompression (excluding patients with large intracerebral or extraaxial hematomas). It is also important to remember that the concomitant presence of traumatic cerebrovascular and spinal column injury can modify or complicate the operative plan in many patients.[5,6]

Operative Plan. If the decision has been made to perform a decompressive craniectomy, every effort should be made to make the bone removal as large as possible. The recommendation is that the size of the decompression be, at a minimum, 14 cm (anteroposterior) by 12 cm (superoinferior) if the intention is to perform a frontotemporoparietal craniotomy (Fig. 1). If extensive anterior cranial fossa disruption, bifrontal injury, or transventricular fragment trajectories are present, one can perform an extensive bifrontal craniotomy with sinus cranialization (Fig. 2). Although not specifically referred to in this study, there were circumstances in which limited decompressions resulted in the need for additional bone removal or initiation of moderate hypothermia to control refractory intracranial hypertension on arrival in the continental US. Further work by our group will quantify the relationship between the size of decompression, ICP, and outcomes.

Head CT scans must also be thoroughly examined prior to operative intervention to determine the extent of skull base and sinus disruption. Should either of these conditions be present, every effort should be made to "cranialize" the disrupted sinus and/or repair the skull base disruption at the time of the original intervention. This is supported by previous analyses strongly linking CSF leak with meningitis.[2,5]

Cranial Reconstruction. Although it is often not the responsibility of the battlefield neurosurgeon to subsequently perform the reconstruction, several initial maneuvers can aid in the future cranioplasty procedure. Most neurosurgeons have adopted a reverse question mark–shaped incision to initiate a trauma flap. In the setting of frontotemporoparietal decompressions, the incision initially described by Dr. Ludwig Kempe, and reinitiated in this conflict by Dr. Jonathan Martin (Fig. 3), has the advantage of preserving, in most cases, both the occipital and superficial temporal artery angiosomes.[17] This aids wound healing both initially and following future reconstructive procedures.

In the setting of penetrating injury, the skin, bone, dura mater, and brain are violated. Though surgically difficult, reestablishing some form of dural continuity (vascularized pericranium, tensor fascia lata, and so on) in the setting of both skull base injury and sinus disruption has the advantage of initially reducing the incidence of CSF leak while subsequently providing a stable connective tissue barrier for dissection should future reconstructive procedures be necessary. Onlay graft materials like Duragen, while sufficient over the convexity, may not be sufficient as a sole reconstructive material over the skull base.

With respect to bone removal, the general recommendation is that it not be saved or implanted in the abdomen. Just over one-half of the patients with severe CNS injury had concomitant systemic infectious processes of some type.[5] When evaluating a source of infection, the inevitable fluid collection surrounding abdominal bone implantation could not be definitively excluded as a source. This resulted in explantation and discarding of the bone in almost every case. While subsequent synthetic implants are not ideal, the technology concerning their construction has improved dramatically.

Conclusions

Cranial decompression following severe closed and penetrating brain injury during OIF and OEF resulted in meaningful survival in many cases. This form of damage-control neurosurgery facilitated transport of the wounded patient over long distances without direct neurosurgical supervision. While aspects of this aggressive approach may be applicable to civilian settings, it is important to remember that these patients are different from civilian trauma patients. They are, by and large, younger and healthier than the average civilian trauma patient, and despite the significantly increased forces involved (higher-caliber missiles, blast, and blast fragmentation injury), they are outfitted with significant protective gear that shields them from some of the damage.

With respect to ongoing and future conflicts, several recommendations are appropriate. First, early, aggressive cranial decompression should be considered in almost every case of penetrating and in most cases of closed head injury. This excludes patients with injuries traversing the "zona fatalis." Second, every effort should be made, at the time of the initial operation, to ensure a watertight dural closure and adequate cranialization of violated sinuses. Third, in every case of penetrating head injury in theater, the removed bone should be discarded. Overall, the approach by the neurosurgeon should take into account the future critical and operative care the patient will receive.

Disclosure

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

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The authors certify that all individuals who qualify as authors have been listed; that the document represents valid work; that if they used information derived from another source, they obtained all necessary approvals to use it and made appropriate acknowledgments in the document; and that each takes public responsibility for it.

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Address correspondence to: Randy S. Bell, M.D., Cerebrovascular Neurosurgery and Interventional Neuroradiology, NAVMED MPT&E, and Department of Neurosurgery, National Naval Medical Center, 8901 Wisconsin Avenue, Bethesda, Maryland 20889. email: randy.s.bell@us.army.mil.

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Wartime decompressive craniectomy: technique and lessons learned

Brian T. Ragel, M.D.,[1] Paul Klimo Jr., M.D., M.P.H.,[2] Jonathan E. Martin, M.D.,[3] Richard J. Teff, M.D.,[4] Hans E. Bakken, M.D.,[5] and Rocco A. Armonda, M.D.[6]

[1]Department of Neurological Surgery, Oregon Health & Science University, Portland, Oregon; [2]Neurosurgical Service, Wright Patterson Air Force Base, Ohio; [3]Division of Neurosurgery, Connecticut Children's Medical Center, Hartford, Connecticut; [4]Department of Neurosurgery, Brooke Army Medical Center, Fort Sam Houston, Texas; [5]Department of Neurosurgery, Madigan Army Medical Center, Fort Lewis, Washington; and [6]Department of Neurosurgery, Walter Reed Army Medical Center, Washington, DC

Object. Decompressive craniectomy (DC) with dural expansion is a life-saving neurosurgical procedure performed for recalcitrant intracranial hypertension due to trauma, stroke, and a multitude of other etiologies. Illustratively, we describe technique and lessons learned using DC for battlefield trauma.

Methods. Neurosurgical operative logs from service (October 2007 to September 2009) in Afghanistan that detail DC cases for trauma were analyzed. Illustrative examples of frontotemporoparietal and bifrontal DC that depict battlefield experience performing these procedures are presented with attention drawn to the L.G. Kempe hemispherectomy incision, brainstem decompression techniques, and dural onlay substitutes.

Results. Ninety craniotomies were performed for trauma over the time period analyzed. Of these, 28 (31%) were DCs. Of the 28 DCs, 24 (86%) were frontotemporoparietal DCs, 7 (25%) were bifrontal DCs, and 2 (7%) were suboccipital DCs. Decompressive craniectomies were performed for 19 penetrating head injuries (13 gunshot wounds and 6 explosions) and 9 severe closed head injuries (6 war-related explosions and 3 others).

Conclusions. Thirty-one percent of craniotomies performed for trauma were DCs. Battlefield neurosurgeons use DC to allow for safe transfer of neurologically ill patients to tertiary military hospitals, which can be located 8–18 hours from a war zone. The authors recommend the L.G. Kempe incision for blood supply preservation, large craniectomies to prevent brain strangulation over bone edges, minimal brain debridement, adequate brainstem decompression, and dural onlay substitutes for dural closure. *(DOI: 10.3171/2010.3.FOCUS1028)*

Key Words • **battlefield** • **decompressive craniectomy** • **military**

Kocher and Cushing were the first to report cranial decompression for recalcitrant intracranial hypertension around the turn of the 19th century.[8,23] Decompressive craniectomy is a life-saving neurosurgical procedure performed for refractory elevation of ICP due to trauma, stroke and a multitude of other etiologies. Recently, authors have shown that DC improves brain tissue perfusion and oxygenation, as well as improving patient outcomes when performed for middle cerebral artery stroke and traumatic brain injury.[5,14,15,23,25]

Military neurosurgeons have a strong history of advancing the treatment of head trauma in general and penetrating head trauma in particular. The treatment of wartime penetrating head injury has evolved over the last century from Cushing's recommendation of aggressive brain debridement and watertight dural closure in World War I to minimal brain debridement instituted by Israeli physicians during the Lebanon War of 1982 with improvement in long-term seizure outcomes.[7,18] Interestingly, the surgical challenges facing neurosurgeons in today's conflicts are similar to those encountered in previous wars, with limited hospital beds, supplies, and personnel.[24] This mandates prompt operative decision-making to optimally balance patient outcome with rapid, safe transfer of the wartime injured out-of-country (as for example, US forces) or to local hospitals (as, for example, members of the Afghan Army).[1–3,17]

In the current Iraq and Afghanistan conflicts, neurosurgeons have continued to expand on previous wartime surgical lessons by combining minimal brain debridement with maximal bone removal. Decompressive craniectomy allows for the safe transfer of neurologically ill patients to tertiary military hospitals, which can be located 8–18

Abbreviations used in this paper: CJTH = Heathe N. Craig Joint Theater Hospital; DC = decompressive craniectomy; GCS = Glasgow Coma Scale; GSW = gunshot wound; ICP = intracranial pressure; IED = improvised explosive device; MVC = motor vehicle collision; NATO = North Atlantic Treaty Organization; RPG = rocket-propelled grenade.

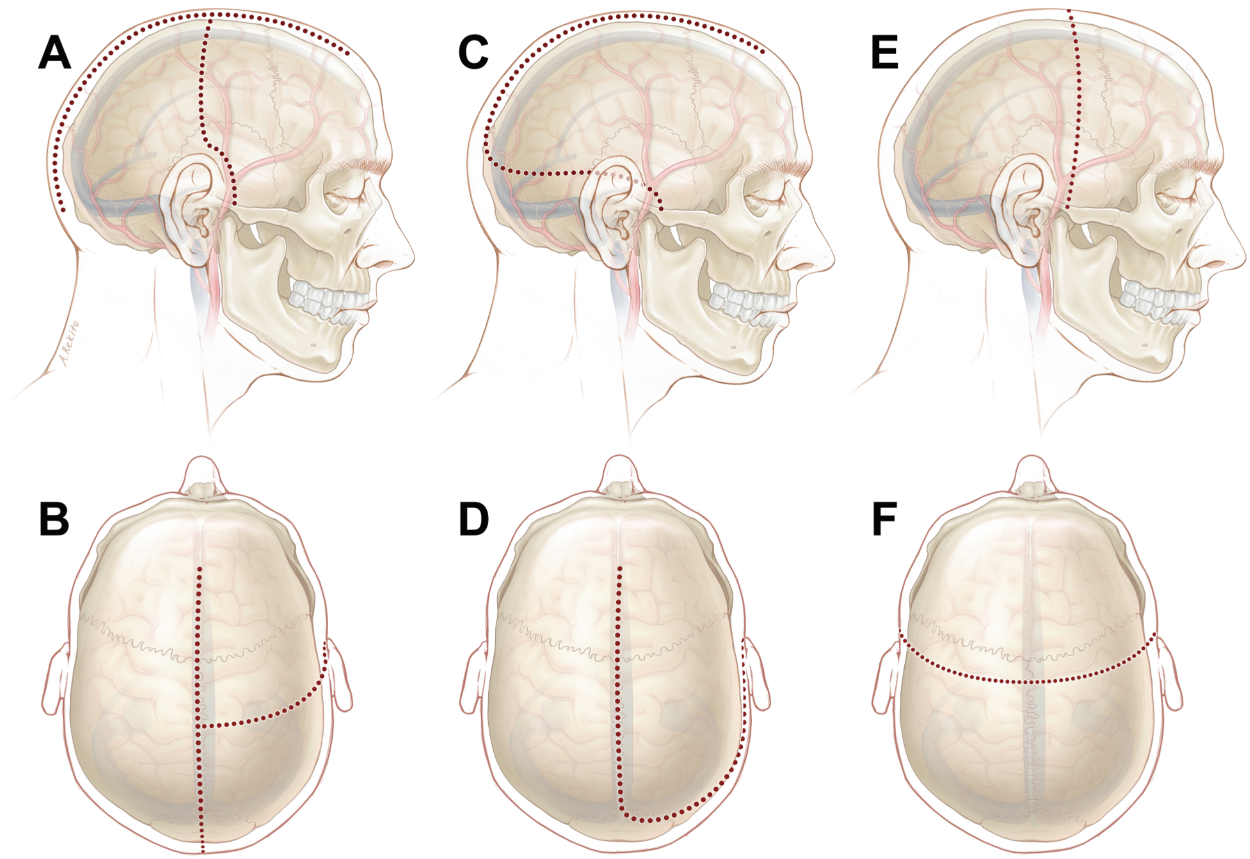

Fig. 1. Illustration depicting possible decompressive craniectomy incisions for both frontotemporoparietal and bifrontal craniectomies. Lateral **(A, C, and E)** and top-down views of the head **(B, D, and F)** depicting the midline sagittal incision with "T-bar" extension or Ludwig G. Kempe hemispherectomy incision (**A and B**, *dotted red lines*), large reverse question mark frontotemporoparietal incision (**C and D**, *dotted red lines*) and standard bicoronal incision (**E and F**, *dotted red lines*). The L. G. Kempe sagittal incision with "T-bar" extension **(A and B)** starts at the widow's peak and is carried posteriorly along the sagittal suture to the inion; the "T-bar" extension is started 2 cm anterior to the tragus at the temporal root of the zygoma, curving slightly above the ear and then incised superiorly to meet the midline sagittal suture. The large reverse question mark frontotemporoparietal scalp incision **(C and D)** starts 2 cm anterior to the tragus at the temporal root of the zygoma, curves posteriorly above and gently behind the ear to the asterion, and sweeps around the parietal boss to the midline and forward to the widow's peak. The standard bicoronal scalp incision **(E and F)** starts at the root of the zygoma, 2 cm anterior to the tragus, extends superiorly to or just behind the coronal suture, and ends at the root of the opposite zygoma, 2 cm anterior to the tragus. Note: The L.G. Kempe incision spares the posterior auricular and occipital arteries, unlike the large reverse question mark incision **(B vs D)**.

hours from the war zone.[1–3,17] These long medical flights are without neurosurgical expertise, and DC allows for maximal ICP management prior to transfer. Additionally, in comparison with the low-velocity bullets associated with penetrating head injuries in civilians, high-velocity military rounds and explosive devices impart a higher degree of global trauma to the brain, causing global swelling.[10,11,19,20] For in-country patients, early DC allowed for quicker transfer to local hospitals, which lacked the expertise or equipment to manage patients with elevated ICP.[17] Decompressive craniectomy has evolved as the procedure of choice for penetrating head injury and recalcitrant ICP elevation to address the clinical and logistical challenges present. Here we describe our technique and lessons learned utilizing DC for battlefield trauma as well as reporting our 2-year experience in Afghanistan.

Methods

War Records

At the onset of the US Air Force mission in Bagram, Afghanistan, neurosurgeons deployed to Craig Joint Theater Hospital (CJTH), Bagram Airfield, kept track of their personal war records.[17] Data collected included: sex, age, country of origin, diagnosis, mechanism of injury if applicable, operation performed, and complications. The mechanism of injury was classified as: gunshot wound (GSW), improvised explosive device (IED), rocket-propelled grenade (RPG), land mine, motor vehicle collision (MVC), or fall from height. Battlefield injuries were defined as injuries sustained by soldiers while in the line of duty.

Incision Types

Three types of incisions were used by the authors

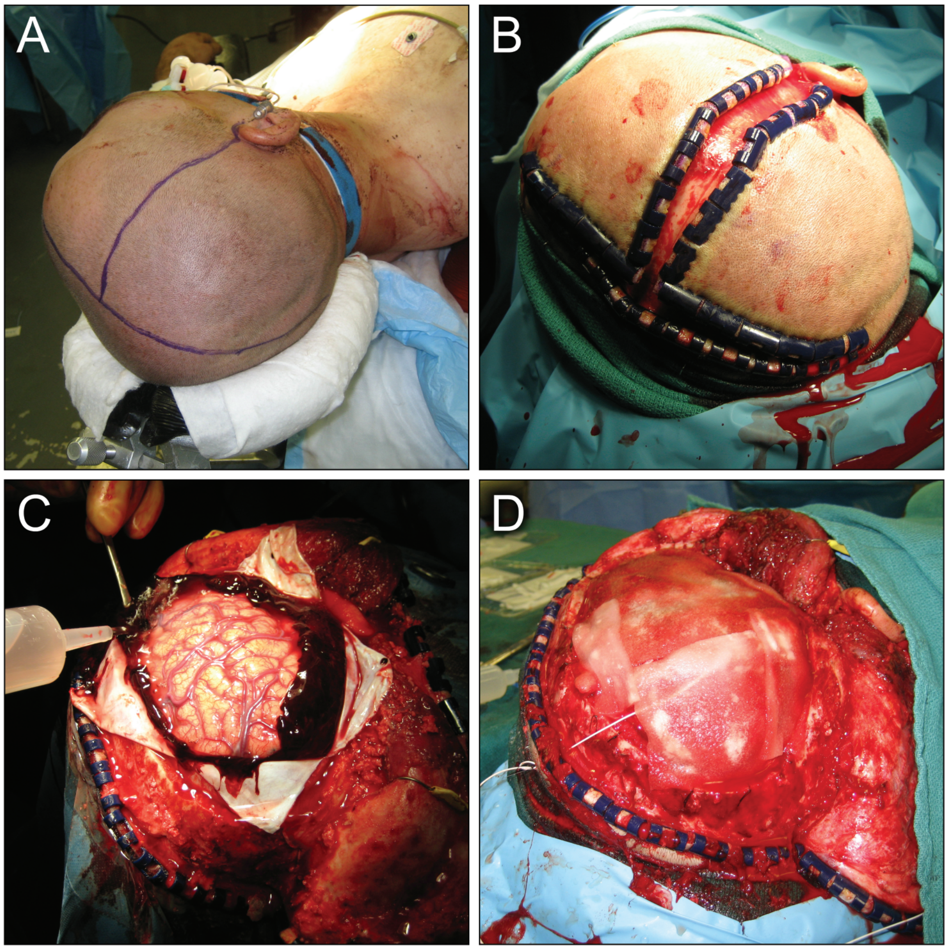

Fig. 2. Intraoperative photographs depicting the L. G. Kempe hemispherectomy incision and frontotemporoparietal DC. **A and B:** Patient position with the scalp marked **(A)** and incised **(B)**. **C:** Frontotemporoparietal DC with cruciate durotomy. **D:** Dural substitute onlay graft.

when performing wartime DCs: the midline sagittal incision with "T-bar" extension (the hemipherectomy incision of Ludwig G. Kempe)[16] (Fig. 1A and B and Fig. 2), the standard large reverse question mark (Fig. 1C and D), and the bicoronal incision (Fig. 1E and F).[16] For the L.G. Kempe incision, the scalp was incised overlying the sagittal suture from the widow's peak to the inion with a "T-bar" extension starting 1–2 cm anterior to the tragus at the temporal root of the zygoma, and extending superiorly to meet the midline sagittal incision approximately 1 cm behind the coronal suture (Fig. 1A and B and Fig. 2).[16] Closure involved placing a stay stitch at the apex of the wound followed by galea sutures, staples, and removal of the apical suture. The large reverse question mark scalp incision starts 1–2 cm anterior to the tragus at the root of the zygoma, curving posteriorly above and gently behind the ear toward the asterion. This incision then gently curves around the parietal boss to the midline and forward to the widow's peak. The scalp is incised and reflected anteriorly as a myocutaneous flap of scalp and temporalis muscle (Fig. 1C and D). The standard bicoronal scalp incision is performed, starting at the root of the zygoma, 1–2 cm anterior to the tragus, extending superiorly to or just behind the coronal suture and ending at the opposite root of the zygoma, 2 cm anterior to the tragus. The scalp is reflected anteriorly as a myocutaneous flap (Fig. 1E and F).

Surgical Technique: Frontotemporoparietal DC

Frontotemporoparietal craniectomies were performed as illustratively detailed in Fig. 3. Bur holes are placed at the pterion (exposing the frontal and temporal dura), at the root of the zygoma, about 2 cm above the asterion (to avoid the transverse sinus) inferior to the parietal boss, and superior to the parietal boss, and an additional one or two bur holes are placed 2 cm off midline on the ipsilateral side of the planned craniectomy.[9] Dura is stripped from the bur holes using a dissector. When turning the bone flap with the craniotome, it is important to hug the floor of the middle fossa above the mastoid air cells to get as low as possible, extending back staying at least 2 cm above the asterion and lambdoid suture, around the parietal boss toward midline, leaving a 2-cm lip of bone adjacent to the lambdoid and sagittal sutures.[9] Additional removal of the squamous portion of the temporal bone and greater wing of the sphenoid bone is accom-

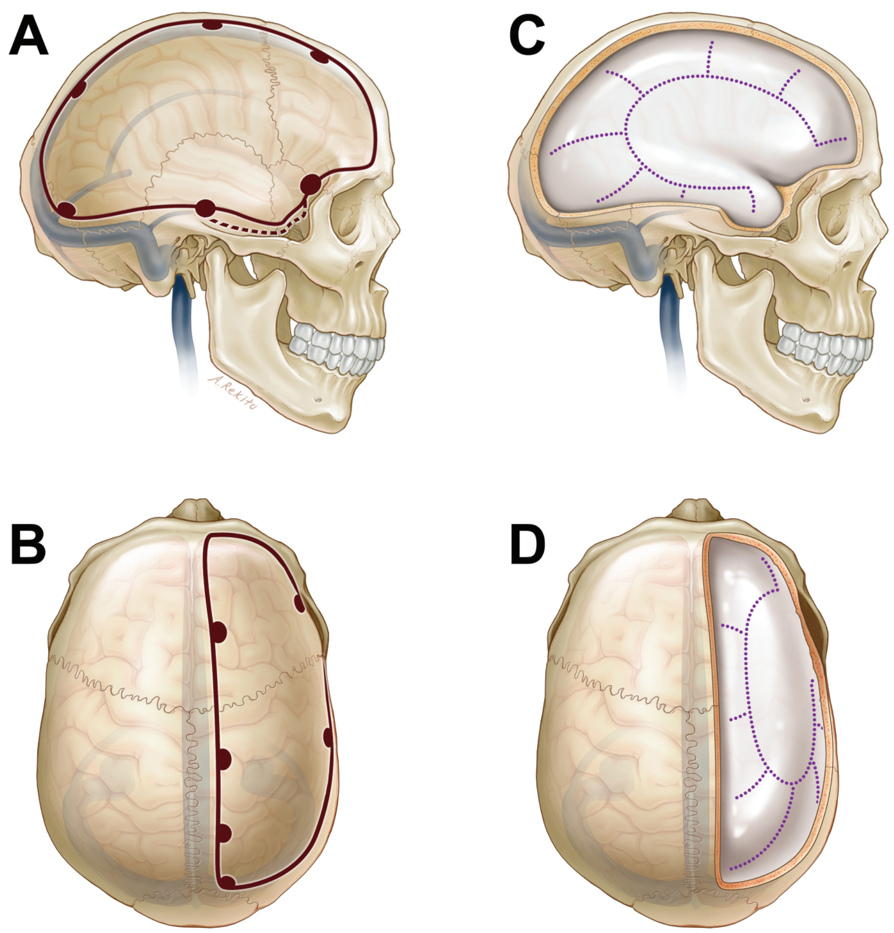

Fig. 3. Illustration depicting frontotemporoparietal DC. **A and B:** Lateral **(A)** and top-down **(B)** views of the head showing the craniectomy outline *(solid red line)* and the bur holes placed at the pterion (exposing frontal and temporal dura), at the root of the zygoma, about 2 cm above the asterion (to avoid the transverse sinus) inferior to the parietal boss, and superior to the parietal boss and an additional one or two bur holes 2 cm off midline on the ipsilateral side of the craniectomy. When turning the bone flap, it is important to hug the floor of the middle fossa above the mastoid air cells to get as low as possible, extending back and around the parietal boss toward midline, leaving a 2-cm lip of bone adjacent to the sagittal suture. **C and D:** Lateral **(C)** and top-down **(D)** view of the C-shaped dural incision (**C and D**, *dotted purple line*), starting in the midportion of the temporal lobe curving around the sylvian point and ending in the frontal region. Spoke-wheel relief cuts are made to allow for brain swelling. Care is taken to stay 2 cm off the midline to avoid superior sagittal sinus bleeding.

plished with a rongeur, removing bone to the floor of the middle fossa. This maneuver will allow maximal bony decompression of the brainstem. Bone edges and exposed mastoid air cells are waxed. The dura is incised in a C-shaped fashion starting at the anterior tip of the temporal lobe, curving back about 8 cm crossing the sylvian fissure, and ending in the frontal region. Spoke-wheel relief cuts are made to allow for brain swelling. Care is taken to stay 2 cm off midline to avoid bleeding from the superior sagittal sinus (Fig. 3). Dural leaves are laid over the surface of the brain, and a large piece of dural substitute is placed over the opened dura (Fig. 2D). Alternatively, the dura can be opened in a cruciate fashion (Fig. 2C). Bone edges are waxed and dural tack-up sutures are placed for epidural hemostasis. The scalp is closed by reapproximating the galea and staples are applied.

Surgical Technique: Bifrontal DC

Bifrontal craniectomies were performed as illustratively detailed in Fig. 4. Standard bicoronal scalp incision was performed (Fig. 1E and F). Bur holes are placed in the pterion, root of the zygoma just below the superior temporal line, and straddling the superior sagittal sinus. Bilateral frontal and subtemporal craniectomies are performed, exposing the frontal and anterior temporal lobes. Additional removal of the squamous portion of the temporal bone and greater wing of the sphenoid bone is accomplished with a rongeur, removing bone to the floor of the middle fossa. Alternatively, a strip of bone can be left over the sagittal sinus for protection (not depicted in figure). The dural cuts are depicted in Fig. 4 by dotted lines running parallel to the superior sagittal and parallel to the posterior bone edge. Mitral valve–type dural

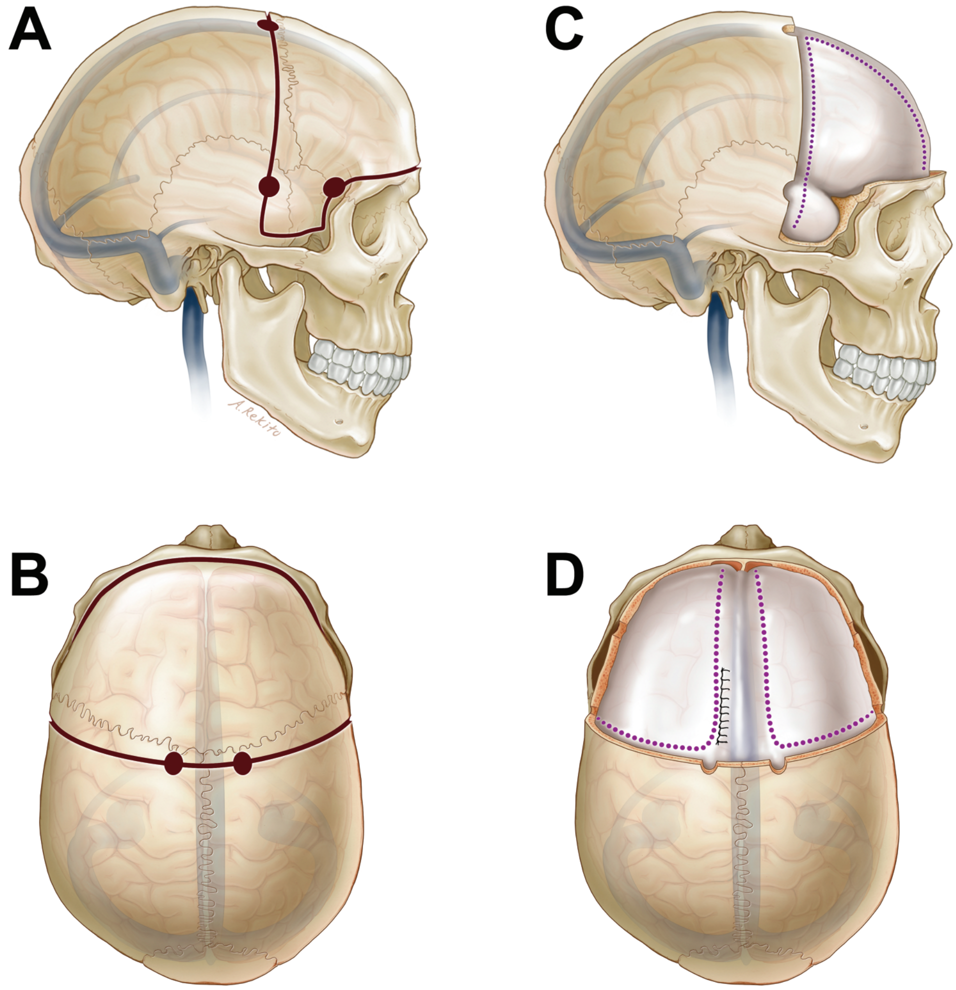

Fig. 4. Illustration depicting bifrontal DC. **A and B**: The *solid line* and *bur hole marks* show a standard bifrontal craniectomy with bur holes placed in the pterion, posterior to the pterion just below the superior temporal line, and straddling the superior sagittal sinus **(A and B)**. **C and D:** The dural cuts are depicted by *dotted lines* running parallel to the superior sagittal sinus and parallel to the posterior bone edge. Note: Mitral valve–type dural incisions were made due to the penetrating nature of injuries seen, versus standard Shelberg procedure with open fish mouth cuts made along the floor of the anterior fossa, with release of the inferior aspect of the interhemispheric falx.

incisions are made due to the penetrating nature of the injuries seen, as compared to a standard Shelberg procedure with open fish-mouth cuts made along the floor of the anterior fossa with release of the inferior aspect of the interhemispheric falx.

Technique: Bone Flap Management

Three bone flap scenarios were encountered. For US soldiers, bone flaps were discarded because of infection fears and excellent cosmesis results with 3D methyl methacrylate prosthetic implants.[22] For other NATO forces, bone flaps were placed in an abdominal subcutaneous pocket, preferably the left lower quadrant to avoid contamination by feeding tube placement and to decrease confusion with an appendectomy scar. For Afghan patients, bone flaps were washed with bacitracin irrigation, sterilely wrapped, and stored at –30°F for later autologous cranioplasty.

Results

Decompressive Craniectomy

Two hundred and ten neurosurgical operations were performed in 185 patients at CJTH from October 2007 through September 2009. Of these procedures, 90 were craniotomies performed for wartime trauma (Table 1), including 28 DCs (31% of craniotomies) in 27 patients. Of 19 craniotomies performed in NATO soldiers, 8 (42%) were DCs; the average age of these patients was 25.7 years (range 19–38 years). Of 43 craniotomies performed in members of the Afghan military and security forces, 14 (33%) were DCs; the average age of these patients was 24.3 years (range 20–32 years). Of 7 craniotomies performed in enemy combatants, 1 (14%) was a DC. Of 21 craniotomies performed in local Afghan civilians for war-related injuries, 5 (24%) were DCs; the average age of these patients was 14.2 years (range 3–34 years) for wartime related injuries.

TABLE 1: Decompressive craniectomies performed for wartime trauma by military neurosurgeons in Afghanistan from October 2007 to September 2009 during Operation Enduring Freedom

						Injury & Mechanism†			
						PHI		CHI	
Patient Category	Craniotomies	DCs (% of Craniotomies)	FTP DCs	BF DC	SO DC	GSW	Expl	Expl	Other
NATO	19	8 (42)	5	1	2	6	0	2	0
AMSF	43	14 (33)	12	2	0	6	2	3	3
enemy combatants	7	1 (14)	0	1	0	0	0	1	0
local Afghan civilians w/ war-related injuries	21	5 (24)	7	3	0	1	4	0	0
total	90	28 (31)	24	7	2	13	6	6	3

* Values represent numbers of procedures. Abbreviations: AMSF = Afghan Military and Security Forces; BF = bifrontal; CHI = closed head injury; Expl = Explosion; FTP = frontotemporoparietal; PHI = penetrating head injury; SO = suboccipital.
† Numbers of DCs stratified by type and mechanism of injury as well as by patient category.

Three types of DCs were performed: frontotemporoparietal, bifrontal, and suboccipital. Of the 28 DCs performed over the time studied, 24 (86%) of the DCs were frontotemporal, 7 (25%) were bifrontal, and 2 (7%) were suboccipital. These procedures were performed for management of 19 penetrating head injuries (mechanism of injury: GSW in 13 cases and explosion in 6), and 9 severe closed head injuries (6 due to war-related explosions, 2 to MVCs, and 1 to fall from a height).

All NATO soldiers undergoing neurosurgical operations for trauma were medically evacuated to the US Landstuhl Regional Medical Center in Landstuhl, Kirchberg, Germany. United States soldiers were subsequently transported back to the US 3–4 days after injury.[2,22] Afghanistan military and security forces were transferred to the local Afghanistan Army hospital in Kabul after their acute surgical issues had resolved (usually 1–2 weeks), whereas local Afghan civilians sustaining wartime injuries were discharged home (usually in 1–2 weeks).

Complications

One patient who underwent DC was returned to the operating room for craniectomy expansion and there were 4 postoperative deaths (14%, 4/28). Craniectomy expansion was performed due to strangulating brain herniating over bone edges. All deaths were attributed to the initial mechanism of injury, 3 penetrating head wounds (caused by a GSW in 1 case, mortar in 1, and an IED in 1) and 1 severe closed head injury after fall from a height.

Case Illustrations

Case 1—Frontotemporoparietal Craniotomy With Brain Herniation

This case illustrates herniating brain over bone edges with the threat of subsequent strangulation due to an inadequate DC (Fig. 5), thus prompting larger DCs. This 15-year-old Afghan boy was in a mortar attack, resulting in a penetrating head injury, with the shrapnel entrance wound in the right parietal region, traversing brain to lodge in the left frontal lobe. Examination revealed a Glasgow Coma Scale (GCS) score of 14 and left hemiplegia. The patient underwent a right frontotemporoparietal DC centered at the shrapnel entrance site with minimal brain debridement and repair of dural laceration. Intraoperatively, the brain swelled, necessitating leaving the bone flap off. An external ventricular drain was placed on the left and subsequently removed after several days of normal ICP measurements. Neurologically, the patient regained motor function on his left side with antigravity strength noted in the left leg and trace movement in his left arm on discharge.

Case 2—Frontotemporoparietal DC

This case illustrates an adequate wartime frontotemporoparietal DC (Fig. 6). This 28-year-old NATO soldier was wounded by an IED and sustained an open depressed skull fracture with penetrating metal fragments. He underwent a right frontotemporoparietal DC with sufficient bone removal to accommodate swelling without strangulation of brain over bone edges. Postoperatively, he was transported to Landstuhl Regional Medical Center, arriving within 48 hours of the IED injury.

Case 3—Bifrontal DC

This case illustrates an adequate wartime bifrontal DC (Fig. 7). This 14-year-old Afghan boy was struck by shrapnel from an RPG. The boy had a penetrating head wound with an entrance site in the left frontal region; the shrapnel had traversed the right frontal lobe, ricocheting off the inner skull, and finally come to rest in the right occipital lobe (Fig. 7). A bifrontal DC was performed to accommodate severe bilateral frontal lobe swelling. Postoperatively, the patient was neurologically intact, but emotionally labile at 3-month follow up.

Discussion

Thirty-one percent of cranial procedures performed by battlefield neurosurgeons in Afghanistan were DCs.

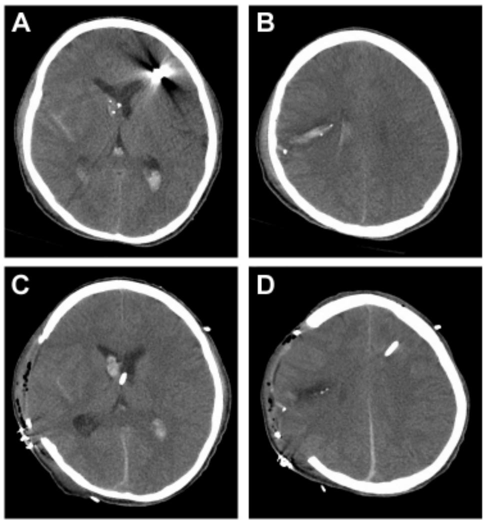

Fig. 5. Axial CT scans showing example of brain herniation over bone edges due to an inadequate DC. **A and B:** Preoperative scans depicting shrapnel wound to the head after mortar attack with the fragment traversing from the right parietal to the left frontal lobe. **C and D:** Scans obtained after right frontoparietal craniectomy, showing brain herniating over bone edges with threat of brain strangulation. Note: As a result of experience with these types of cases, larger craniectomies were performed for penetrating head injuries.

The wartime lessons learned include an early decision regarding the performance of DC, choice of scalp incision, brainstem decompression, dural closure with onlay dural substitutes, and considerations regarding future cranial reconstruction. Finally, we give a historical prospective of the management of penetrating head injuries and add maximal bony decompression and dural onlay substitutes in the management of these injuries.

Wartime DC: Rationale and Decision Making

The decision for early DC was based upon the ability to safely transfer patients with wartime head injuries to hospitals both far (tertiary military hospitals for injured NATO forces) and near (community hospitals without adequate intensive care units for local patients).[1–3,17] For NATO soldiers, DC allows for the safe transfer of neurologically ill patients to tertiary military hospitals, located 8–18 hours from a war zone.[1–3,17] These long medical flights are without neurosurgical expertise; thus DC allows maximal ICP management prior to transfer. For in-country patients (for example, members of the Afghan Army), early DC allowed for quicker transfer to local community hospitals. Afghan hospitals lacked the expertise or equipment to manage patients with elevated ICP.[17] This lack of in-country expertise, combined with a wartime military hospital with limited resources (intensive care unit beds, personnel, equipment), necessitated an aggressive approach for maximal ICP management in these patients. Performing a DC permitted the safe transfer of in-country patients to local hospitals while ensuring hospital readiness to treat the next wartime wounded.

Wartime DCs fell into 3 categories. First, patients with penetrating head injuries were prone to significant brain swelling because of the diffuse trauma caused by high-velocity military rounds and explosive devices.[10,11,19,20] Large DCs were performed because traditional craniotomy bone flaps could not be replaced and resulted in brain herniation over bone edges (Fig. 5 vs Fig. 6). The second group consisted of patients with persistent intracranial hypertension despite traditional ICP management maneuvers, including invasive ICP monitoring, administration of mannitol, administration of hypertonic saline, sedation, administration of paralytic agents, and external ventricular drainage. Finally, the third group were patients who the neurosurgeon believed were highly likely to develop intracranial hypertension, making long transport flights without neurosurgical care unsafe.[3]

Lessons Learned: Performing Wartime DCs

Management of wartime head trauma involves focused neurological examination, review of head CT findings, and a quick decision regarding surgery. Patient hemodynamic stabilization was a priority, with treatment of life-threatening bleeding attended to prior to or in conjunction with the craniotomy. Without access to MR imaging equipment, CT angiograms proved valuable for evaluation of intra- and extracranial vascular injury due to a roughly 30% incidence of cerebrovascular injury.[3] Because of the high incidence of cerebrovascular injury,

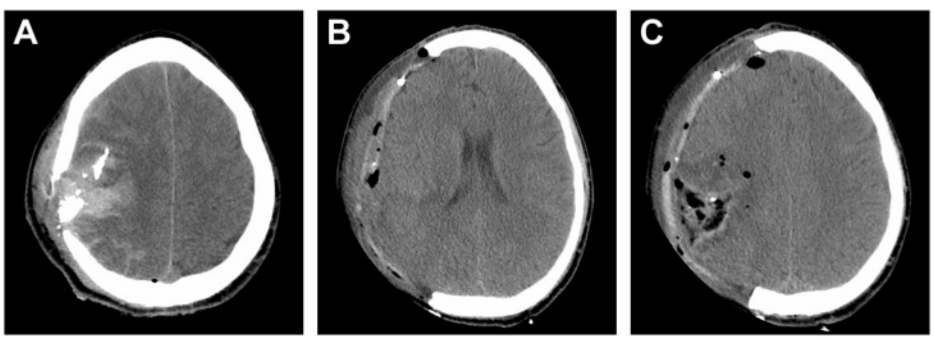

Fig. 6. Axial CT scans obtained in a patient who had a penetrating head injury from an IED before **(A)** and after **(B and C)** right frontotemporoparietal DC. **A:** Scan showing imploded bone and metal fragments from IED embedded in the right frontal and parietal lobes with surrounding contusion. **B and C:** Scans showing large, right frontotemporal parietal decompressive craniectomy. Note: Sufficient bone removal allows for brain swelling without strangulation of brain over bone edges.

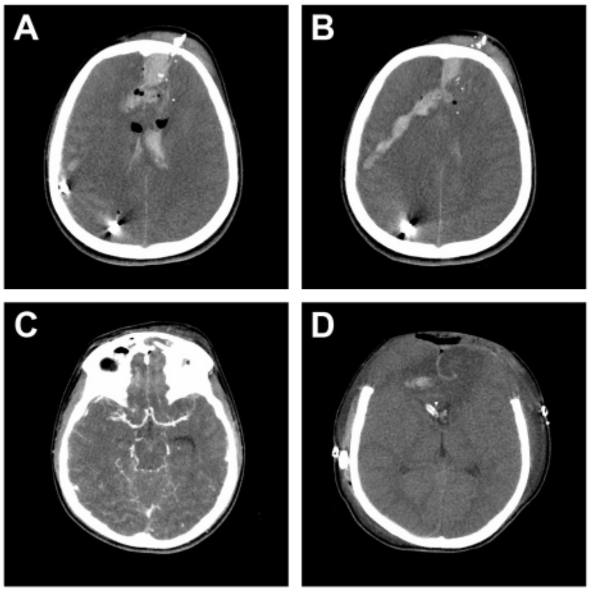

Fig. 7. Computed tomography of the head depicting penetrating head injury caused by shrapnel from RPG attack. **A:** Axial CT showing bullet entering left frontal region, traversing the right frontal lobe, ricocheting off the inner skull, and finally resting in the right occipital lobe. **B:** Axial CT angiogram showing intact anterior circulation arteries. **C:** Bifrontal DC performed to accommodate severe bilateral frontal lobe swelling. Note: Frontal bone removal performed so as not to leave overlying bone edges, which can strangulate herniating brain.

exposure of the internal carotid artery in the neck for proximal control was always considered when injury to the intracranial portion of the artery was suspected.

Frontotemporoparietal DCs were performed for unilateral injuries and/or swelling, whereas bifrontal craniectomies were preferred for bilateral frontal lobe and/or anterior temporal lobe injuries. Particular attention was paid to making the craniotomy as large as possible to prevent herniating brain tissue from becoming lacerated and ischemic at the cut bone edges. To ensure adequate brainstem decompression, the squamous portion of the temporal bone and lateral greater wing of the sphenoid were removed. This allowed for maximal bone removal along the lateral and anterior aspect of the middle fossa. The durotomy was carried to the anterior temporal tip. Finally, an anterior temporal lobectomy was performed if needed. These maneuvers allow the temporal lobe to swell laterally, thus preventing medial displacement of the mesial temporal lobe and subsequent brainstem compression.

Intraparenchymal injuries were debrided without overly aggressive pursuit of deep and small bone or foreign fragments, and large hematomas were evacuated. The first surgery often represented "damage control" surgery with an emphasis on quick removal of mass lesions, homeostasis, and a quick decision with respect to DC; deep imploded bone fragments and foreign bodies were not chased.[3] Second or third operations were sometimes necessary for further debridement of necrotic brain tissue, and it was found that deep imploded bone fragments and foreign bodies would often deliver themselves to the surface at this time. Interestingly, for repeat surgeries the choice of scalp incision became increasingly important.

Lessons Learned: Scalp Incisions

Early in the Iraq experience, neurosurgeons at Walter Reed Army Medical Center (WRAMC, Washington DC) were noting breakdown of the reverse question mark incision along the posterior curve, as well as in soldiers with complex scalp wounds. The posterior portion of the scalp flap, overlying the lambdoid suture, is subject to dependent swelling and more surface contact, especially on long evacuation flights. Also, when the reverse question mark incision is used in the setting of complex scalp wounds it can result in islands of devascularized scalp, prone to necrosis. Because of this, the Ludwig G. Kempe incision for hemispherectomy came into favor (Figs. 1 and 2).[16] This midline-sagittal incision with "T-bar" extension offers the advantage of limiting the dependent portion of the scalp incision and takes advantage of the robust blood supply to the scalp. Unlike the reverse question mark incision, the L.G. Kempe incision preserves the occipital and posterior auricular arterial supply to the scalp flap, making the posterior portions less dependent on the superficial temporal, frontal, and supraorbital arteries (Fig. 1B vs Fig. 1D). We also found this incision to be versatile in managing complex scalp lacerations in terms of taking advantage of the arterial blood supply to the scalp with less likelihood of creating islands of devascularized scalp. The long-term WRAMC experience with the L.G. Kempe incision showed less posterior wound breakdown and less temporalis muscle atrophy and easier cranioplasty exposure (R.A.A., J.E.M., R.J.T, and H.E.B.). This incision also allows for easy surgical access to the contralateral side by placing a second "T-bar" extension if bilateral surgical access is needed. However, if bilateral craniotomies were surgically planned, a bicoronal incision was preferred.

Lessons Learned: Dural Closure and Cranial Reconstruction

Cushing recommended watertight dural closure in World War I to help prevent infection.[7] However, in our experience dural substitutes used in an onlay fashion obviate the need for watertight dural closure (Fig. 2D). Dural onlay substitutes create a barrier between swollen, injured brain and the myocutaneous scalp flap. We found that performing watertight closures with harvested pericranial grafts or suturable dural substitutes was time consuming. Keeping operative times to a minimum was imperative in polytrauma patients prone to blood loss and worsening coagulopathy. Also, war zone military hospitals have finite supplies (for example, blood products) and personnel (for example, neurosurgeons) that are stretched thin during mass casualty scenarios. Economic use of these resources is crucial to effective management of all injured patients. With this in mind, cranial reconstruction was accomplished if time permitted.

Future cranioplasty and cranial reconstructive procedures were aided by preservation of the orbital bandeau and skull base reconstruction (Fig. 8). Bone flaps from US

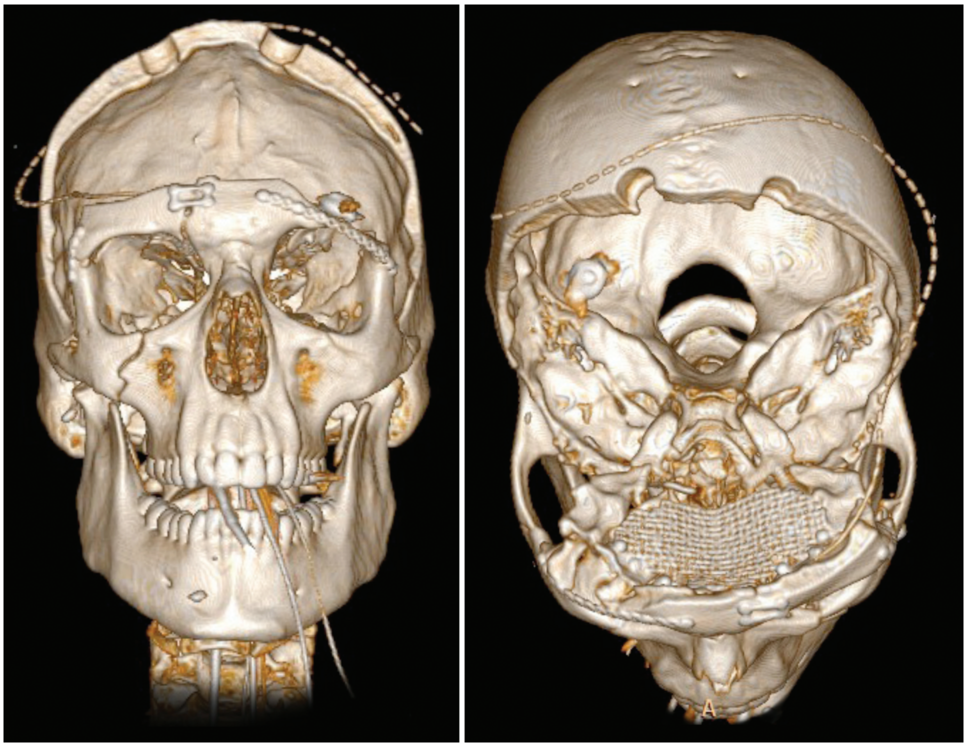

Fig. 8. Reconstructed CT of the skull after bifrontal and subtemporal craniectomy illustrating orbital bandeau **(left)** and anterior fossa reconstruction **(right)**. Reconstructing the orbital bandeau prevents ptosis of the frontal lobe into the orbit and aids in future reconstructive procedures **(left)**. Skull base reconstruction with titanium mesh prevents herniation of the frontal lobes into the orbit and ethmoid sinuses **(right)**. Note: The image on the left provides a good example of a bitemporal subtemporal craniectomy for treatment of brainstem compression.

patients were routinely discarded because of fear of infection and because of the excellent cosmetic results obtained with 3D custom-fit prosthetic implants.[22] Preservation of the orbital bandeau with autologous bone and titanium plates prevented ptosis of the frontal lobes, making future reconstruction easier. Anatomical restoration of the skull base was accomplished with contoured titanium sheets with or without opposed split-thickness calvarial grafts and dural onlay substitutes (Fig. 8). This restores separation of brain from the orbit and nasal sinuses, reducing infection risk and CSF leakage and aiding in an aesthetic orbitofacial reconstructive outcome.

Neurosurgical Management of Wartime Head Trauma: Cushing to the Present

The goal in managing head injuries is to prevent secondary brain injury.[6,26] Over the last century the management of wartime head trauma has evolved from those initially described during World War I to current conflicts. Cushing described his observations of 250 penetrating head injuries during World War I, advocating aggressive wound debridement of fragments at the entrance and watertight dural closure.[7] After analyzing World War II and Korean War head trauma data, Matson[21] recommended addressing life-threatening injuries first, followed by treatment of penetrating head injuries with cranial decompression, aggressive debridement, watertight closure, and cranial reconstruction. In Vietnam, Matson's principles of large craniotomies for the treatment of penetrating head injuries were continued.[12,13] It was not until the Israeli-Lebanese conflicts of the 1980s that less aggressive or even no surgical intervention was associated with better seizure outcomes noted after penetrating head wounds.[4,12,18,19] Interestingly, changes in the management of these injuries have been made due to medical and technological advancements. For example, the ability to obtain CT images of the head in the Israeli conflict allowed for minimal brain debridement. The current conflicts in Iraq and Afghanistan further these lessons learned from previous conflicts with the addition of aggressive bony decompression and dural onlay substitutes.[3]

In an analysis of the Iraq experience, 205 early DCs for severe head injury were reported, with the patients who underwent early DC having significantly lower initial GCS scores than patients undergoing craniotomy alone or no surgery.[3] This difference in GCS scores was not noted on hospital discharge to rehabilitation indicating that DC was associated with improvement in GCS scores.[3] Bell et al.,[3] have attributed the high rate of DC in the wartime scenario to battlefield decision making. In the Iraq experience, patients with focal intracranial injuries, higher GCS scores, and limited intracranial exposure to blast injuries were treated with craniotomy alone in theater.[3] These patients were often extubated postoperatively with the ability to follow their clinical neurological status prior to transfer out of the war theater.[3] In comparison, patients with low GCS scores, diffuse brain injury, and exposure to explosive injuries (for example, IED injuries) were more likely treated with early DC.[3] These neurologically ill patients remained intubated and sedated for transfer out of the war theater.[3]

Conclusions

Decompressive craniectomy has evolved as the procedure of choice for penetrating head injury and recalcitrant elevation of ICP, to address the clinical and logistical challenges present in military hospitals in Iraq and Afghanistan. Battlefield neurosurgeons use DC to allow for safe transfer of neurologically ill patients to tertiary military hospitals, which can be located 8–18 hours from a war zone. These long medical flights are without neurosurgical expertise, and DC allows maximal ICP management prior to transfer. For in-country patients, early DC allows for quicker transfer to local hospitals that lack the expertise or equipment to manage patients with elevated ICP. We recommend the L.G. Kempe incision for blood supply preservation, large craniectomies to prevent brain strangulation over bone edges, minimal brain debridement, adequate brainstem decompression, and dural onlay substitutes for dural closure.

Disclosure

The opinions and assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of the US Air Force, the US Army, the Department of Defense, or the Department of Veterans Affairs.

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: Ragel, Klimo, Armonda. Acquisition of data: all authors. Analysis and interpretation of data: Ragel, Klimo, Armonda. Drafting the article: Ragel, Klimo, Armonda. Critically revising the article: all authors. Reviewed final version of the manuscript and approved it for submission: Ragel, Martin, Teff, Bakken.

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Address correspondence to: Brian T. Ragel, M.D., Department of Neurological Surgery, Mail Code CH8N, Oregon Health & Science University, 3303 SW Bond Avenue, Portland, Oregon 97239. email: brian.ragel@gmail.com.

Cranioplasty complications following wartime decompressive craniectomy

Frederick L. Stephens, M.D., Correy M. Mossop, M.D., Randy S. Bell, M.D., Teodoro Tigno Jr., M.D., Michael K. Rosner, M.D., Anand Kumar, M.D., Leon E. Moores, M.D., and Rocco A. Armonda, M.D.

Department of Neurosurgery, Walter Reed Army Medical Center, Washington, DC; and Department of Neurosurgery, National Naval Medical Center, Bethesda, Maryland

Object. In support of Operation Iraqi Freedom (OIF) and Operation Enduring Freedom-Afghanistan (OEF-A), military neurosurgeons in the combat theater are faced with the daunting task of stabilizing patients in such a way as to prevent irreversible neurological injury from cerebral edema while simultaneously allowing for prolonged transport stateside (5000–7000 miles). It is in this setting that decompressive craniectomy has become a mainstay of far-forward neurosurgical management of traumatic brain injury (TBI).

As such, institutional experience with cranioplasty at the Walter Reed Army Medical Center (WRAMC) and the National Naval Medical Center (NNMC) has expanded concomitantly. Battlefield blast explosions create cavitary injury zones that often extend beyond the border of the exposed surface wound, and this situation has created unique reconstruction challenges not often seen in civilian TBI. The loss of both soft-tissue and skull base support along with the need for cranial vault reconstruction requires a multidisciplinary approach involving neurosurgery, plastics, oral-maxillofacial surgery, and ophthalmology. With this situation in mind, the authors of this paper endeavored to review the cranial reconstruction complications encountered in these combat-related injuries.

Methods. A retrospective database review was conducted for all soldiers injured in OIF and OEF-A who had undergone decompressive craniectomy with subsequent cranioplasty between April 2002 and October 2008 at the WRAMC and NNMC. During this time, both facilities received a total of 408 OIF/OEF-A patients with severe head injuries; 188 of these patients underwent decompressive craniectomies in the theater before transfer to the US. Criteria for inclusion in this study consisted of either a closed or a penetrating head injury sustained in combat operations, resulting in the performance of a decompressive craniectomy and subsequent cranioplasty at either the WRAMC or NNMC. Excluded from the study were patients for whom primary demographic data could not be verified. Demographic data, indications for craniectomy, as well as preoperative, intraoperative, and postoperative parameters following cranioplasty, were recorded. Perioperative and postoperative complications were also recorded.

Results. One hundred eight patients (male/female ratio 107:1) met the inclusion criteria for this study, 93 with a penetrating head injury and 15 with a closed head injury. Explosive blast injury was the predominant mechanism of injury, occurring in 72 patients (67%). The average time that elapsed between injury and cranioplasty was 190 days (range 7–546 days). An overall complication rate of 24% was identified. The prevalence of perioperative infection (12%), seizure (7.4%), and extraaxial hematoma formation (7.4%) was noted. Twelve patients (11%) required prosthetic removal because of either extraaxial hematoma formation or infection. Eight of the 13 cases of infection involved cranioplasties performed between 90 and 270 days from the date of injury ($p = 0.06$).

Conclusions. This study represents the largest to date in which cranioplasty and its complications have been evaluated in a trauma population that underwent decompressive craniectomy. The overall complication rate of 24% is consistent with rates reported in the literature (16–34%); however, the perioperative infection rate of 12% is higher than the rates reported in other studies. This difference is likely related to aspects of the initial injury pattern—such as skull base injury, orbitofacial fractures, sinus injuries, persistent fluid collection, and CSF leakage—which can predispose these patients to infection. *(DOI: 10.3171/2010.2.FOCUS1026)*

Key Words • **cranioplasty** • **craniectomy** • **traumatic brain injury**

The management of traumatic brain injury in the combat theater during OIF and OEF-A presents a unique challenge given the austere environment in which the military neurosurgeon finds himself. Forward neurosurgical treatment of traumatic brain injury has been defined in this era by immediate decompressive craniectomy. This procedure has become established to prevent irreversible neurological injury from cerebral edema associated with blast-induced injury during stateside transport, which can involve more than 7000 miles. Principles of damage-control neurosurgery are applied and include decompressing the brainstem, achieving homeostasis, and restoring anatomical continuity of the skull base when possible. The violent force of a blast

Abbreviations used in this paper: GCS = Glasgow Coma Scale; GOS = Glasgow Outcome Scale; NNMC = National Naval Medical Center; OEF-A = Operation Enduring Freedom-Afghanistan; OIF = Operation Iraqi Freedom; WRAMC = Walter Reed Army Medical Center.

TABLE 1: Patient demographics

Characteristic	Value
mean age (yrs)	26 ± 6.4
mean initial GCS score	7.5 ± 4.0
mean time interval to cranioplasty (days)	190 ± 91

TABLE 2: Injury types and mechanisms

Parameter	No. of Patients (%)
injury type	
penetrating head injury	93 (86)
closed head injury	15 (14)
mechanism of injury	
explosive blast	72 (67)
gunshot wound	30 (28)
motor vehicle accident	3 (2.7)
helicopter crash	1 (0.9)
fall	1 (0.9)
stabbing	1 (0.9)

explosion creates a complex cavitary injury zone that extends beyond the limits of the disrupted surface wounds. Reconstructing these patients presents unique challenges not commonly seen in the civilian sector. The loss of both a functioning soft-tissue envelope and skull base support as well as cranial vault disruption requires the multidisciplinary work of neurosurgery, reconstructive plastics, oral-maxillofacial surgery, and ophthalmological surgery. Craniofacial-orbital reconstruction in each patient must be individualized for the specific injury pattern. Our purpose in this report was to review the cranial reconstruction complications encountered in these combat casualties and to introduce strategies to avoid and manage such challenging cases.

Methods

Study Design

A retrospective database review was conducted for all soldiers injured in OIF and OEF-A who had undergone decompressive craniectomy and subsequent cranioplasty between April 2002 and October 2008 at the WRAMC and NNMC. During this time, both facilities received a total of 408 OIF and OEF-A patients with head injuries, 188 of whom underwent decompressive craniectomies in the combat theater before transfer to the US. Criteria for inclusion in our study consisted of either a closed or a penetrating head injury sustained in combat operations, resulting in the performance of a decompressive craniectomy and subsequent cranioplasty at either the WRAMC or NNMC. Excluded were all those patients for whom primary demographic data could not be verified. Also excluded from the study were patients initially hospitalized at the WRAMC or NNMC for an initial injury but who underwent cranioplasty at an outside facility.

Abstracted data included age at the time of initial

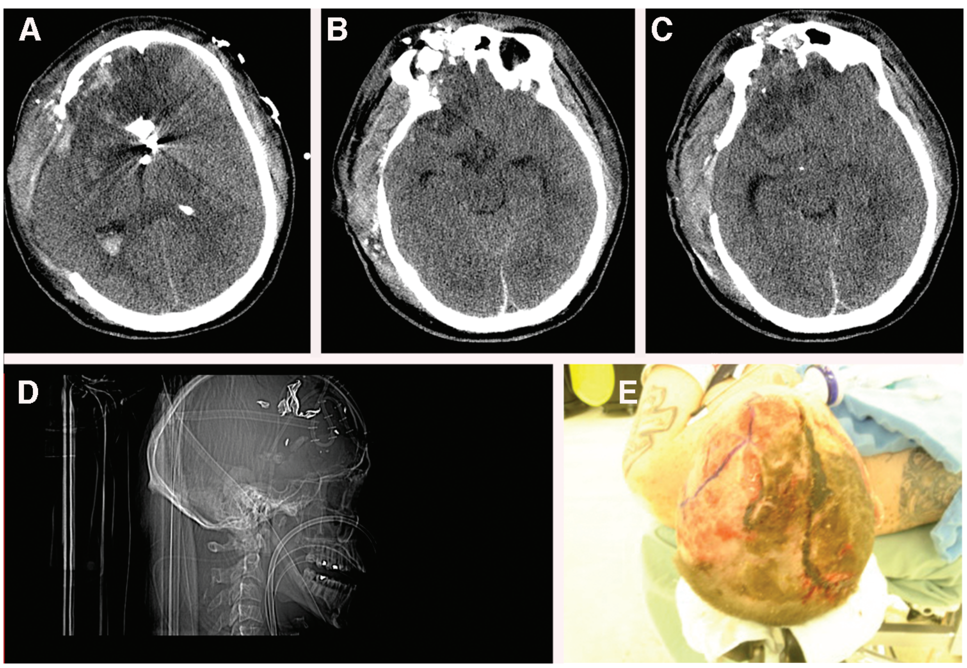

Fig. 1. Noncontrast CT scans **(A–C)**, radiograph **(D)**, and photograph **(E)** obtained in a 29-year-old service member who sustained a penetrating brain injury due to an improvised explosive device, showing a large metallic fragment lodged in the interhemispheric fissure **(A and D)**. This case illustrates several factors thought to contribute to cranioplasty infections, such as orbitofacial fractures **(B)**, injuries involving the sinuses **(C)**, and overlying soft-tissue defects due to burns or traumatic disruption **(E)**. The soldier did require a latissimus-free flap to recreate the soft-tissue envelope due to tissue loss from his burns, degloving injury, and scalp ischemia.

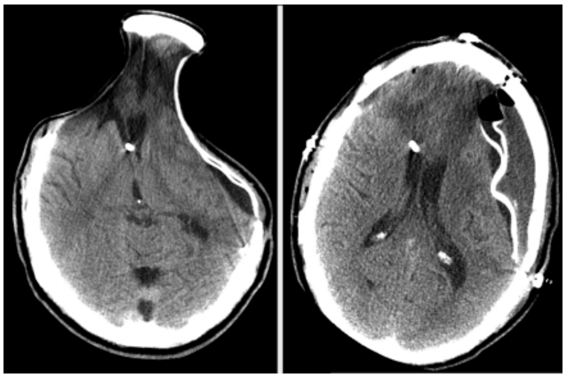

Fig. 2. Non–contrast-enhanced CT scans obtained in a 22-year-old service member who sustained a severe penetrating head injury due to a grenade blast. Preoperative image **(left)** showing the cranial defects associated with his bilateral decompressive craniectomies. On postoperative Day 2 (approximately 6 hours after the discontinuation of a subgaleal drain) the patient went into status epilepticus, and an emergently performed CT scan **(right)** revealed a large epidural collection exerting mass effect upon the left frontoparietal region. He was emergently transported to the operating room for decompression; however, he died on postoperative Day 9 due to secondary neurological complications of the epidural collection.

injury, sex, type of injury (closed head or penetrating head injury), mechanism of injury (explosive blast injury, motor vehicle accident, and so forth), initial GCS score, admission Injury Severity Score (a scoring system that provides an overall score in patients with multiple injuries), the presence or absence of CSF leakage, and CNS infection associated with a patient's initial injury. We also noted the time interval between initial injury and cranioplasty (days), the cranioplasty prosthesis material, the presence or absence of extraaxial hematoma formation (defined as either a subgaleal, epidural, or subdural hematoma judged by a qualified neuroradiologist to be out of the range of typical postoperative radiographic findings), new-onset seizure or infection associated with a patient's cranioplasty, the need to revise or reverse a patient's cranioplasty, and the GOS score at 1–2 years after injury.

Direct comparisons were then made to determine the differences between groups of patients. The effects of the presence or absence of extraaxial hematoma formation, seizure activity, infection, and the need to reverse or revise the cranioplasty prosthesis on patient outcome were compared. The impact of prior CSF leakage, CNS infection, systemic infection, and time interval from a patient's initial injury to cranioplasty on the prevalence of cranioplasty-associated complications was also examined. Initial GCS scores and the time interval from initial injury to cranioplasty were stratified to determine if a pattern of effect on other outcome variables could be elucidated.

Statistical Analysis

The Statistical Package for the Social Sciences, version 14 (SPSS, Inc.) was used to perform all inferential statistical analyses. Data were analyzed and results were expressed as the means ± SD for all descriptive variables. Percentages for descriptive variables were calculated and expressed as a function of the total number of patients in the study. Comparability between subpopulations in this study was analyzed using chi-square tests for categorical variables and logistic regression models for continuous variables.

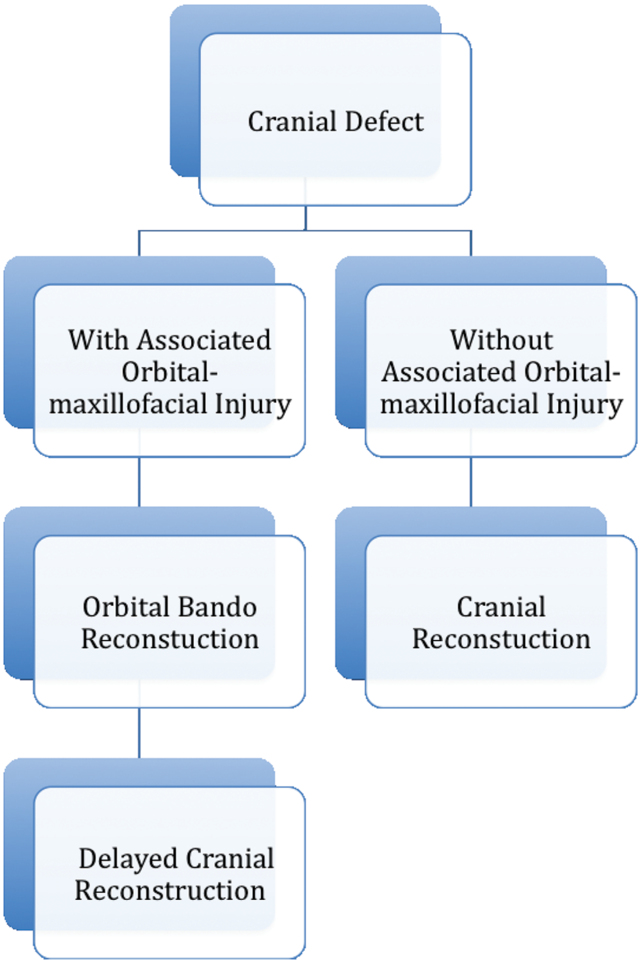

Fig. 3. Cranial reconstruction algorithm.

Results

Demographics and Medical Characteristics

We identified 108 patients who underwent cranial reconstruction at the WRAMC and NNMC due to trauma sustained in OIF/OEF-A, accounting for the performance of 117 cranioplasties. The cohort had a mean age of 26 ± 6.4 years (Table 1), 99% were male (107 patients), and 86% had sustained penetrating head injuries (93 patients; Table 2 and Figs. 1–3). Explosive blast injury (72 cases [67%]) was the predominant mechanism of injury. Other injury mechanisms included high-caliber gunshot wounds (30 cases [28%]), motor vehicle accidents (3 cases), helicopter crash (1 case), falling (1 case), and stabbing (1 case). The average GCS score on initial presentation in the combat theater was 7.5 ± 4.0 with a mean Injury Severity Score 33 ± 9.1. The mean time interval from the date of injury to cranioplasty was 190 ± 91 days. Of the 117 cranioplasties performed, the prosthesis material was

TABLE 3: Complication rates

Complication	No. (%)
infection	13 (12.0)
seizure	8 (7.40)
extraaxial hematoma	8 (7.40)
death	1 (0.93)
total	29 (24.0)

TABLE 4: Effects of time interval to cranioplasty on infection rates

Time Interval (days)	No. (%)
0–90	1 (7.7)
90–180	4 (30.8)
180–270	4 (30.8)
270–360	1 (7.7)
>360	3 (23.1)

polymethylmethacrylate in 89 patients (82%), whereas the rest of the prostheses were constructed of a woven titanium mesh (19 patients [18%]).

Complications and Outcomes

An overall complication rate of 24% was identified (Tables 3–5). The prevalence of perioperative infection (13 patients [12%]), seizure (8 patients [7.4%]), and extraaxial hematoma formation (8 patients [7.4%]) was characterized. Twelve patients (11%) required prosthesis removal due to either extraaxial hematoma formation (3 patients) or infection (9 patients).

Chi-square tests were performed to evaluate the effects of injury type, precranioplasty CSF leakage, or CNS infection on the need to revise or reverse a cranioplasty. No significant associations were found between these factors and the risk for cranioplasty failure. Moreover, when the time from injury until cranioplasty was stratified by 90-day intervals, there was no significant statistical difference in the prevalence of complications or the need to revise or reverse a cranioplasty. However, the increased prevalence of infection (8 of 13 cases) with cranioplasties performed between 90 and 270 days after the initial injury approached but did not reach statistical significance ($p = 0.061$).

Notably, with regard to prosthesis material, there was no significant difference in the rates of reversal or revision in polymethylmethacrylate versus woven titanium mesh prostheses. Moreover, the initial GCS score (when stratified into quartiles) had no statistically significant effect on the prevalence of extraaxial hematoma, seizure, infection, or reversal after cranioplasty.

The mean GOS score was 4.0 ± 0.93 at 1–2 years after injury. Finally, chi-square tests were again performed to evaluate the effects of extraaxial hematoma formation, seizure, and infection associated with cranioplasty on the GOS score at 1–2 years after injury. None of these factors significantly affected the GOS score at 1–2 years after injury.

Discussion

While much has been written on the surgical indications and techniques for cranioplasty, relatively little has been written specifically regarding the complications of this procedure.[3] Additionally, those authors looking at cranioplasty complications have had a smaller cohort of patients presenting with penetrating head injuries, making the results of our study particularly unique. The present study of cranioplasty and its complications in a trauma population undergoing decompressive craniectomy represents the largest analysis to date. Moreover, it may serve to reignite debate regarding the optimal time interval from craniectomy to cranioplasty specifically within a population undergoing craniectomies for penetrating head trauma.

Complications Associated With Cranioplasty

The overall complication rate of 24% in our study is commensurate with prior authors' findings.[1,2,4,5,6,8–10,14–16] In their recent work on complications associated with cranioplasty, Gooch et al.[3] reported an overall complication rate of 34%, with bifrontal cranioplasty as the only statistically significant factor associated with the need for reoperation. This finding is not surprising given the potential anatomical communication with the frontal sinus; a prior study has shown an increased risk of infection to be associated with violation of this space.[11,12] The infection rate of 12% in our study is higher than that reported by Gooch and colleagues,[2,3,7,12,13] likely reflecting the nature of these complex craniofacial injuries, such as soft-tissue, bony framework, and intracranial injuries.

With regard to the observed prevalence of seizures (8 patients [7.4%]), 5 patients experienced a seizure within the first 7 days following cranioplasty, whereas the other 3 had seizures after this time interval. Five patients in this group had a history of seizures and were taking either Keppra or Dilantin at the time of cranioplasty; the 3 patients with no history of seizures received Keppra postoperatively. While it may appear that the rate of seizures in our population is higher than that observed in Gooch and colleagues' cohort of patients (1 case [1.6%]), it must be remembered that we account for both early and delayed seizures as well as cases with a history of seizures from the initial trauma. If patients with a history of seizures are excluded, the 3 cases of new-onset seizures compare favorably with prior reports.[3]

Complications Requiring Reoperation

In our cohort, 12 patients (11%) required prosthesis removal because of either extraaxial hematoma formation (3 patients) or infection (9 patients). These 12 patients requiring reoperation constituted 41% of those experiencing complications related to cranioplasty. While this figure is lower than that reported by Gooch et al.,[3] it is still a high rate of reoperation.

Nine of 13 patients experiencing infectious complications required reoperation. The most common offending

TABLE 5: Characteristics associated with infectious complications in 13 patients*

Characteristic	No. (%)
skull base injury	7 (53.8)
orbitofacial fracture	5 (38.5)
sinus injury	4 (30.8)
preexisting fluid collection	1 (7.7)
CSF leakage	1 (7.7)

* Two of the 13 infected patients sustained transmaxillary/transorbital fractures without concomitant sinus injury, and thus the assertion that the injuries could be independent risk factors.

organism was methicillin-resistant *Staphylococcus aureus* (2 patients), with *Acinetobacter* species, *Enterococcus faecalis*, *Candida albicans*, and *S. aureus* each causing 1; in 3 patients the causative organism was unknown. In the 5 instances in which patients' Gram stains were positive, they were started on empirical antimicrobial treatment with cultures that subsequently proved to be negative.

Three of 8 patients experiencing a postoperative hematoma (defined as either a subgaleal, epidural, or subdural hematoma judged by a trained neuroradiologist to be outside of normal postsurgical changes) required reoperation. Notably, on postoperative Day 2 approximately 6 hours after the removal of a subgaleal drain, 1 patient demonstrated a rapid neurological decline. A head CT scan revealed a hyperacute epidural hematoma for which the patient was emergently taken back to the operating room. This patient died on postoperative Day 9 due to secondary neurological complications of his epidural hematoma.

Patient Outcomes

Cranioplasty is considered not only cosmetic but also therapeutic for continued neurological recovery, especially reversing the effects of the "syndrome of the trephine," which is defined as neurological deterioration in patients with large cranial defects that subsequently improve with cranioplasty. Although we are conducting a study aimed at separating the syndrome of the trephine from posttraumatic stress disorder, we have noted an incidence of approximately 30% for the syndrome of the trephine. Ongoing progressive neurological improvement has occurred in the majority of patients through Years 1, 2, and 3 of follow-up. Historically, improvement continued in similar injuries for 5–7 years. Of note, the mean GOS score at 1–2 years after injury in this series of patients was 4.0 ± 0.93, with no significant associations between the incidence of complications and eventual outcome. This result suggests that most of this cohort were able to attain functional independence despite a moderate degree of disability. The practical and ethical considerations in a control group without cranial reconstruction limits the traditional statistical analysis.

Study Limitations

It is important to remember that this study represents a preliminary analysis of a wartime population managed at 2 hospitals and does not include patients, albeit a small number of cases (< 30), who underwent cranioplasties at institutions outside the WRAMC or NNMC. The duration of the follow-up has also revealed delayed infections associated with invasive scalp or head and neck interventions; such cases included patients who underwent hair implantation (1 patient), body piercing (2 patients), and tattooing (1 patient) during the follow-up. Additionally, 2 cranial implant infections were associated with the spread of delayed orbital and maxillofacial infections. One case included the infection of a maxillary acrylic implant at 5 years after treatment. Our study is descriptive (Class III), and all observations apply to this study population only. Also, given its retrospective nature, this study is subject to the typical shortcomings associated with this format, including the loss of patient data, inadequate follow-up, and variable surgical techniques and/or materials. Note, however, that our data do provide valuable insights into the complications seen with cranioplasty in a unique population afflicted with severe multidimensional blast, blunt, and penetrating wartime traumas. Longitudinal studies of this patient cohort will educate us further on the ideal timing and type of cranial reconstruction to avoid complications.

Conclusions

Currently, cranial reconstruction cases are divided into those with or without associated orbitomaxillofacial injuries. A staged approach with early maxillofacial reconstruction followed by delayed cranial reconstruction has been applied. If the supraorbital bar is disrupted, then a staged approach is used to reconstruct the orbital band with autologous bone. Cranial reconstruction is then performed in a delayed manner by using autologous split-thickness bone or woven titanium mesh. Autologous bone is preferred in cases in which the skull base or air sinuses may be in contact with the implant. The avoidance of complications by making cranial implants more resistant to infection remains one of our ultimate objectives. A variety of strategies are being studied to include antibiotic-embedded implants as well as a more natural biologically active implant that allows integration with the surrounding cranial vault and skull base. As a nation and a military medical service, we are forever indebted to the men and women of our armed forces for service and sacrifice and are obligated to improve their care throughout their lifetime.

Disclosure

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

The views expressed in this manuscript do not represent the official policy or opinion of the United States Army, the United States Navy, the Department of Defense, or the United States Government.

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Analysis and interpretation of data: FL Stephens, RS Bell. Drafting the article: FL Stephens. Critically revising the article: MK Rosner, RA Armonda. Reviewed final version of the manuscript and approved it for submission: RA Armonda. Study supervision: MK Rosner, LE Moores, RA Armonda.

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Address correspondence to: Frederick L. Stephens, M.D., Department of Neurosurgery, Walter Reed Army Medical Center, Washington, DC 20307. email: frederick.stephens@us.army.mil.

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Can surgery improve neurological function in penetrating spinal injury? A review of the military and civilian literature and treatment recommendations for military neurosurgeons

Paul Klimo Jr., M.D., M.P.H.,[1] Brian T. Ragel, M.D.,[2] Michael Rosner, M.D.,[3] Wayne Gluf, M.D.,[4] and Randall McCafferty, M.D.[5]

[1]88th Medical Group, Wright-Patterson Air Force Base, Ohio; [2]Department of Neurological Surgery, Oregon Health & Science University, Portland, Oregon; [3]Division of Neurosurgery, Walter Reed Medical Center, Washington, DC; [4]Naval Medical Center, San Diego, California; and [5]Wilford Hall Medical Center, Lackland Air Force Base, Texas

Object. Penetrating spinal injury (PSI), although an infrequent injury in the civilian population, is not an infrequent injury in military conflicts. Throughout military history, the role of surgery in the treatment of PSI has been controversial. The US is currently involved in 2 military campaigns, the hallmark of both being the widespread use of various explosive devices. The authors reviewed the evidence for or against the use of decompressive laminectomy to treat PSI to provide a triservice (US Army, Navy, and Air Force) consensus and treatment recommendations for military neurosurgeons and spine surgeons.

Methods. A US National Library of Medicine PubMed database search that identified all literature dealing with acute management of PSI from military conflicts and civilian urban trauma centers in the post–Vietnam War period was undertaken.

Results. Nineteen retrospective case series (11 military and 8 civilian) met the study criteria. Eleven military articles covered a 20-year time span that included 782 patients who suffered either gunshot or blast-related projectile wounds. Four papers included sufficient data that analyzed the effectiveness of surgery compared with nonoperative management, 6 papers concluded that surgery was of no benefit, 2 papers indicated that surgery did have a role, and 3 papers made no comment. Eight civilian articles covered a 9-year time span that included 653 patients with spinal gunshot wounds. Two articles lacked any comparative data because of treatment bias. Two papers concluded that decompressive laminectomy had a beneficial role, 1 paper favored the removal of intracanal bullets between T-12 and L-4, and 5 papers indicated that surgery was of no benefit.

Conclusions. Based on the authors' military and civilian PubMed literature search, most of the evidence suggests that decompressive laminectomy does not improve neurological function in patients with PSI. However, there are serious methodological shortcomings in both literature groups. For this and other reasons, neurosurgeons from the US Air Force, Army, and Navy collectively believe that decompression should still be considered for any patient with an incomplete neurological injury and continued spinal canal compromise, ideally within 24–48 hours of injury; the patient should be stabilized concurrently if it is believed that the spinal injury is unstable. The authors recognize the highly controversial nature of this topic and hope that this literature review and the proposed treatment recommendations will be a valuable resource for deployed neurosurgeons. Ultimately, the deployed neurosurgeon must make the final treatment decision based on his or her opinion of the literature, individual abilities, and facility resources available. *(DOI: 10.3171/2010.2.FOCUS1036)*

Key Words • **penetrating spinal injury** • **spinal gunshot wound** • **blast injury** • **military** • **decompression** • **laminectomy** • **outcome**

Patients with PSIs present very complex, multidisciplinary management challenges for military surgeons. Not only can the patient have immediate and delayed life-threatening damage to organs along the path of the projectile, the spinal column and possibly the neurological structures contained within can also, by definition, suffer injury, the severity of which depends on multiple factors. Spinal cord injury from spinal GSWs is more often a complete lesion with a decreased potential for neurological recovery than with closed trauma.[43] There are a number of potential surgical indications, the most controversial of which is whether decompressive laminectomy has any effect on neurological recovery. Medical civilian and military literature is replete with opinions for and against the use of surgery.

Although missile characteristics such as size, composition and design are important, the major determinant of the destructive ability of a projectile is velocity at impact and thus the kinetic energy imparted to the surrounding tissue.[10] Energy is calculated based on mass and velocity as follows: energy = $1/2mv^2$. Therefore, velocity has a significantly greater effect on energy than projectile mass.

Abbreviations used in this paper: GSW = gunshot wound; IED = improvised explosive device; PSI = penetrating spinal injury; SCI = spinal cord injury; VB = vertebral body.

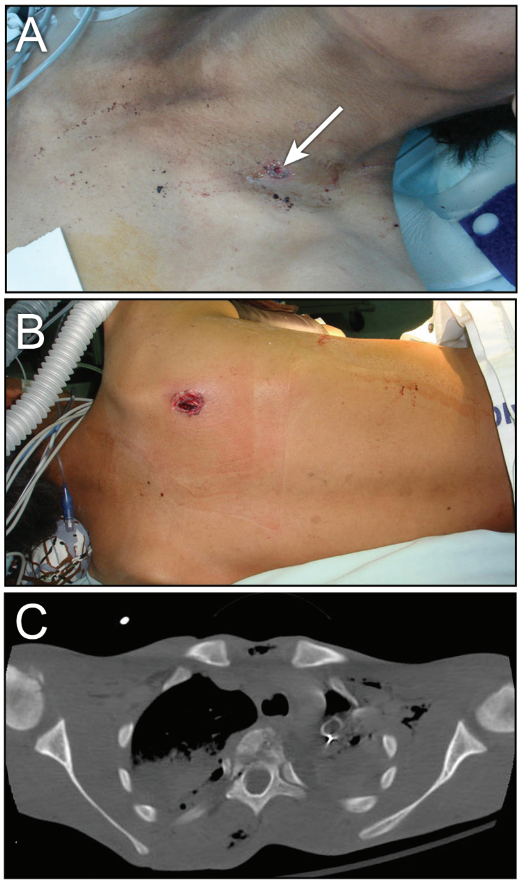

Fig. 1. Example of a spinal cord concussion with incomplete neurological injury. This 13-year-old male was tending his flock of camels when he was struck at the base of the neck just above the left clavicle (**A**, *arrow*) with an exit wound on the right medial aspect of the scapula (**B**). The weapon was thought to be an AK-47. The bullet traversed the T-3 and T-4 (**C**) VBs, but there was no canal compromise. The patient had no motor or sensory function in his legs but evidence of sacral sparing. The patient was treated nonoperatively; the spine was not believed to be unstable.

Civilian spinal GSWs are generally caused by low muzzle velocity (< 1000 ft/second) handguns, whereas military injuries may be due to high-velocity assault weapons or fragments from IEDs. For example, the muzzle velocities of the M-16 and AK-47 are approximately 3300 and 2810 ft/second, respectively.[11] A bullet damages tissues and structures by the following 3 known mechanisms: 1) direct impact injury of the bullet along its path; 2) pressure or shock waves created by the bullet impacting on tissue; and 3) temporary cavitation. Spinal cord injury may therefore occur even without any obvious injury to the spinal canal, termed spinal cord concussion (Fig. 1). Given the differences in ballistics and other factors discussed below, one may reasonably infer that penetrating injuries received on the battlefield are more destructive and therefore carry a worse prognosis than their civilian counterparts.

The US is currently engaged in 2 major military conflicts, Operation Enduring Freedom in Afghanistan and Operation Iraqi Freedom. These conflicts have seen the use of explosive weapons, most notably the IED as the weapon of choice that is used by adversaries.[34] Conventional assault weapons, however, are still used. The stimulus for this paper was the frequent admission of patients with PSIs seen by the primary author during his recent deployment to Afghanistan and the challenge posed in determining the optimal treatment. Current neurosurgery clinical practice guidelines available to neurosurgeons in deployed locations do not address the management of PSIs. The most important question that the neurosurgeon faces is whether a decompressive laminectomy can improve the chance of regaining lost neurological function. The goal of this paper is to review in detail the civilian and the military medical literature over the last 30 years to develop an evidence-based answer to this age-old question and to put forth succinct treatment recommendations for the management of war-related PSIs. This triservice (US Air Force, Army, and Navy) effort will hopefully enable the deployed military neurosurgeon to make the most informed decision in a timely fashion and ultimately provide the best care for troops.

Methods

Applying specific search terms, we used the US National Library of Medicine PubMed database to identify all articles dealing with PSIs in military conflicts, particularly in the post–Vietnam War period. To identify additional articles not identified by PubMed, the reference lists of appropriate articles were hand searched. We selected the post–Vietnam War period to capture management of spinal injuries in a relatively modern era of military medicine that reflected state-of-the-art battlefield evacuation and stabilization, and resuscitative, surgical, and postoperative care. This was done to achieve a balance between minimizing the chance that potentially antiquated medical care (> 25–30 years) would confound the results of surgical intervention, and collecting an adequate amount of medical literature on an infrequently published topic. Information identified in each article, when available, included the number of patients, average age, sex, military conflict, mechanism of injury, level of spinal involvement (cervical, thoracic, or lumbosacral), incomplete versus complete neurological injury, number of patients who underwent decompressive laminectomy, surgical outcomes, and incidence of injury to other organs or organ systems.

Since there were relatively few military articles identified during the post–Vietnam War period, a similar search was conducted to identify all papers dealing with civilian PSIs during a similar time span. The same information from each article was recorded.

Results

Military Literature

Eleven retrospective case series were identified in the 20 years that spanned 1984–2004 (Tables 1 and 2). Countries where the conflicts took place included Croatia (3 reports[21,36,40]), Turkey (3 reports[2,12,22]), Iran-Iraq (1 report[1]), Lebanon (2 reports[13,30]), India (1 report[6]), and Panama (1 report[31]). There were 782 patients collectively, the majority being male and soldiers, although some papers also identified civilians as part of their patient population. The

TABLE 1: Demographics of patients with PSIs in military conflicts*

Authors & Year	Conflict	No. of Patients	Mean Age (yrs)
Janković et al., 1998	Croatian War	96 (86 soldiers, 10 civilians [4 F, 6 M])	28.3 (soldiers), 38.8 (civilians)
Alaca et al., 2002	terrorism in Turkey	105	25
Splavski et al., 1996	Croatian War	21 (10 soldiers, 11 civilians [7 M, 4 F])	30.7
Aarabi et al., 1996	Iran-Iraq War	205 (145 w/ follow-up)	NA
Kahraman et al., 2004	terrorism in Turkey	106	21.2
Ohry & Rozin, 1984	Lebanon War	12 (7 soldiers, 5 civilians)	19.7
Duz et al., 2008	terrorism in Turkey	129	20.3
Rukovansjki, 1996	Croatian War	20 (16 M, 4 F)	NA
Bhatoe & Singh, 2003	India	22	30.7
Hammoud et al., 1995	Lebanon War	64	25
Parsons et al., 1993	Operation Just Cause (Panama)	2 (M)	23
total		782	19.7 (soldiers), 38.8 (civilians)

* NA = not available.

mean age ranged from 20 to 39 years, the latter being the average from a group of injured citizens included in one report.[21] Gunshot wounds were clearly identified as the mechanism in 333 patients and fragmentation from an explosive device in 378. One paper did not make the distinction between the two mechanisms.[13] Two papers specified the kinetics of the weapon used (low velocity vs high velocity).[6,12] The thoracic spine was most commonly involved (317 [41%] of 782 patients), followed by lumbosacral (285 [36%] of 782 patients) and cervical (180 [23%] 782 patients). Of the 606 patients in whom their admission neurological function was known, 306 (50%) had a complete SCI. Decompressive laminectomy was performed in 382 patients, 31 of whom underwent stabilization as well. Associated organ injuries occurred in 45% of patients (350 of 775).

Only 4 papers had sufficient data to allow any conclusion to be drawn regarding the efficacy of decompressive surgery compared with conservative management (Table 2). The other papers either did not present adequate pre- and postoperative neurological data or were biased in their treatment (that is, they treated all patients either surgically or nonoperatively), thus rendering any comparison impossible. Despite presenting inadequate supportive data, the authors of 4 other papers rendered a position statement on the role of surgery. Overall, 6 papers concluded that decompressive surgery was of no benefit, 2 indicated that surgery was a benefit in all patients with a neurological deficit (1 report) or only in those with an incomplete or cauda equina injury (1 report), and 3 papers made no comment.

Civilian Literature

Eight retrospective case series met our search criteria in the 9 years that spanned 1987–1996 (Tables 3 and 4). Although 2 papers were published in the post–Vietnam War era, their data collection occurred during the Vietnam War era and thus were excluded.[17,41] Metropolitan trauma centers included Philadelphia (2 reports[16,25]), Houston (2 reports[35,38]), Los Angeles (1 report[45]), Shreveport (1 report[5]), Chicago (1 report[9]), and The Bronx (1 report[23]). There were 694 patients collectively, the vast majority being male (639 patients). The mean age ranged from 24.7 to 32 years. Gunshot wounds from low-velocity handguns were the most common mechanism. Although some series also included patients with stab wounds, the neurological data in Table 4 reflect only those patients with GSWs, but some of the demographic data in Table 3 includes the stab wound victims. The thoracic spine was again the most commonly involved region (360 [52%] of 694), followed by lumbosacral (236 [34%] of 694), and cervical (98 [14%] of 694). Of the 633 patients in whom the admission neurological function was known, 377 (60%) had a complete SCI. Decompressive laminectomy was performed in 231 patients, and only 9 underwent concurrent stabilization. Associated organ injuries occurred in a high percentage of patients (356 [77%] of 461).

Only 2 papers had sufficient data to draw any conclusion on the efficacy of decompressive surgery compared with conservative management (Table 4). This was due to treatment bias. Cybulski et al.[9] operated on all patients; Kihtir et al.[23] did not operate on any patient. Despite lack of comparative data in these 2 papers, the authors of all papers rendered an opinion on the role of surgery based on their experience. Overall, 2 papers concluded that decompressive surgery had a beneficial role (in cauda equina or incomplete lesions [1 report each]), 1 paper indicated that removal of the bullet was of benefit between T-12 and L-4 in either incomplete or complete SCI, and 5 papers indicated that there was no evidence to support the use of decompressive laminectomy.

Discussion

History

An early and one of the most well-known fatalities due to a PSI was that of the great British naval Vice Ad-

TABLE 2: Neurological outcome of PSIs sustained during military conflict*

Authors & Year	No. of Patients (%): Mechanism: GSW	Mechanism: Expl/Blast	Level of Injury: Cervical	Level of Injury: Thoracic	Level of Injury: Lumbar	Level of Injury: Sacral	Neurological Injury: CSCI	Neurological Injury: ISCI	Op: Laminectomy	Op: Stabilization	Other Organ Injury (%)	Sufficient Data?†	Neurological Results	Authors' Opinion
Janković et al., 1998	49	47	19	21	56		NA	NA	27	6	50/96 (52)	no	NA	decompressive op is of no benefit
Alaca et al., 2002	98	7	2	68	30	5	88	17	56		72/105 (69)	no	NA	NA
Splavski et al., 1996		12	3	8	8	2	10	11	17	1	10/21 (48)	no	no CSCI pt improved; all ISCI pts improved	all pts w/ neurological deficit should undergo decompressive op immediately
Aarabi et al., 1996	60	138	40	102	63		90/145 (62)	55/145 (38)	87/145 (60)		49/205 (24)	yes	improved: CSCI+op 24%; CSCI w/o op 27.5%; ISCI+op 91%, ISCI w/o op 100%	decompressive op is of no benefit
Kahraman et al., 2004	8	68	35	25	46		23	83	65		49/106 (46)	yes	36/53 (68%) w/ op improved; 17/28 (60%) w/o op improved	decompressive op is of no benefit
Ohry & Rozin, 1984	11	1	4	5	3		7	5	2		5/12 (42)	no	1 pt improved w/ op; 2 pts improved w/o op	decompressive op is of no benefit
Duz et al., 2008	53 (37 high vel, 16 low vel)	76	39	31	59		24	105	74	24	54/129 (41.9)	yes	56.9% improved w/ op; 57.5% improved w/o op	decompressive op is of no benefit
Rukovansjki, 1996		11	8	8	4		NA	NA	12		13/20 (65)	no	no preop data; postop 8 were Frankel Grade A or B, 10 were Grade C or D, 1 was Grade E	NA
Bhatoe & Singh, 2003	4 (all low vel)	18	6	12	3	1	15	7	17		10/17 (59)	no	no CSCI pt improved; all ISCI pts improved	decompressive op is of benefit in pts w/ incomplete or cauda equina injury
Hammoud et al., 1995	NA	NA	24	37	3		47	17	23		38/64 (59)	yes	improved: CSCI+op 0%; CSCI w/o op 3.7%; ISCI+op 100%; ISCI w/o op 80%	decompressive op is of no benefit
Parsons et al., 1993					2		2		2		NA	no	CSCI pts did not improve	NA
total	333	378	180	317	277	8	306	300	382	31	350/775 (45)			

* CSCI = complete SCI; Expl = explosion; ISCI = incomplete SCI; pt = patient; vel = velocity.
† The study was considered to have sufficient data if the paper had neurological outcome data for patients who underwent a decompressive laminectomy and those that were treated nonoperatively.

TABLE 3: Demographics regarding PSIs sustained during civilian conflict

Authors & Year	City	No. of Patients & Sex	Mean Age (yrs)
Cybulski et al., 1989	Chicago	83 M, 5 F	24.7
Benzel et al., 1987	Shreveport	27 M, 8 F	30
Kihtir et al., 1991	The Bronx	21 M	26
Simpson et al., 1989	Houston	150 M, 10 F	29
Waters & Adkins, 1991	Los Angeles	81 M, 9 F	29.6
Heary et al., 1996	Philadelphia	222 M, 17 F	26
Robertson & Simpson, 1992	Houston	30 M, 3 F	30
Kupcha et al., 1990	Philadelphia	25 M, 3 F	32
total		639 M, 55 F	range 24.7–32

miral Lord Horatio Nelson. A French sharpshooter felled him during the epic naval battle of Trafalgar.[14] He was hit in the left shoulder, experienced immediate paraplegia, and died of his injury shortly thereafter. Other notable fatalities from spinal GSWs in history include the 20th President of the US James A. Garfield[47] and the assassin of the 16th President of the US (Abraham Lincoln), John Wilkes Booth.[39] Throughout the military conflicts of the 19th century such as the American Civil War and the Crimean, Boer, and Balkan Wars, PSIs were relatively rare, but came with a very high mortality rate, typically greater than 50%, which discouraged many from performing any surgical intervention.[14]

This reluctance to render treatment to these patients based on their grim prognosis continued into the Great War (World War I, 1914–1918). For example, during the brief but bloody American involvement, 0.4% of the injured had compound spinal injuries with a mortality rate of 56%.[14] After the war, the British Medical Research Council, in a review of World War I spinal cord injuries, concluded that the only indication for a laminectomy was an incomplete lesion with progressive neurological loss, which admittedly was quite a rare scenario.[42] At the onset of World War II (1939–1945), surgeons were faced with another onslaught of PSIs with little treatment to offer as a result of the continuation of the fatalistic attitude born through the previous conflicts. As stated by Dr. Milton Tinsley, "This was the confusion existing when we began to care for compound spinal injuries in World War II."[42] Before becoming one of the founding fathers of pediatric neurosurgery, then Major Donald Matson[28] summarized the feelings of many surgeons: "This has always been a difficult and discouraging group of cases to treat and perhaps for this reason they have been neglected."

During the early American land campaigns of World War II such as Africa and Sicily, surgeons initially managed PSI using the same pessimistic philosophy of World War I. However, this was becoming increasingly unacceptable to surgeons. As stated by Dr. Walter Haynes,[15] consultant neurosurgeon for the American First Army, "No one of us was ever satisfied with the defeatist attitude prevalent as to the prognosis of cord wounds. Yet, in light of previous experience of such men as Cushing, and the results of surgery in hardly comparable closed cord injuries, it seemed foolhardy to laminectomize more of those patients."

As World War II progressed, the pendulum of opinion swung sharply in favor of aggressive surgical debridement, decompression of the spinal canal, and often intradural exploration through a laminectomy in virtually all patients with compound spinal wounds, even those with complete neurological injuries.[15,28,29,37,42] Previously unheard of results were being reported. In Pool's series[32] of 57 patients treated during the years 1943–1944, 35 underwent a laminectomy and 57% showed a marked neurological improvement, compared with 4.5% spontaneous improve-

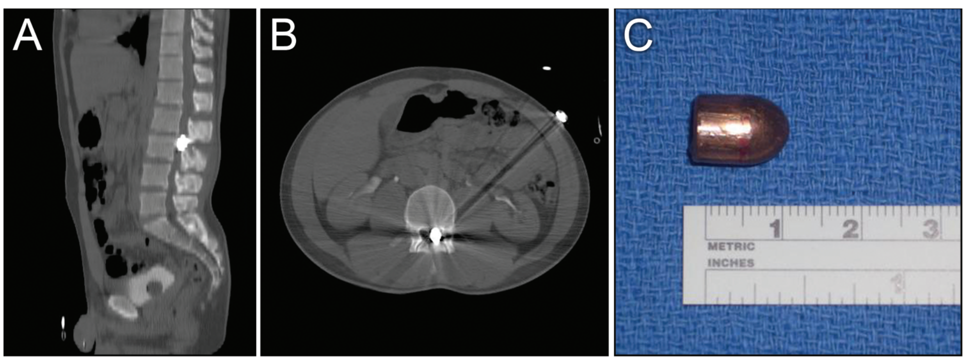

Fig. 2. This patient was shot with a 9-mm bullet and suffered an incomplete neurological injury. The CT images showed the bullet was lodged in the spinal canal at the L-3 level **(A and B)**. The bullet was removed **(C)** with no change in the patient's neurological examination in the immediate postoperative period.

TABLE 4: Neurological outcomes after PSIs sustained during civilian conflict*

	No. of Patients (%)												
		Level of Injury			Neurological Injury		Op						
Authors & Year	Mechanism	Cervical	Thoracic	Lumbosacral	CSCI	ISCI	Laminectomy	Stabilization	Other Organ Injury	Mean FU	Sufficient Data?	Neurological Results	Authors' Opinion
Cybulski et al., 1989	handgun	0	0	88	29	59	88		NA	NA	no	47.5% improved w/ op done w/in 72 hrs; 48.1% improved w/ op done after 72 hrs	decompressive op is of benefit in cauda equina whether done early or late
Benzel et al., 1987	33 handgun, 2 rifle	8	21	6	20	15	13		NA	NA	yes	improved: CSCI+op 100%; CSCI w/o op 0%; ISCI+op 100%, ISCI w/o op 75%	decompressive op is of benefit in incomplete injuries w/ evidence of compression
Kihtir et al., 1991	all GSWs	0	7	14	11	10	0	2	18/21 (86)	3 mos	no	no pt showed neurological improvement	decompressive op is of no benefit
Simpson et al., 1989	142 GSWs, 18 SWs	43	87	30	94	48	31		107/160 (67)	NA	yes	improved: CSCI+op 13%; CSCI w/o op 15%; ISCI+op 40%, ISCI w/o op 58%	decompressive op is of no benefit
Waters & Adkins, 1991	all GSWs	19	49	22	54	36	32		NA	NA	yes	removal of bullet improved motor function only for complete & incomplete T12–L4 injuries	removal of bullet is beneficial only in T12–L4 region
Heary et al., 1996	219 GSWs, 20 SWs	0	196	43	144	52	44	7	169/219 (77)	NA	yes	improved: CSCI+op 0%; CSCI w/o op 0%; ISCI+op 5%, ISCI w/o op 21%	decompressive op is of no benefit
Robertson & Simpson, 1992	30 GSWs, 3 SWs	0	0	33	4	29	18		21/33 (64)	22 wks	yes	improved: CSCI+op 100%; CSCI w/o op 0%; ISCI+op 47%, ISCI w/o op 71%	decompressive op is of no benefit
Kupcha et al., 1990	handgun	28	0	0	21	7	5		10/28 (36)	46 mos	yes	improved CSCI+op 67%; CSCI w/o op 50%; ISCI+op 50%, ISCI w/o op 60%	decompressive op is of no benefit
total	653 GSWs, 41 SWs	98	360	236	377	256	231	9	356/461 (77)				

* FU = follow-up; SW = stab wound.

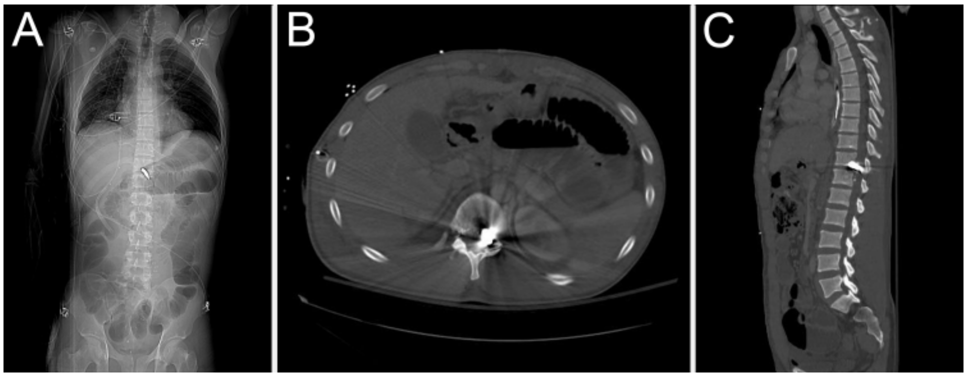

Fig. 3. This enemy combatant was injured by a large fragment from an artillery round. The fragment lodged in the spinal canal at the T11–12 level, and the patient had a complete neurological injury. The patient was treated nonoperatively. There was no neurological improvement after several months.

ment in the nonoperative group. His mortality rate was 7%. Haynes reported a 39.4% neurological improvement in laminectomized patients compared with virtually zero in nonoperated patients with a mortality rate of 9.8%.[15] He strongly believed that all patients with incomplete cord injuries and static or progressive neurological deficits should undergo exploration and decompression, and also that those with a complete physiological lesion should be treated if there was any suspicion that the spinal cord was intact.

This aggressive and early surgical management carried over into the Korean and Vietnam conflicts. Of the 300 patients with spinal injuries treated at the Tokyo Army Hospital between September 1950 and May 1952, 254 were penetrating and only 46 were closed.[44] It was believed that unless other associated injuries required life-saving surgery, laminectomy was to be performed as soon as possible. Thus, 249 of the 254 open spinal injured patients underwent a laminectomy, 44 of them within 24 hours of injury, with only 3 deaths (1.2%). Neurological improvement or complete recovery was seen in 121 patients (48%), although 130 (51%) did not have improvement. Amazingly, neurological improvement in those with complete injuries was best observed in the group with cervical cord injuries. Between 1965 and 1966 at the Neurosurgical Treatment Center in Saigon, Jacobs and Berg[18] operated on all 32 patients with penetrating wounds, but had dismal short-term outcomes—none of the patients with complete injuries improved and only 2 patients with incomplete injuries showed any improvement prior to evacuation. In the series by Jacobson and Bors,[19] all but one of their 90 patients with an open spinal injury from the Vietnam conflict had a laminectomy. However, during this time, reports from civilian trauma centers were raising questions about the effectiveness of indiscriminate use of laminectomy for patients with a PSI.

Between 1966 and 1973, Stauffer et al.[41] treated 185 patients with GSWs of the spine from low-velocity missiles, 106 with complete lesions and 79 with incomplete lesions. None of the patients with complete lesions showed any improvement regardless of whether they underwent a laminectomy. Of the patients with incomplete lesions, 71% showed measureable neurological improvement after a laminectomy compared with 76.5% who did not have surgery. Yashon et al.[48] also found similar equivocal results between surgery and nonoperative care and concluded the following: 1) the final neurological outcome was most closely related with the initial neurological status rather than with surgery; and 2) surgery should only be performed in grossly contaminated wounds or in patients with progressive neurological decline. Surgery also appeared to be ineffective in the series of patients with cervical GSWs presented by Heiden et al.,[17] in contrast to the Korean War experience described previously. They too believed that the sole indication for surgery was progressive neurological deficit. Chronologically, this leads into our literature review.

Current Literature

The purpose of this review was to evaluate the evidence for or against decompressive laminectomy use to treat PSIs since the Vietnam War. We started by reviewing the military medical literature and found that there were a number of issues with the quality of the data and the conclusions put forth by the authors as stated in *Results*. Although a large number of total patients (782) have been reported from these studies, only 4 papers had a reasonable amount of operative and nonoperative data within their studies to make a legitimate statement about the efficacy of surgery. Only 2 papers asserted that surgery was beneficial, and neither one of these had data to support this conclusion. Despite having a bias toward surgery (17 of 21 patients had a decompressive laminectomy and did not report the outcomes on those who did not have surgery), Splavski et al.[40] made the inappropriate conclusion that all patients with PSIs and a neurological deficit be treated with immediate surgery. The same flaws (bias toward surgery and lack of nonoperative data) marred the paper by Bhatoe and Singh[6] in which they similarly concluded that surgery was beneficial. One paper correctly stated in their abstract the lack of benefit for surgery based on their observed data, but then contradictorily concluded that patients with incomplete or cauda equina injury have a better prognosis for functional recovery when surgery is performed.[22] The highest quality papers in the military medical literature were by Aarabi et al.[1] and Hammoud et al.[13] In both papers, there were sufficient numbers of nonoperative and operative patients and within each, complete and incomplete neurological deficits, for data analysis. In both, surgery was not found to improve neurological functional recovery.

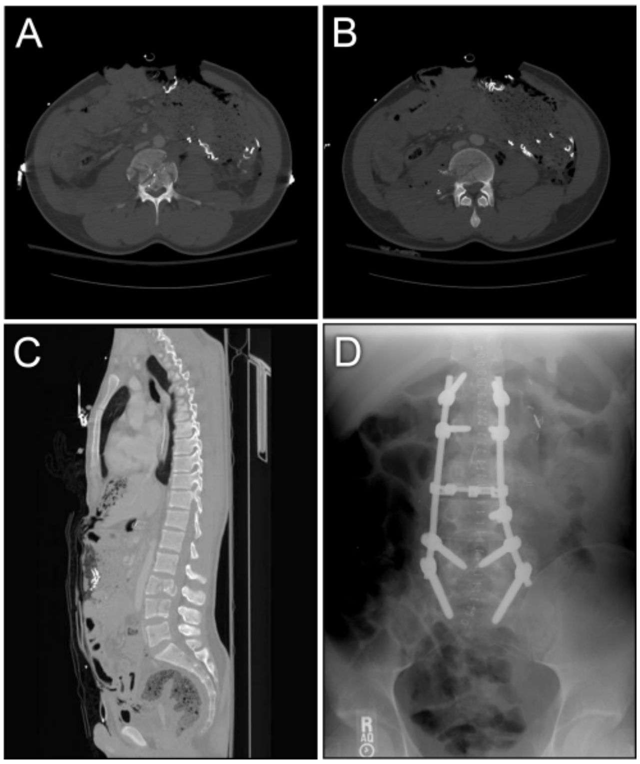

Fig. 4. Example of transabdominal/transspinal GSW with instability and incomplete neurological injury. This local national suffered a transabdominal GSW from an AK-47 that caused extensive comminution to the L-3 VB **(A)** as well as fractures spanning the full length of the L-4 VB **(B)**. There was retropulsion of bone at L-3 **(C)**. After undergoing immediate abdominal surgery and 1 week of intravenous antibiotics, the patient underwent an L1–S1 posterior fusion and stabilization with L-3 decompression **(D)**.

Given the aforementioned methodological deficiencies in existing military medical literature, we performed a similar search in the civilian medical literature. Here, the quality of the literature was superior. Eight papers were identified, and of these 3 advocated a role for surgery. Cybulski et al.[9] only evaluated patients with injuries of the cauda equina and concluded that surgery was of benefit whether done early (< 72 hours) or late (> 72 hours), but there were no control data (nonoperative) to support their conclusion. Benzel et al.[5] concluded that surgery was indicated in those patients with incomplete injury and evidence of continued compression of neurological structures within the spinal canal. In a multicenter study, Waters and Adkins[45] found that bullet removal benefited those with complete or incomplete lesions between T-12 and L-4 (Fig. 2), but there was no effect in those between T-1 and T-11. Four papers in which there was complete preoperative, postoperative, and nonoperative data, containing patients with both complete and incomplete neurological injury, strongly concluded that surgery was of no benefit.[16,25,35,38]

Our Recommendations for Deployed Military Neurosurgeons

A deployed military neurosurgeon works in an environment devoid of many administrative responsibilities, family support responsibilities, and other issues that comprise life. Thus, they are able to focus all of their energy on providing the best care for the casualties of war even though it may be in less than an ideal clinical setting. Repetitively facing injured soldiers and civilians with a clinical problem not often encountered in civilian practice and with limited guidance is extremely unsettling. As described by World War II surgeons in the preceding section, the motivation to act and provide maximal intervention, regardless of whether such intervention is known to provide actual benefit, is strong. Such has been the dilemma with patients with PSI, for whom recommendations have not appreciably changed in more than 100 years of military conflicts.

The literature thus far for PSI has provided some answers to other questions.[7,8,16,20,24] It is quite clear that the strongest prognostic predictor of future neurological function is the initial neurological grade. There is no need to perform exploratory surgery or bullet or fragment removal as a means to reduce infection beyond local wound care unless there is gross contamination of the wound.[13,43,46] A minimum of 3 days but more typically a 7–14-day course of broad-spectrum intravenous antibiotics with coverage of gram-positive, gram-negative, and anaerobic bacterial flora is effective at preventing most infections, including those in patients with transcolonic wounds.[7,27,33] There is no need to operate to remove bullet fragments to prevent lead or copper toxicity as this is an extremely rare complication even in the new era of IEDs. There is also no role for the administration of trauma-dose Solu-Medrol in these patients.[26] The only absolute indications for surgery are to repair a CSF-cutaneous/pleural fistula or if the patient has progressive neurological decline correlated with compression of neural elements on imaging studies.

The question that has always been of greatest importance is whether decompressive laminectomy can provide the patient a better chance at regaining neurological function compared with nonoperative supportive measures. The gravity of this question is obvious when considering that the vast majority of patients who sustain PSIs in the military are young, healthy, physically active individuals, many of whom have spouses and children eagerly awaiting their return home from deployment. Does surgery work? The literature reviewed here is inconclusive, but the data reported to date suggest it does not, especially in those with complete lesions. Most of the military and civilian literature does not support surgery. Furthermore, the findings in the civilian literature are particularly important when one considers that the differences between civilian and military injuries make the argument for nonoperative treatment even stronger. Civilian injuries are almost universally caused by low-velocity projectiles that impart only a fraction of the energy to the tissue on impact in comparison with what is found in high-velocity injuries. The associated organ injuries are less severe and the wounds are less contaminated. Civilian patients can often be transported to a trauma center and can rapidly start receiving advanced care. Despite significant advancement in battlefield resuscitation and transport, the process of getting a wounded warrior to a Level III Air Force Theater Hospital, which may have neurosurgical assets, can be lengthy. If there is merit to the argument that early decompression leads to better outcomes, patients extracted from a battlefield may be at a disadvantage.

However, we believe that decompressive laminectomy may be indicated for patients with penetrating SCI beyond those patients requiring repair of a CSF fistula or experiencing progressive neurological decline. We stress that these recommendations are the collective opinions of the authors and in no way should be interpreted as treatment standards or guidelines; each neurosurgeon or spine surgeon must make their own clinical decision based on their opinion of the literature, their abilities, resources available at their deployment location, and each individual patient scenario:

1. Laminectomy is to be considered only if the patient is stabilized from other life-threatening injuries, most notably abdominal, thoracic, or intracranial injury.

2. Laminectomy should not be performed in patients with complete neurological injury (Fig. 3), with the possible exception of patients with a cervical injury who demonstrate clear compressive pathology on imaging and arrive early after sustaining their injury. Here, the recovery of even one spinal segment is highly significant in their rehabilitive function.

3. Laminectomy should be considered in all patients with an incomplete neurological deficit (especially if the lesion is in the cauda equina) and there is evidence on imaging of significant spinal canal compromise (for example, bone or metal). Surgery should be performed as soon as possible, ideally within 24–48 hours. Segmental instrumentation and fusion should be considered at the same time if the injury is deemed unstable.

We offer these recommendations for several reasons. The available medical literature as we have detailed is far from conclusive. All the components to provide timely surgical intervention in-theater are currently in place: a well-integrated, rapid, military medical evacuation system, in-theater neurosurgeons, and medical facilities that are able to provide all aspects of perioperative care. There has been a significant change in the paradigm for delivery of neurosurgical care for the wounded military service member over the past 2 decades. Since the first Gulf War, neurosurgeons are now deployed directly in the combat theater, often quickly accessible via helicopter evacuation with times comparable to those seen at major civilian trauma centers. This previously unseen access to neurosurgical evaluation and treatment should be considered when establishing a treatment algorithm in current and future military conflicts. Additionally, many military spinal cord and cauda equina injuries are the result of IEDs, which are low velocity shrapnel wounds similar to injuries sustained in civilian GSW injuries. Direct injury from a high-velocity military firearm, such as from a sniper attack, is fortunately less frequent than low-velocity shrapnel wounds. Another point we believed was an important consideration was the transportation of these patients out of the operational theater to other medical facilities, typically in Europe and North America. These are long (commonly 8 or more hours) transcontinental and transoceanic flights aboard military aircraft, which may encounter significant turbulence with additional risk for further neurological injury. A similar rationale is used to support the use of decompressive craniectomy in patients with severe head injury.[4] There are several additional issues with these recommendations that require further discussion and clarification.

Perioperative Complications

A number of authors have cited an increased rate of complications in patients who undergo surgery and use this finding to strengthen their argument against performing surgery.[1,7,16,35,38] This finding, however, has not been supported by others.[12] Complications that have been reported include CSF leak, postoperative instability, neurological decline, epidural hematoma, meningitis, and local infection. If such a difference truly exists, it would not be surprising and in fact expected, but we believe that these complications are manageable and should not dissuade the surgeon from rendering potentially beneficial treatment.

Transgastrointestinal Injuries

Projectiles that pass through the abdomen and in particular the colon before striking the spinal column are particularly ominous injuries. These patients typically require a life-saving laparotomy as the initial treatment. These patients are often too critically ill or have other issues such as an open abdominal wound that precludes them from being placed prone for several hours to perform a laminectomy. Furthermore, several authors have found that the risk of developing a postoperative spinal wound infection is significantly higher in those patients with transcolonic injuries.[16,33] Therefore, whether to perform a laminectomy in patients with transgastrointestinal injuries needs a careful analysis of all issues, neurological and nonneurological. We believe that if the patient has an incomplete injury with continued canal compromise from bone or foreign objects, and it is thought the patient could tolerate a laminectomy, and the patient has been placed on appropriate broad-spectrum intravenous antibiotics, then a laminectomy should be performed as soon as possible. We believe that the potential of achieving neurological recovery outweighs the risk of developing an infection that should be readily treatable with appropriate antibiotics.

If it is thought that the patient has an unstable spine (see *Instability*), then the decompression and instrumentation should be delayed until the patient has completed a full course of antibiotics (Fig. 4). Alternatively, the decompression may be performed initially and the instability treated with segmental instrumentation in a delayed fashion or with prolonged immobility and bracing. In this circumstance, stabilization for coalition personnel would most likely occur at a medical facility out of theater because nonnative patients would most likely have been transferred before completion of their course of antibiotics.

Instability

As seen in this literature review, few patients in either the military or the civilian articles required stabilization. In general, low-velocity injuries typically seen in civilian casualties rarely create an unstable spine.[3] However, high-velocity injuries, which are more common in military patients, probably have a higher risk of instability because of the greater destructive capability of the projectile. Some of the cases of instability in the literature were associated with overly aggressive laminectomy.[41] The largest series of military patients with PSI requiring stabilization was recently published by Duz et al.[12] Of 129 patients, 24 required stabilization, 17 of them for what the authors classified as a Type III or side-to-side injury in which the bullet passed through both facet joints and/or pedicles.

In the area of operation, spinal imaging is accomplished with plain radiographs and CT scanning. Magnetic resonance imaging is not available until the patient reaches medical centers in either Europe or North America. In addition, MR imaging is often contraindicated in the wounded warrior due to retained fragments from the IEDs. Computed tomography with reconstructed images in the coronal and sagittal planes is adequate for determining the integrity of the VB, spinal canal, facets, and overall alignment of the spine in the area of the injury. Severely comminuted anterior and posterior elements with evidence of segmental deformity can be indicative of instability. Furthermore, a laminectomy in the presence of an anterior or middle column injury may produce an unstable spine.

Instrumentation should be performed if deemed necessary as part of the decompression operation if possible. Although coalition soldiers do not typically have permanent orthopedic or spinal implants placed in-theater for fear of infection, the state of the major in-theater medical centers, for example the Craig Joint Theater Hospital in Bagram, Afghanistan, is such that all the intraoperative equipment and spinal instrumentation needed to perform a fusion and stabilization are available. The decision to perform an instrumented fusion must take into account the risks of a potentially increased infection rate, which can be highly variable depending on the maturity of the deployed facility versus the risks of neurological decline during a long and complicated transport in a turbulent environment. In the more than 2 years that Air Force neurosurgeons have been deployed to Afghanistan, a number of spinal stabilization surgeries have been performed and, to date, there have been no deep or superficial wound infections. However, we stress that the final determination on whether to pursue instrumentation must be made by the deployed on-site neurosurgeon or spine surgeon as he or she will have the most accurate assessment of all factors that need to be taken into account when making such a decision.

Conclusions

The treatment of patients with PSIs continues to be a great challenge to all involved and may present considerable uncertainty for the in-theater neurosurgeon with regard to treatment. Despite the numerous conflicts of today and yesterday, there is still ambiguity as to the role of decompressive laminectomy in regaining lost neurological function. It is clear that the most important factor that determines future neurological function is the initial neurological status. Surgery may or may not have a beneficial role. However, the medical literature, both civilian and military, is inadequate at answering this question. This underscores the great need for future studies that are currently underway. Based primarily on the lack of conclusive evidence, we believe that there is a role for surgery when it is done with the hope of restoring neurological function. Despite more than 60 years of amazing advancement in medical treatment and technology, our recommendations are hauntingly similar to the opinions expressed by Dr. Matson[28] in 1946 as a result of his experience in treating these injuries in the European Theater of Operations from 1944 to 1945:

> Patients who exhibit a neurological picture consistent with an incomplete transection of the spinal cord where this picture has altered since the time of injury, especially where the neurological deficit is increasing.…
>
> Patients with a neurological picture of incomplete cord transection where x-rays reveal clear-cut encroachment on the spinal canal by a foreign body or reveal definite fracture of a lamina or pedicle with or without depressed bone fragments.…
>
> Patients who have sizable wounds directly over or near the spinal column and are leaking spinal fluid profusely.…

Disclosure

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

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Address correspondence to: Paul Klimo Jr., M.D., 88th Medical Group, 4881 Sugar Maple Drive, Wright-Patterson Air Force Base, Ohio 45433. email: atomkpnk@yahoo.com.

The evolution of the treatment of traumatic cerebrovascular injury during wartime

A review

Randy S. Bell, M.D.,[1,3] Robert D. Ecker, M.D.,[1,3] Meryl A. Severson III, M.D.,[1] John E. Wanebo, M.D.,[1] Benjamin Crandall, D.O.,[2] and Rocco A. Armonda, M.D.[1,3,4]

Departments of [1]Neurosurgery and [2]Radiology, National Naval Medical Center; [3]Department of Neurosurgery, Uniformed Services University of the Health Sciences, Bethesda, Maryland; and [4]Department of Neurosurgery, Walter Reed Army Medical Center, Washington, DC

The approach to traumatic craniocervical vascular injury has evolved significantly in recent years. Conflicts prior to Operations Iraqi and Enduring Freedom were characterized by minimal intervention in the setting of severe penetrating head injury, in large part due to limited far-forward resource availability. Consequently, sequelae of penetrating head injury like traumatic aneurysm formation remained poorly characterized with a paucity of pathophysiological descriptions. The current conflicts have seen dramatic improvements with respect to the management of severe penetrating and closed head injuries. As a result of the rapid field resuscitation and early cranial decompression, patients are surviving longer, which has led to diagnosis and treatment of entities that had previously gone undiagnosed. Therefore, in this paper the authors' purpose is to review their experience with severe traumatic brain injury complicated by injury to the craniocervical vasculature. Historical approaches will be reviewed, and the importance of modern endovascular techniques will be emphasized. *(DOI: 10.3171/2010.2.FOCUS1025)*

Key Words • **traumatic vasospasm** • **endovascular** • **traumatic aneurysm** • **penetrating head trauma**

The effects of modern warfare and its constituent military-grade weaponry have resulted in considerable craniocervical injuries. Nowhere is this more poignant than the injuries suffered by US servicemen and women during OIF and OEF over the last 6 years. Although the loss of life and limb is tragic, the medical advancements achieved during efforts to save individuals are substantial and apply to every field of medicine. One particular example includes the advances in approaches to traumatic craniocervical vascular injury made by military neurosurgical personnel. Improvements in endovascular technologies (coils, microcatheters, and liquid embolic agents) have shifted what was traditionally a treatment paradigm dominated by open surgical techniques to one in which a multidisciplinary approach is the standard of care. The purpose of this paper is to review the historic approach to these lesions and subsequently to summarize the most recent experience with the largest population of patients with traumatic craniocervical vascular injury ever reported. For the purposes of discussion, this paper will focus on 2 subtypes of cerebrovascular injury: traumatic aneurysms and traumatic vasospasm.

Abbreviations used in this paper: DS = digital subtraction; OEF = Operation Enduring Freedom; OIF = Operation Iraqi Freedom; SAH = subarachnoid hemorrhage; TCD = transcranial Doppler.

Historical Approach to Neurovascular Trauma

Traumatic Aneurysms

The true incidence of traumatic aneurysms due to the lethal nature of a penetrating missile or fragment is largely speculative. Estimates in the setting of penetrating head injury range from 5 to 40%.[1,2,4,10,16–18] The lower end of this range is likely an underestimate if one considers that 1) many patients, both civilian and military, do not survive to reach hospital care; and 2) standard of care at many institutions does not include mandatory cerebral angiography for all penetrating head injuries. Overall, traumatic aneurysms comprise 1% of all forms of intracranial aneurysms.

Prior to and long after the advent of cerebral angiography by Egas Moniz in 1927, the diagnosis of traumatic aneurysms was observational, relying heavily on what was seen during surgical exploration. The advent

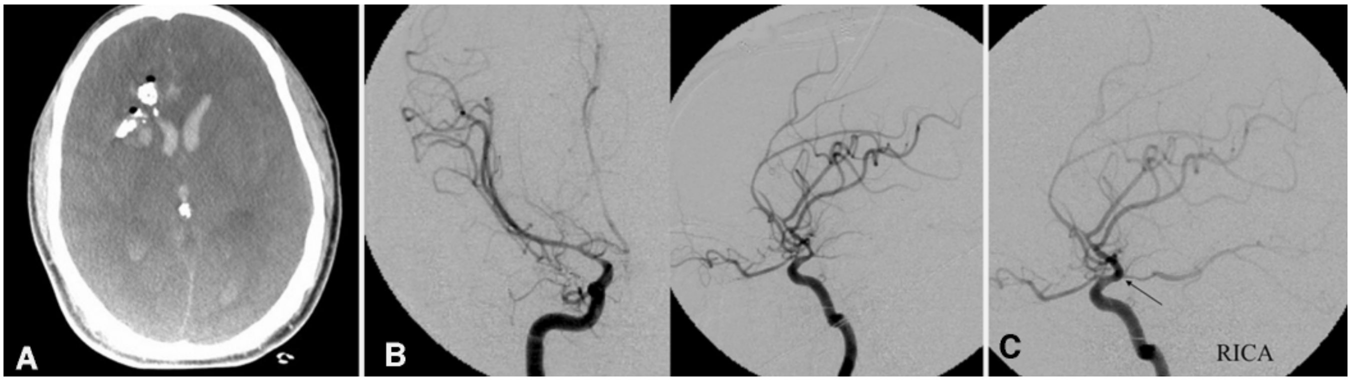

Fig. 1. **A:** Penetrating head injury accompanied by intraventricular hemorrhage. **B:** Anteroposterior *(left)* and lateral *(right)* angiograms of the right internal carotid artery (ICA) demonstrating severe supraclinoid and proximal middle cerebral artery vasospasm. **C:** Lateral angiogram of the right ICA (RICA) following balloon angioplasty showing resolution of the vasospasm.

of DS technology made noninvasive diagnosis possible and accurate.[3,8,13,21,24,28] Although several small studies within the civilian sector exist concerning these entities, it has been through large-scale military conflict that advances in diagnosis, natural history, and treatment have occurred.[1,2,4,10,17]

Groundbreaking work in the area of traumatic aneurysms was first reported in 1988 following the Iran-Iraq War. Aarabi[2] analyzed his experience with 255 head-injured patients who received diagnostic angiography. What is important to remember about this remarkable population is that these were the individuals who survived their injury, often without the protective benefits of a helmet, and survived their subsequent transport (often protracted through hostile territory) through rough Iranian terrain. This work was the first to characterize the wounding patterns that, if present, correlate strongly with the concomitant presence of cerebrovascular injury. Specifically, fragment or missile penetrations through orbitofrontal and/or pterional windows were associated with the formation of traumatic aneurysms. Although only 7 individuals were diagnosed with injury in this group, all were diagnosed more than 10 days after their injury, and all were treated with open surgical clip exclusion.

A subsequent study from the same conflict on a larger population of head-injured patients further characterized this disease entity. Amirjamshidi et al.[4] analyzed their experience with more than 1100 head injuries, including outcomes associated with surgical intervention. They identified within this population a uniform subpopulation of individuals who received diagnostic angiograms within a consistent time frame. Within this group, 5.7% of those studied had traumatic aneurysms and were subsequently treated by either open surgical clipping or observation.

Traumatic Vasospasm

Although the natural history of aneurysmal SAH–induced vasospasm has been well characterized, several questions remain concerning the same for posttraumatic vasospasm. What is known is that the incidence of vasospasm after trauma increases with the amount of traumatic SAH present on the admission head CT,[31,32,36] that the incidence of vasospasm is inversely proportional to admission Glasgow Coma Scale scores,[6,36,37] that the vasospasm can be reliably monitored with TCD ultrasonography,[7,31,32,34] and the time course of spasm in this setting is variable.[6,31,32,36,37] There is, however, continued debate concerning whether, like aneurysmal SAH vasospasm, traumatic vasospasm causes delayed ischemic neurological deficits and worsens outcomes.[6,15,32] It is because of this debate that, prior to 2006, very few studies were available that evaluated the effect of endovascular treatment interventions in this setting.[12,34] Overall and with respect to military trauma populations, there are no studies prior to OIF and OEF evaluating the incidence or importance of traumatic vasospasm in a wartime trauma population.

Operation Iraqi Freedom

Operation Iraqi Freedom began on April 18, 2003. Since that time, the vast majority of in-theater casualties, following their initial resuscitation and surgical stabilization, were treated at the Walter Reed Army Medical Center and the National Naval Medical Center, Bethesda. A recent study chronicled the extent of severe CNS injury that survived to reach the continental US.[11] Between April 2003 and April 2008, 513 patients transferred from OIF/OEF to National Naval Medical Center and Walter Reed Army Medical Center required neurosurgical evaluation. In this group, 408 patients presented with severe head trauma, with the majority suffering a penetrating head injury from blast. Several salient observations were made from the study of general head injury. First, early decompressive craniectomy (within the first 2–4 hours from injury) was successful in mitigating the effects of swelling and increased intracranial pressure during the long air evacuation transfer to the continental US. Second, the relative incidences of pulmonary embolism, cerebrovascular injury, and associated spinal column injury exceeded previously published civilian reports in head injury populations. Third, outcomes at all time points were directly proportional to the extent of initial neurological and systemic injury.

Of the many observations made, the most striking was the incidence of traumatic cerebrovascular injury. More than one-third of those presenting with severe head trauma suffered concomitant vascular injury. This represents a significant increase from the 5–20% reported previously in similar studies.[1,2,4,18] Reasons for this observed increase include improved far-forward care (immediate resuscitation and early cranial decompression) resulting in longer survival as well as improved diagnostic techniques (DS angiography with 3D reconstruction). The following discussion will address the most current approaches to and treatment of traumatic vasospasm and traumatic aneurysms.

Traumatic Vasospasm

Vasospasm can be simply defined as a reduction in the caliber of a blood vessel, usually in response to an external stimulus that results in increased flow velocities (Fig. 1). Although clinically silent in many circumstances, vasospasm can result in delayed ischemic neurological deficits.[32]

Prior to OIF, the indication to perform diagnostic cerebral angiography in penetrating head injury populations was limited to those with penetrating head injury in whom traumatic aneurysms were suspected. Because a considerable proportion of those studied (in our population) had either concomitant or isolated vasospasm, we expanded our indications to include all those with penetrating head injuries, all those who suffered either a closed or penetrating head injury as a result of blast, and all those in whom increased cerebral blood flow velocities were documented by TCD ultrasonography.

Initial results in this population were reported in 2006.[6] Specifically, the incidence of vasospasm in our population approached 50% and was associated with the presence of traumatic aneurysms and intracranial blood of any type. The incidence of vasospasm peaked at 14 days and was reliably followed by TCD ultrasonography. Roughly two-thirds of those with vasospasm received either balloon angioplasty or direct intraarterial infusions of nicardipine to mitigate the vasospasm. While those aggressively treated did not show statistical improvement with respect to early Glasgow Outcome Scale scores when compared with those treated conservatively, there was a statistical reduction in the vasospasm as measured by TCD ultrasonography. Overall, those with vasospasm had statistically lower early and late Glasgow Outcome Scale scores than those who did not have vasospasm.

While previous studies characterized the formation of vasospasm following trauma,[19,20,22,23,29,31,32,36,37] few were able to correlate delayed ischemic deficits and outcomes with its presence,[15,31,32,37] and even fewer described the safety or efficacy of endovascular interventions in this setting.[12] In addition, while not specifically correlated with vasospasm occurrence, there was a considerable predominance of blast-induced head injury in our population. In approximately 10% of those with vasospasm, no penetrating injury was present. We theorized that the blast overpressure wave that accompanies all explosions may be responsible, at least in part, for the duration and severity of the vasospasm seen in our population. Experiments conducted in porcine systems (unpublished data) confirm that isolated blast overpressure can cause early vasospasm (within 12 hours), although long-term studies have not been completed.[9] Overall, it is possible that the vasospasm seen in this population differs mechanistically from that seen in general civilian and military nonblast trauma.

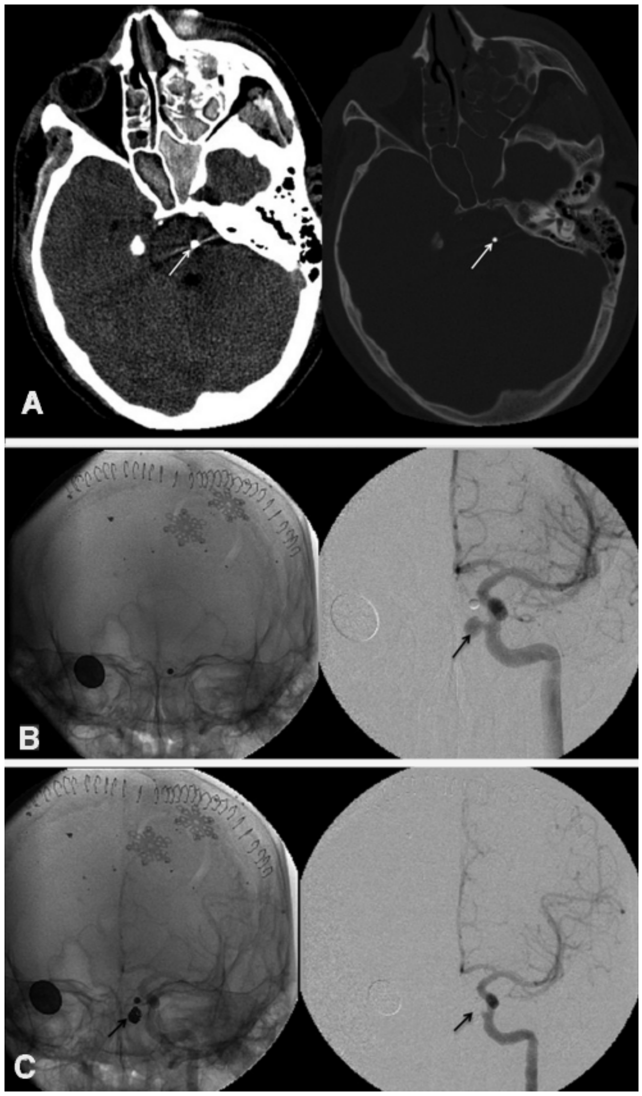

Fig. 2. **A:** Head CT scans with soft-tissue *(left)* and bone *(right)* windows revealing a penetrating facial injury by a small spherical fragment that traversed the sphenoid sinus and came to rest within the brainstem *(arrows)*. This patient presented to the continental US with severe epistaxis that resulted in a code arrest. **B:** Native *(left)* and anteroposterior (AP) DS *(right)* angiograms of the left ICA demonstrating a traumatic aneurysm projecting medially from the proximal cavernous segment of the ICA *(arrow)*. **C:** Native AP *(left)* and AP DS *(right)* angiograms of the left ICA following successful coil occlusion of the traumatic aneurysm *(arrows)*. The patient made a full recovery and returned to active duty.

Traumatic Aneurysms

Traumatic aneurysms result from injury to the arterial wall from an external source (Figs. 2 and 3). Connective tissue remnants or frank clot form the components of the “dome” of the aneurysm. It is the unpredictable

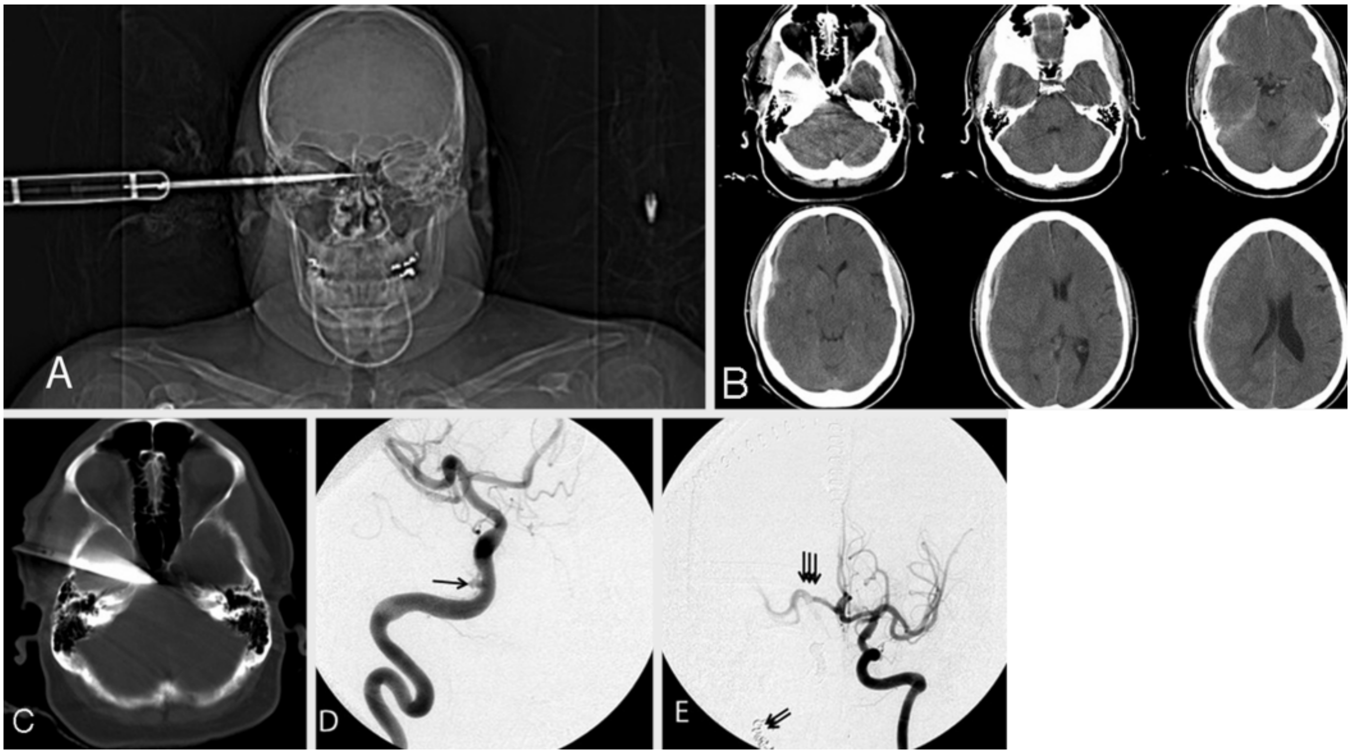

Fig. 3. **A:** Scout image obtained from a CT scan in a patient, revealing a penetrating knife wound to the head **B:** Axial CT images of the brain revealing subdural hematoma and evidence of SAH. **C:** Axial CT scan of the brain, bone window, revealing the course of the knife through the middle cranial fossa with the tip lodging medially near the inferior aspect of the cavernous sinus. **D:** Oblique DS angiogram of the right ICA revealing a traumatic aneurysm at the proximal portion of the cavernous segment of the ICA *(arrow)*. **E:** Digital subtraction angiogram of the left ICA showing right ICA occlusion *(double arrows)* with excellent cross-filling of the right anterior cerebral artery and middle cerebral artery via a patent anterior communicating artery *(triple black arrows)*. The patient made an excellent recovery.

rupture rate of this type of aneurysm that makes early treatment important. That said, unlike spontaneous saccular aneurysms for which a significant body of published information is available concerning their natural history and treatment,[14,25–27,35] very little of the same data were available for traumatic aneurysms prior to 2010. Recommendations based on available case series (< 80 cases) were made by the Head Trauma Society in the Guidelines for the Management of Vascular Complications of Penetrating Head Injury.[5] At no more than the level of Option, the Society recommends diagnostic cerebral angiography in most cases, and recommends treatment, although the timing and type of treatment remain vague. Prior to the current conflict, open surgical approaches mainly consisting of clip exclusion of the diseased arterial segment were the mainstay of treatment, with little to no experience in endovascular options.

Operations Iraqi and Enduring Freedom have seen the largest concentration of penetrating and closed head injury in US servicemen and women since the Vietnam War. As previously stated, as a result of improved imaging technology and heightened awareness, vascular injuries were identified in nearly one-third of those injured, with traumatic aneurysms seen in nearly one-third of those studied with DS angiography. The results of our analysis of this population were published in January 2010.[12] Overall, 64 arterial injuries were seen in 187 patients studied with DS angiography. Fifty traumatic aneurysms (31 traumatic intracranial aneurysms and 19 traumatic extracalvarial aneurysms) were seen. While some aneurysms were treated with clip exclusion at the time of the original cranial intervention, many presented in a delayed fashion at the time of the first angiographic study (on average 10 days after injury).

Several conclusions were reached as a result of this study. First, the pattern of rupture of these aneurysms was not consistent, but trended toward larger aneurysm size. Second, some traumatic aneurysms (on average, 2 mm in size) healed without treatment. Lastly, endovascular options (coil occlusion, liquid embolic agents, and stent-buttressed coil embolization) are viable and safe. In most cases they can prevent or delay an additional open surgical exploration in the acute setting where sequelae of head injury (high intracranial pressure and scarring) can hamper surgery and worsen outcome.

Lessons Learned and Recommendations for Future Conflicts

The impact of head trauma accompanied by neurovascular injury has been significant. Advances in helmet and body armor technology, far-forward systemic resuscitation, early cranial decompression, and a high degree of suspicion with an algorithmic approach to performing DS angiography have improved outcomes in this high-risk population.

With respect to future conflicts, it is imperative that an infrastructure be maintained to aggressively manage these conditions. Neurosurgeons and neurocritical care specialists must maintain a high degree of suspicion for these injuries. This approach should include mandatory DS angiography performed in all patients with penetrating brain injury, and most patients with traumatic brain injury from blast. As technology improves, moving higher resolution portable angiographic suites far-forward (Level III) may improve diagnosis and long-term outcomes.

With respect to the approach to traumatic aneurysms, if the intent is to treat in an open surgical fashion, this is best accomplished at the time of initial cranial decompression. This is predicated on the high degree of suspicion of their presence. If this approach is not possible, every effort should be made to temporize the patient by endovascular means during the acute posttrauma period. Open surgery, if conducted in a delayed fashion, should be undertaken with the preoperative expectation that vessel sacrifice will be necessary. Coils, if present within the aneurysm, may aid in both the location of a distal aneurysm (intraoperative radiograph), and the manipulation of both the "dome" and the parent artery. That said, as in the setting of previously coiled spontaneous saccular aneurysms, tearing at the aneurysm neck is a distinct possibility, highlighting the need for good proximal and distal control. If coils are not present and the aneurysm is distal, the use of image guidance using fine-cut CT angiography should be considered.

Overall, because of the unpredictable nature of both vasospasm and traumatic aneurysms, there must be a willingness by the neurosurgeons involved with the care of these patients to treat safely and early.

Disclosure

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Address correspondence to: Randy S. Bell, M.D., Cerebrovascular Neurosurgery and Interventional Neuroradiology, NAVMED MPT&E, and Department of Neurosurgery, National Naval Medical Center, 8901 Wisconsin Avenue, Bethesda, Maryland 20889. email: randy.s.bell@us.army.mil.

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Delayed detection of carotid–cavernous fistulas associated with wartime blast–induced craniofacial trauma

Report of 2 cases

Sudhakar Vadivelu, D.O., Randy Scott Bell, M.D., Ben Crandall, D.O., Tom DeGraba, M.D., and Rocco A. Armonda, M.D.

National Capital Neurosurgery Consortium, Division of Neurosurgery at the National Naval Medical Center, Bethesda, Maryland

Blast-induced neurotrauma is a leading cause of military casualties. Its effects on cerebrovascular structures are not well understood. Vascular injury resulting from overpressure shock wave impact may have a delayed presentation and detection. The authors present the cases of 2 patients who sustained blast-induced craniofacial trauma and brain injury. Detection of a cervical dissection was delayed in one patient, and detection of carotid-cavernous fistulas was delayed in both patients. The authors report the successful obliteration of both the dissection and the carotid-cavernous fistulas via an endovascular approach. Endovascular management provides both a reasonable and effective therapeutic option to blast-induced cerebrovascular injuries. *(DOI: 10.3171/2010.2.FOCUS09257)*

Key Words • **craniofacial trauma** • **blast injury** • **missile injury** • **overpressure wave** • **transarterial embolization** • **vasospasm**

Blasts are the most prevalent mechanism of injury during war times, concomitant with the increase in terrorist activity and their terrorists' preference for explosive devices over chemical, biological, and radiation means of attacks.[6] Recent figures of combat casualties during the War on Terrorism in Afghanistan and Iraq estimate a total of 17,501 casualties with 303 soldiers who "died of wounds" (deaths after arriving to a medical facility) and 1266 soldiers who were "killed in action" (deaths before reaching a medical facility). Comparative analyses against World War II and Vietnam suggest a 6% decrease in the killed-in-action rate and a 9 and 6% decrease in case fatality rate, respectively.[12] However, there has been an increase in the estimated percentage of deaths after reaching a medical facility, indicating patients being treated earlier with a greater burden of injury.[7,12] In addition, TBI cases have increased to an estimated 22% of military admissions in Germany during combat in Iraq and Afghanistan, compared with the 12–14% of cases during the Vietnam War.[19] The direct effect of traumatic blast shock waves becomes more apparent as morbidity remains high, including a higher incidence of recognized postinjury vasospasm[2] and as many as 25% of blast-injured patients die.[17]

Several reports have observed patients with blast-induced trauma, especially seen during war times, presenting and responding in various ways compared with most civilian craniofacial trauma and traumatic brain-injured patients.[11,14,19] Despite the lack of longitudinal studies, growing evidence demonstrates distinct features of blast-induced TBI as evidenced clinically and in the laboratory, and this may lend evidence to delayed neurological deterioration after blast-induced cerebrovascular trauma, which is not well understood. Ling et al.[14] suggested blast-induced TBI as a separate classification because it shares hemorrhage and cerebral edema (features of brain-tissue deformation seen in penetrating TBI) and vascular and white matter injury (features of closed-head TBI), but that diffuse edema and hyperemia are quite often seen early along side SAH and delayed neurological deterioration as commonly unique features of blast-induced TBI.[16] Furthermore, the military has reported performing fewer decompressive craniectomies in cases of penetrating or closed head–induced TBI than in cases involving this blast-induced TBI presentation.[9,14,15,20] Laboratory studies have demonstrated unique features of persistent, slowing electroencephalographic activity after missile-induced high-impact injuries[8,14,21] and degeneration in white matter tracts without gross associated cellular loss, features different from those of direct contusion or fluid impact injury models.[10,13,14,18] In addition to the knowledge that severe TBI disrupts cerebral autoregulation and the growing evidence that cerebral vasculature is a conduit for blast-impact waves, it is not surprising that in blast-

Abbreviations used in this paper: CCF = carotid-cavernous fistula; ICA = internal carotid artery; TBI = traumatic brain injury; TCD = transcranial Doppler.

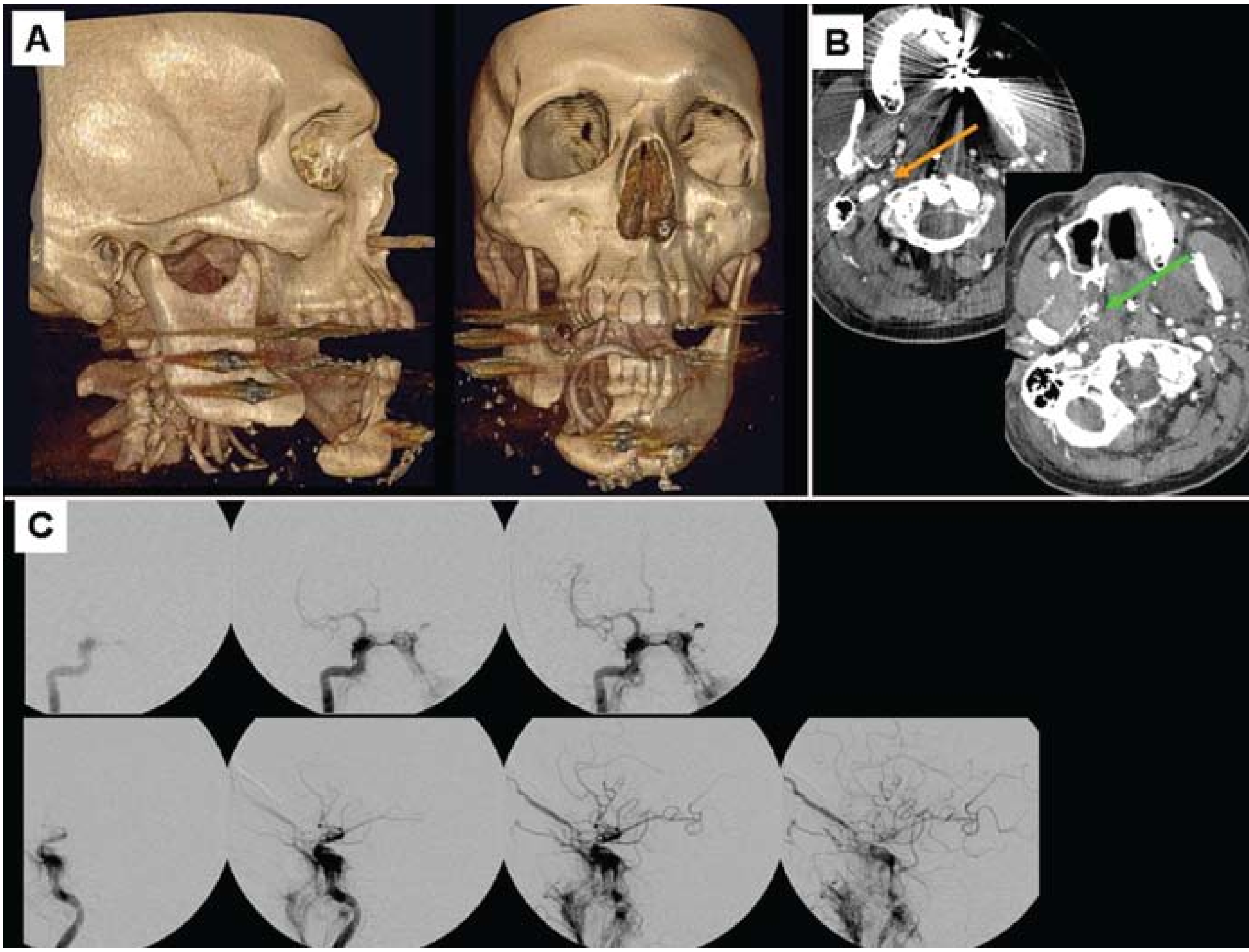

Fig. 1. Case 1. A complex blast-induced CCF was associated with a maxillofacial fracture and carotid dissection. **A:** External fixation of the comminuted internal mandibular fracture. **B:** Computed tomography angiograms showing a narrowed right distal cervical ICA *(orange arrow)* and dilation of the right pterygoid venous plexus *(green arrow)*. **C:** Angiograms demonstrating direct high-flow Barrow Type A CCF with dual drainage through the pterygoid plexus and orbital veins.

induced penetrating and nonpenetrating TBI a significant incidence of traumatic cerebral vasospasm and delayed neurological deterioration has been demonstrated.[2]

Understanding the complex nature of blast-induced cerebrovascular trauma may help us identify vascular compromise in the acute and delayed setting. During the Iran-Iraq conflict, Amirjamshidi et al.[1] reported the need for early angiography after evaluating 31 cases of traumatic cerebral aneurysms and 3 associated CCFs, 1 of which was followed for spontaneous resolution and the other 2 of which were trapped and embolized for occlusion.[2] Here, we describe the cases of 2 patients with blast-induced craniofacial injuries and delayed-presentation traumatic CCF.

Case Reports

Case 1

History. This 36-year-old man presented with an improvised explosive device blast injury to his face and jaw. The result was a comminuted mandibular fracture and soft-tissue neck injury at the level of the cricoid cartilage. In the combat theater he underwent surgical exploration bilaterally of the common cervical carotid artery bifurcation and open reduction and rigid internal fixation to stabilize the mandibular fracture (Fig. 1A). No external injury to the carotid arteries was appreciated (Fig. 2A). On arrival, his GCS score was 11 (combined scores of E4, V1, and M6) and neurological examination unremarkable.

Examination. Two weeks later, while at the National Naval Medical Center, serial TCD ultrasonography demonstrated significant abnormalities, including reduced right middle cerebral artery velocities and reversal of flow in the right ophthalmic artery. This steal phenomenon was likely indicative of a CCF. The patient had no ophthalmological signs of orbital hypertension, and no audible bruit. A CT angiogram confirmed this suspicion with an additional cervical pre-petrous right ICA dissection and Type A high-flow separate cavernous-seg-

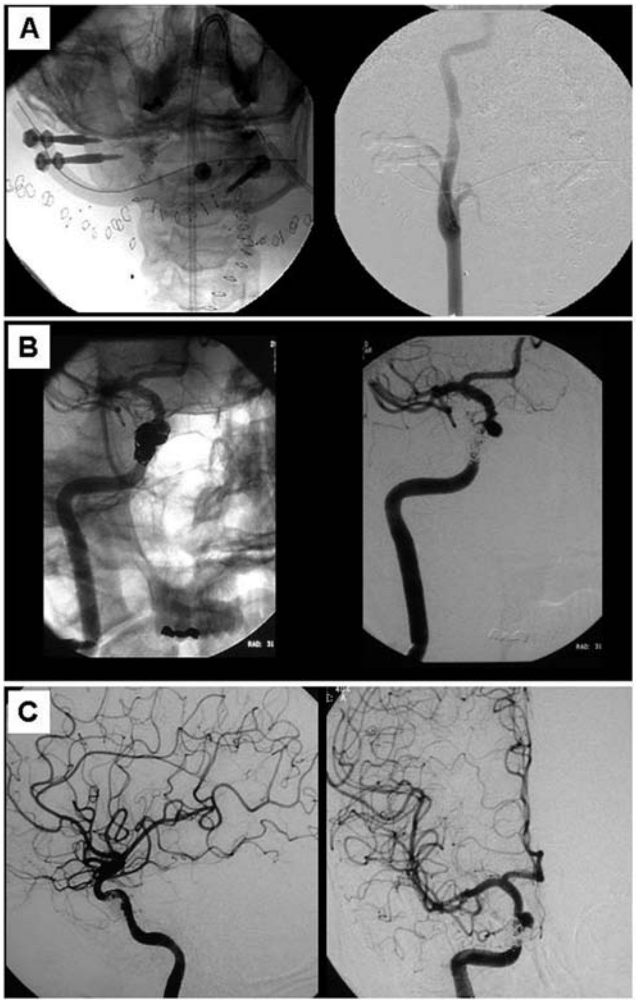

Fig. 2. Case 1. Endovascular treatment and follow-up of the complex blast-induced CCF. **A:** Mandibular ramus fixator in place with an associated distal ICA subintimal dissection, missed during open neck exploration. **B:** Endovascular vessel reconstructed with a combination of a self-expanding stent for the cervical dissection and a stent/coil buttress occlusion of the direct CCF with parent vessel preservation. **C:** Twelve-week follow-up angiograms demonstrating obliteration of the CCF, parent vessel preservation, and endovascular reconstruction.

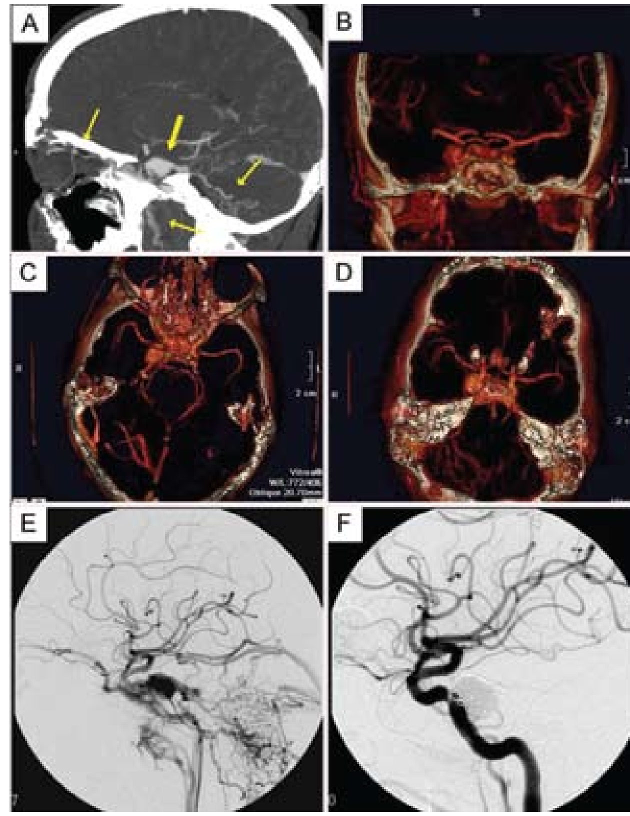

Fig. 3. Case 2. A delayed CCF appearance after blast injury to the head. Color CT angiograms **(A–D)** and repeat angiogram **(E)** 6 weeks postinjury revealing a giant ruptured pseudoaneurysm with marked filling of the cavernous sinus, superior petrosal sinus, cerebellar veins, as well as filling anteriorly to the superior ophthalmic vein, inferior ophthalmic vein, and pterygoid veins (*gold arrows,* A). **F:** One-month postoperative angiogram demonstrated no filling of the aneurysm, maintenance of ICA patency, and complete resolution of the CCF.

ment CCF (Fig. 1B and C). The cervical dissection was treated with a self-expanding stent, the venous pouch of the CCF was treated with coil occlusion, and stent reconstruction was performed to preserve the cavernous-carotid artery. After endovascular treatment, transient partial cranial nerve III and VI palsies were noted. The patient's condition remained stable and his GCS score continued to be 11.

Postoperative Course. Two weeks after surgery, the patient returned to the neurointerventional operative suite for repeated angiography. Transvenous inferior petrosal microcatheterization was used to re-coil the residual persistent CCF, with drainage via the pterygoid venous plexus as well as retrograde filling via clival venous plexus into the jugular bulb. Completion angiography demonstrated resolution of the dissection with a widely patent lumen (Fig. 2B) and near obliteration of the fistula with stasis of flow in the cavernous sinus. At 12-week follow-up, angiography revealed complete obliteration of the fistula and the patient's cranial nerve deficits had resolved (Fig. 2C).

Case 2

This 25-year-old male platoon leader, whose vehicle was struck by a rocket-propelled grenade (RPG), sustained a depressed frontal sinus fracture and a complex flail jaw fracture involving the maxilla and mandible. He underwent an emergency cricothyroidotomy and a subsequent elevation of the frontal sinus fracture with epidural hematoma evacuation after the initial head CT scans. His mandible and zygomatic arch were stabilized and fixed with internal plates and screws. Although the patient was initially neurologically intact, a delayed right gaze diplopia developed 6 weeks after injury, and the patient began to notice a marked pulsatile machine-like bruit. There was no evidence of chemosis or exophthalmoses. Color CT angiography and angiography at that time revealed a giant pseudoaneurysm at the proximal portion of the cavernous ICA segment, with both cortical venous reflux into the posterior fossa veins via the superior petrosal vein and superior orbital vein engorgement, consistent with venous hypertension (Fig. 3A–E). Selective catheterization demonstrated marked filling of the cavernous sinus, superior petrosal sinus, cerebellar veins, and filling anteriorly to the superior ophthalmic vein, inferior ophthalmic vein, and pterygoid veins. Rapid filling was noted through the CCF, with filling of the cavernous sinus, superior inferior ophthalmic veins, and predominately into the posterior fossa and veins of the lateral mesencephalic region of the cerebellum and brainstem. Transarterial coil embolization was performed using 210 cm of Matrix G coils to occlude the pseudoaneurysm and prevent filling of the CCF. One month follow-up angiography demonstrated no filling of the pseudoaneurysm, maintenance of ICA patency, and complete resolution of the CCF (Fig. 3F). The cranial nerve VI palsy had completely resolved, and the officer returned to full duty at 6 months without limitations.

Discussion

These cases highlight the need for a high degree of suspicion associated with neurovascular injuries in the presence of blast-induced maxillofacial injuries. The delayed detection of CCFs becomes more challenging in the absence of ophthalmic findings. The use of TCD ultrasonography and CT angiography allowed for the identification of the fistula, and endovascular techniques permitted successful safe treatment. A high likelihood for such injuries should exist in the presence of facial fractures such as mandibular, maxillary, and skull base injuries as in these cases. The absence of ophthalmic features indicates that the fistula is draining through intracranial or pterygoid venous channels, and thus, there is the risk of cortical venous drainage. Such venous drainage may result in delayed intracranial hemorrhage or intraoral bleeding.

Both of the CCFs in the present cases can be classified as Barrow Type A high-flow fistulas. Type A fistulas are caused by a direct tear of the cavernous-carotid artery. This can result from traumatic skull base injuries due to the relative high mobility of the cavernous-carotid artery compared with the points of carotid artery fixation in the petrous and clinoid segments. Generally these lesions have a low rate of spontaneous resolution and require definitive treatment, of which endovascular options are preferable. In trauma CCFs are infrequently associated with concomitant traumatic cerebral aneurysmal rupture, which is more commonly seen in cases of spontaneous Type A fistulas. In contrast, Barrow Type B–D fistulas, which generally exhibit dural derivation, frequently resolve spontaneously.[3,5] Interestingly, in both cases reported here the patients did not initially present with typical suspicious findings of classically described traumatically induced CCFs, including the lack of pulsatile exophthalmus, penetrating trauma, SAH, stroke, or chemosis. Evidence of craniofacial trauma and its association with a pseudoaneurysm in both cases suggested blast-induced CCFs. The blast-wave effect on the mobile segment of the cavernous-carotid artery seems a likely cause for a direct tear and resulting high-flow fistula.

A blast wave is described as having 2 important characteristics: 1) a high-pressure shock wave, along with 2) a subsequent inflow of air.[7] This combination allows for high-pressure differences, especially deleterious at air-fluid interfaces. Blast injuries have been classified into 4 categories according to the origin of the blast effect. Primary blast injuries include direct effects of pressure often seen in blunt (nonpenetrating) injuries. Secondary blast injuries include penetrating and projectile fragments entering the body, producing injury alongside blast pressure. Tertiary blast injuries are based on structural collapse of building or structures with people in or on them, allowing these persons to be thrown by blast winds and also encompassing in some respects the effects of primary and secondary blast injuries as well. Quaternary blast injuries include exposure to toxic inhalants producing burns and asphyxia.[7] Blast-induced cerebrovascular injury, seen in the present cases, may have evolved by frank arterial disruption that resulted in a brief subarachnoid hemorrhage due to tamponade or by partial arterial wall disruption, including the subadventitial layers,[2] while allowing for a prolonged series of associated upregulated vasculogenic responses in attempts for arterial recovery. Despite the number of patients with blast-induced TBI and facial injuries, the rate of CCF formation remains low. In the series of 187 patients undergoing cerebral angiography at the National Naval Medical Center and Walter Reed Army Medical Center, only 6 total fistulas were identified: 3 cavernous, 1 orbital, 1 vertebral, and 1 scalp.

The current military experience has witnessed earlier neurosurgical intervention in theater with improved airlift emergency triaging and early access to state-side neurointerventional treatments. Our indications for cerebral angiography have expanded to include maxillofacial injuries and penetrating neck injuries. Screening with CT angiography may be useful in patients without significant metallic artifact obliterating the imaging quality. However, the timing of the contrast bolus, the artifact from bone, metal, and foreign debris, as well as the technical aspects of workstation 3D reconstructions, limit its use. Neck exploration as demonstrated in Case 1 does little to identify a subintimal dissection. Because this is most likely to occur between the mobile segment of the artery, its entrance to the petrous bone, and contact with the styloid process, extraluminal exploration is ineffective. Early out-of-theater angiography and continued repeat imaging becomes essential in those thought to have sustained blast-wave propagation (impact) within the cerebrovascular pathways and/or delayed neurological compromise.[4] Here, we observed 2 patients with delayed identification for CCF. The use of TCD ultrasonography is an essential part of our screening regiment and has helped us expand our evaluation of wartime patients with maxillofacial trauma. We speculate here that blast waves and blunt forces, with the resulting collision and impact, may result in cerebral vasculature injury in the mobile segments of the vessel between points of fixation. Additional theories include the brachiocephalic vasculature as a conduit of blast-wave propagation as a pulse wave from the heart to the cranial cavity.[2,11,14,19] Greater understanding of this blast-wave propagation within the cerebral vasculature becomes even more important in light of recent work from our group in which the incidence of cerebrovascular injury was as high as 27% in this war setting, almost 10-

fold higher than the previously reported incidence.[4] The 2 cases here highlight the need for a high degree of clinical suspicion for cerebrovascular injury in patients with maxillofacial fractures caused by blast-induced trauma. Further studies both in the clinical and laboratory setting to investigate the pathophysiology behind these blast-induced neurovascular injuries may help identify the cause and ultimate prevention of such injuries.

Conclusions

Blast-induced maxillofacial injuries and TBI may develop delayed CCFs. Endovascular approaches that involve coil occlusion and stent reconstruction appear well tolerated and are an effective measure for blast-induced CCFs and traumatic dissections. Neuroendovascular techniques provide a definitive means of treatment for blast-induced cerebrovascular trauma as demonstrated in these 2 cases. The use of TCD screening combined with CT angiography allowed the detection of these lesions and should be used in patients with craniofacial trauma when neurovascular injuries may be located beneath the disrupted contour of the craniofacial skeleton.

Disclosure

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The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Army, the Department of the Navy, the Department of Defense, the United States Government, the Henry Jackson Foundation for the Advancement of Military Medicine, or any of the institutions with which the authors are affiliated.

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Address correspondence to: Rocco A. Armonda, COL, MC, US, M.D., Department of Neurosurgery, Uniformed Services University of Health Sciences, 8901 Wisconsin Avenue, Bethesda, Maryland 20814. email: rocco.armonda@gmail.com.

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Battlefield neurosurgical care in the current conflict in southern Afghanistan

Markus F. Eisenburg, M.D., Ph.D.,[1] Martin Christie, M.B.,Ch.B., Dip.Obs., F.R.A.C.S.,[2] and Peter Mathew, F.R.C.S.(Eng), F.R.C.S.(SurgNeurol), D.T.M.&H.[3]

[1]*Department of Surgery, Division of Neurosurgery, Klinikum Harlaching, Ludwig Maximilians University, Munich, Germany;* [2]*Dunedin Hospital, Dunedin, New Zealand; and* [3]*University of Dundee, United Kingdom*

An international military campaign involving large numbers of troops is ongoing in Afghanistan. To support the military efforts in the conflict zone, a network of military medical services of varying levels has been established. The largest and busiest multinational military hospital in southern Afghanistan is located at Kandahar Air Field where the only neurosurgeon is based. This report outlines the contribution of multinational military health services and the workload of the neurosurgical service in Kandahar. *(DOI: 10.3171/2010.2.FOCUS108)*

Key Words • **battlefield** • **neurosurgery** • **Afghanistan** • **war**

The Islamic Republic of Afghanistan (Fig. 1) is a landlocked country in an important geostrategic location in Central Asia, connecting the East and the West or the Middle East. It is surrounded by Pakistan, Iran, several former Soviet republics and the People's Republic of China. Since the late 1970s Afghanistan has been suffering from a continuous state of civil war, which gave rise to foreign occupation in the form of the Soviet invasion in December 1979 followed by the US-led invasion (OEF-A) in October 2001.

During the Soviet occupation (1979–1989) anticommunist guerrilla groups (Mujahideen) formed and, heavily supported by the US, Saudi Arabia, and other countries, started fighting against the Soviet occupants. After the withdrawal of Soviet troops, the Afghan procommunist government gradually lost power and finally collapsed in 1992. Afghanistan was divided into several territories ruled by rival Mujahideen warlords, who were unable to cooperate and form a stable Afghan government. Finally the devout Taliban, also a Mujahideen group, stood up in 1994 to remove the corrupt and brutal warlords from power, and in 1996 they finally took over control of the whole of Afghanistan. In the Northern Provinces a group of Mujahideen refused to legally accept the Taliban regime and formed the Northern Alliance, or United Islamic Front for the Salvation of Afghanistan, which continued to fight the Taliban.

Consequent to the al-Qaeda terror attacks on New York and Washington in September 2001, the US and its allies started the OEF-A—based on Article 51 of the Charter of the United Nations—as part of their Global War on Terror, removing the Taliban regime from power and decimating al-Qaeda militants. In December 2001 the ISAF, composed of troops from the countries of the NATO alliance, was created and authorized by United Nations Security Council Resolution 1386 and successive resolutions. Its objectives were to assist the Afghan Authority in creating and maintaining a safe, secure, and stable environment while dealing with a strong insurgency. The two military operations of OEF-A and ISAF run in parallel, and although their merging has been intended for some time, this has not yet happened.

The Allied Joint Force Command Headquarters Brunssum carries out NATO's prime mission to ensure that the ISAF can sustain its task over the coming years. The ISAF's multinational headquarters is located in Kabul where operations are planned in close cooperation and coordination with the Combined Forces Command-Afghanistan (OEF-A) and Afghan authorities. Assisted by the Afghan National Security Forces, the ISAF is conducting security and stability operations throughout Afghanistan to secure areas where reconstruction and humanitarian assistance efforts are performed by Afghan governmental organizations, UN missions, and other international or nongovernmental organizations. The ISAF's Provincial Reconstruction Teams are endorsing the provincial Afghan authorities in strengthening their institutions, which are required to fully establish good governance, the rule of law, and human rights.

Starting in 2001 and increasing with tactical demands, an extensive network of forward operating bases and CSHs with attached medical evacuation assets has been established across Afghanistan, providing early

Abbreviations used in this paper: CSH = combat support hospital; GCS = Glasgow Coma Scale; IED = improvised explosive device; ISAF = International Security Assistance Force; KAF = Kandahar Airfield; NATO = North Atlantic Treaty Organization; OEF-A = Operation Enduring Freedom-Afghanistan; RPG = rocket-propelled grenade; UK = United Kingdom.

Fig. 1. Map of Afghanistan.

TABLE 1: Neurosurgical patients admitted to the Role 3 hospital in August 2009

Group	No. of Head Injuries	No. of Spinal Injuries
Coalition Forces	10	1
Afghan Security Forces	19	5
Afghan civilian, male	22	5
Afghan civilian, female	3	1
Afghan children	10	1
total	64	13

and efficient emergency care at varying medical levels. The wounded are being resuscitated on site and then evacuated from the scene by helicopters or ambulances; en route medical care is provided before arriving at the forward operating bases and CSHs for further stabilization and treatment. Medical evacuation response team helicopters will operate 24 hours a day, 7 days a week in all weather conditions. Following local triage protocols, casualties are referred to the ISAF's Role 2 and Role 3 medical units, which are located in southern Afghanistan in Camp Bastion (Helmand Province) and KAF (Kandahar Province), where emergency surgery can be performed promptly and intensive care is provided. The average transport time by helicopter within Helmand and Kandahar Province is approximately 30–40 minutes. After further medical stabilization, patients are airlifted by strategic aeromedical evacuation to Role 4 units in the United Kingdom (Birmingham for British forces) or Germany (Landstuhl for US and Canadian military victims), which can be reached within approximately 7–8 hours after departure from Kandahar, Bagram, or Kabul.

Because of the limited availability of medical assets, changing strategic objectives, and the tempo of combat injuries, admission to military medical facilities in Afghanistan must be restricted. Care for American and NATO forces is provided at all times and for as long as required. Emergency treatment for injured Afghan National Security Forces (army and police soldiers) and local nationals injured as a result of the military conflict is provided until they can be transferred to local Afghan hospitals (for example, Kandahar Regional Military Hospital and Mirwais Hospital) for further treatment or discharged home. Appropriate humanitarian aid for local nationals with nonbattle traumatic injuries and nontraumatic pathology can only be delivered on a case-by-case basis.

Kandahar Airfield is a militarized airport and large military housing complex for approximately 20,000 troops (number rising). It is located approximately 15 kilometers southeast of Kandahar City, the second largest city of Afghanistan with a population of 470,000. The KAF has become the busiest single-runway airport in the world with approximately 5000 aircraft operations per week. The multinational Role 3 hospital at KAF is a medical facility with specialist services and major surgical capabilities, where virtually all traumatic injuries can be treated. It is located on the edge of the airstrip and, as are many other CSHs, is composed of a series of tents, containers, and plywood huts. The hospital generates its own power, is air-conditioned, and has a pharmacy, laboratory, and blood bank as well as radiological capabilities including a CT scanner. Three hard-sided, air-conditioned, and sterile operating rooms are available for emergency interventions. On a regular basis 8 patients can be treated in the intensive care ward and approximately 18 in an intermediate-care ward, with possible expansion in case of mass casualties. The medical staff of the hospital is made up of military and civilian contingents from Australia, UK, Canada, Denmark, Germany, the Netherlands, New Zealand, and the US. Specialties vary according to availability but usually include 2 teams of general and orthopedic surgeons, 2 teams of anesthetists, several emergency physicians, 1 intensivist, 1 internal medicine physician, 1 radiologist, 1 plastic/maxillofacial surgeon, and 1 neurosurgeon. After almost 4 years of Canadian control under the auspices of ISAF, the command is currently assumed by the US Navy (since October 2009). A new, larger hospital made of concrete is presently under construction close to the existing hospital.

No military neurosurgeon was available in Afghanistan until 2007. Up until that time combat casualties received treatment from general, orthopedic, and plastic/maxillofacial surgeons who had undergone some predeployment training in neurosurgery. Some concern arose following a review of several cases managed in the theater, which subsequently led to the deployment of a UK neurosurgeon to Camp Bastion (Lashkar Gar) in May 2007. Since January 2008 a neurosurgeon has been based at the Role 3 Multinational Medical Unit at the KAF. The neurosurgeon, either a military person or a civilian contractor, is supplied through NATO and provides 24/7 coverage for the duration of his or her deployment (6 weeks to 3 months). The neurosurgeons deployed so far came from the UK, Scotland, and Germany.

This Role 3 facility has the only neurosurgeon and plastic/maxillofacial surgeon in southern Afghanistan. Although the precise number of patients admitted and treated at the Role 3 hospital remains classified, we can state that approximately 90% of these trauma cases require primarily orthopedic and/or general surgery, and the majority of wounds are the direct result of blast or pen-

TABLE 2: Mechanism of injury

Cause of Injury	No. of Head Injuries	No. of Spinal Injuries
IED blast	34	5
RPG	9	0
gunshot	6	5
motor vehicle accident	8	0
bomb attack	1	2
rocket attack	3	0
other	3	1

etrating injuries. To demonstrate the workload and spectrum of neurosurgical cases treated at KAF, data on a representative 1-month time span (August 1–30, 2009) and 6 typical clinical cases will be presented in this paper.

The majority of neurosurgical patients treated at the KAF Role 3 hospital during this period were Afghan security forces personnel (24 patients) and Afghan civilians (42 patients). The ISAF troops (11 patients) accounted for only 14% of all cases. Civilian patients admitted to the Role 3 hospital were mostly injured by IED blasts, and only 16% were injured during motor vehicle accidents or from other causes. Space-occupying intracranial hemorrhages and penetrating head injuries are the most frequent pathologies in head-injured patients (40 patients). The impacting force usually causes depressed compound skull fractures or the penetration of bone fragments or foreign material (metallic fragments, gravel, or dirt) into the cerebrum associated with extensive, hemorrhagic, transformed cerebral contusions and cerebral edema. Concomitant damage to the unprotected and vulnerable facial/orbital region in the form of large soft-tissue facial and scalp injuries is frequent. In 21 cases a closed-head injury with or without cerebral contusions of varying extent was the reason for admission. Only a small number of diffuse blast and burn injuries as well as cervical vascular lesions were seen.

The majority of these head and spinal injuries (48 patients) are generated by explosive devices (IED and RPG) and high-velocity gunshots (11 patients). Few lesions are caused during bomb or rocket attacks (6 patients) or motor vehicle accidents (8 patients).

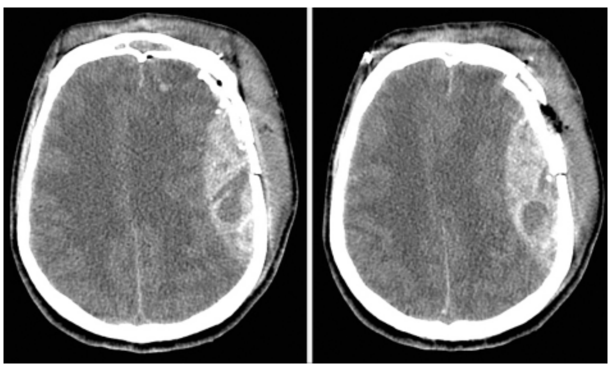

Fig. 2. Case 1. Axial CT scans showing cerebral contusions, a large left-sided temporoparietal epidural hematoma, and a compound depressed skull fracture.

TABLE 3: Injury pattern of traumatic head injuries

Injury	No. of Patients
penetrating head injury	29
epidural hematoma	5
subdural hematoma	7
skull base fracture w/ liquorrhea	2
closed-head injury	21

Spinal injuries are not frequent (13 patients) and are usually caused either directly by the impact of high-velocity projectiles to the spine or spinal canal (5 patients) or indirectly by compressive flexion/extension forces during blasts (8 patients). Spinal injuries are often associated with extensive damage to the abdominal or thoracic structures along the bullet's path.

The majority of injured persons reached the Role 3 hospital in time for emergency neurosurgical intervention (44 patients). Eleven patients died in the hospital from severe brain injury; all had devastating intracranial injuries and were considered not likely to survive.

A limited number of patients (8) were treated for degenerative disc disease, peripheral nerve injury, or severe head or spinal injuries unrelated to the conflict situation (for example, motor vehicle accident, fall, and so forth) as a form of humanitarian aid when resources were available.

Illustrative Cases

Case 1: Penetrating Head Injury. This 35-year-old Afghan man was injured during an IED blast and admit-

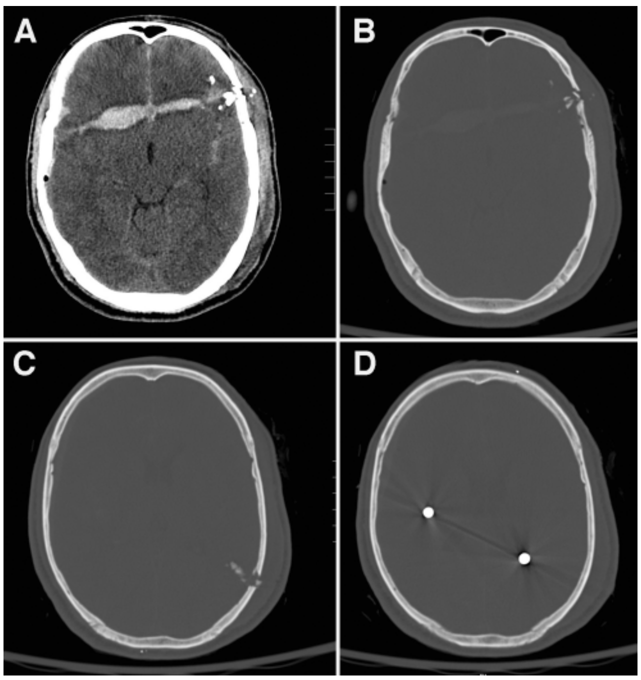

Fig. 3. Case 2. **A:** Axial CT scan demonstrating intracranial hemorrhage and cerebral contusion along the fragment's path. **B–D:** Axial CT scans showing penetration of the skull by 2 RPG metallic fragments, 1 crossing midline structures.

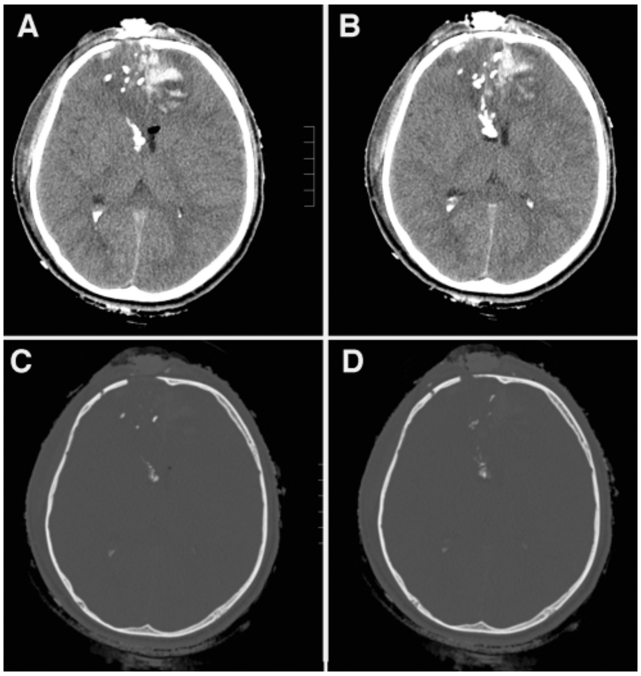

Fig. 4. Case 3. Axial CT scans revealing bifrontal cerebral contusions **(A and B)** caused by the bifrontal penetration of the skull by multiple bone fragments **(C and D)**.

ted to the Role 3 hospital with a GCS score of 9 and a large galea laceration, right-sided hemiparesis, and unequal but reactive pupils. Computed tomography studies showed a compound depressed skull fracture, cerebral contusions, and a large left-sided temporoparietal epidural hematoma. An emergency hematoma evacuation was performed, and the patient was sent to the Kandahar Regional Afghan Military Hospital for further care on postoperative Day 5 (Fig. 2).

Case 2: Penetrating Head Injury. This 25-year-old soldier of the Afghan National Army was struck by the explosion of an RPG. On admission he showed a depressed level of consciousness (GCS Score 8), galea and facial soft-tissue injury, and severe abdominal damage. A CT study showed 2 penetrating RPG metallic fragments, one crossing the midline structures and causing hemorrhage along the fragment's intraparenchymal path before rebounding off the inner table of the skull opposite the entry point. He died as a result of his abdominal injuries (Fig. 3).

Case 3: Penetrating Head Injury. This 30-year-old soldier of the Afghan National Army was hit by fragments of an IED. On admission he had a GCS score of 8 and had suffered severe injury to his face and orbital and frontal region with laceration of the galea, penetrating head injury, and bifrontal cerebral contusions with bifrontally incorporated multiple bone fragments. He died despite emergency neurosurgical intervention (Fig. 4).

Case 4: Penetrating Spinal Injury. This 32-year-old Afghan man was injured during an IED blast. He was admitted awake and alert with both paraplegia from L-4 without rectal tone and associated significant abdominal

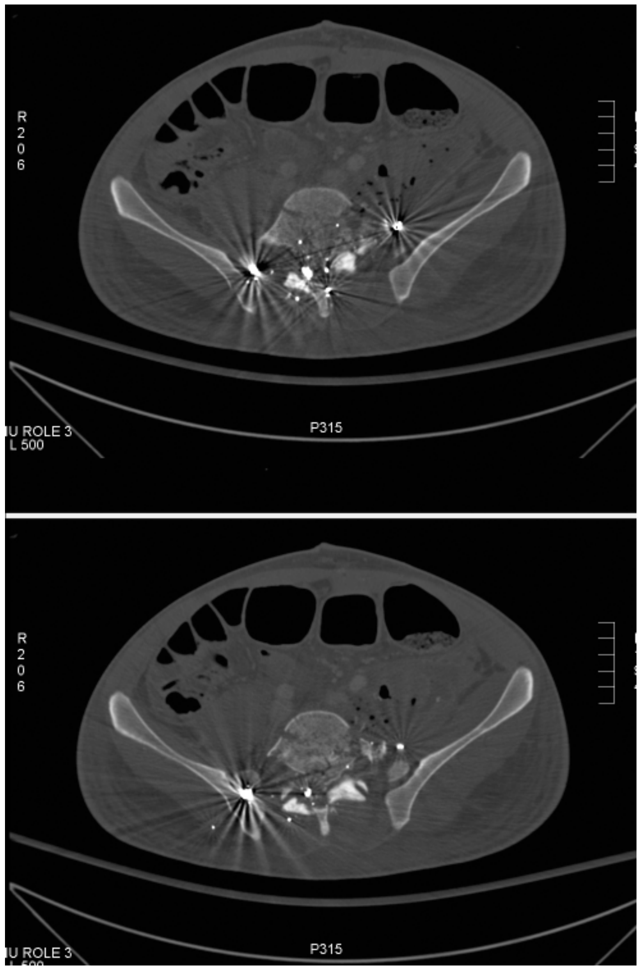

Fig. 5. Case 4. Axial CT scans showing a complex L-5 burst fracture with intra- and paraspinal metallic fragments, penetrating abdominal injury, and retroperitoneal hematoma.

injury. A CT study showed an L-5 burst fracture with intra- and paraspinal metallic fragments, air entrapment within the spinal canal, penetrating abdominal injury, and retroperitoneal hematoma. Initially, the patient underwent surgery for his abdominal injuries. Exploration and debridement of the bullet path revealed the expected CSF leak. The patient underwent neurosurgical decompression and debridement of the cauda equina and dural sac closure. Unfortunately, no spinal instrumentation was available in the hospital at this time. The patient remained paraplegic but survived in good clinical condition and was sent to an external hospital for further care (Fig. 5).

Case 5: Vascular Injury. This 40-year-old soldier of the Afghan National Army was injured during an IED blast. Along with a GCS score of 13 on admission, he had a closed-head injury as well as penetrating cervical and facial injuries without focal neurological signs or symptoms. Computed tomography studies revealed subtotal occlusion of the left vertebral artery by metallic fragments at C-1. After local debridement for his soft-tissue injuries and antithrombotic medical treatment, he was transferred

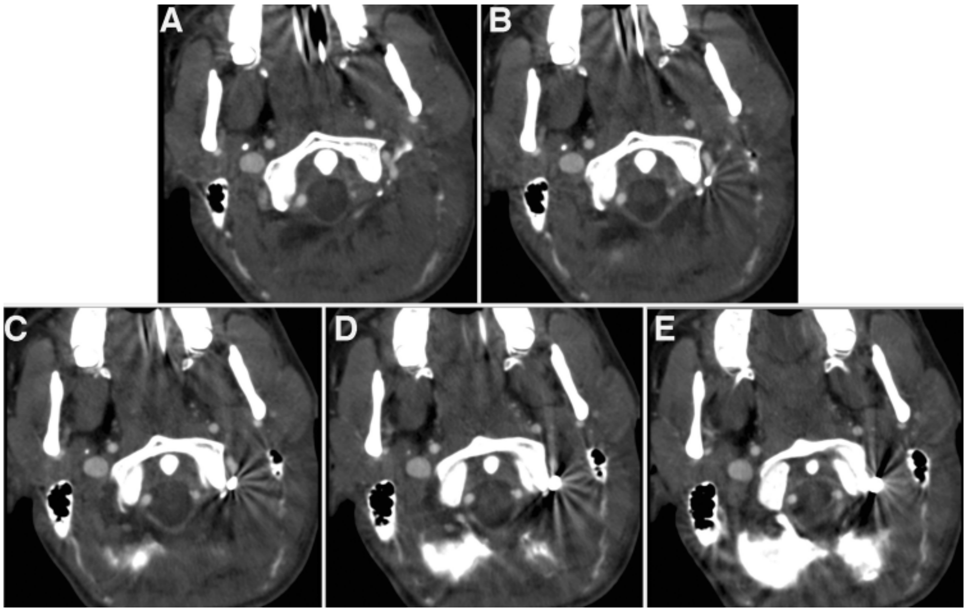

Fig. 6. Case 5. Axial contrast-enhanced CT scans showing subtotal occlusion of the left vertebral artery by metallic fragments at C-1.

to Kandahar Regional Afghan Military Hospital without neurological deficits (Fig. 6).

Case 6: Vascular Injury. This 19-year-old Afghan woman suffered a gunshot wound to her right neck and severe blood loss at the scene. Computed tomography scans showed severe cervical soft-tissue injury with penetration of the left jugular vein and fractures of the transverse processes of C5–7 by the bullet. She underwent surgery with ligature of the left jugular vein, nerve root decompression, and removal of the incorporated bullet. No injuries to other vital structures like the carotid artery, trachea, or esophagus were found intraoperatively. The patient survived with slight numbness in the left C-6 dermatome and mild weakness of the left biceps muscle and was discharged home on postoperative Day 5 (Fig. 7).

Lessons Learned

Based on our experience we would like to stress: 1) the need to attempt to meticulously debride the bone chips, shrapnel, and devitalized brain to minimize the risks of epilepsy and intracranial infection; 2) strict dural repair and closure with dural grafts (pericranium or fascia lata) to restore the best barrier against intracranial infection; 3) generous craniotomy where suitable supplemented by duraplasty as a decompressive measure to counteract the development of the inevitable brain swelling that accompanies high-velocity penetrating brain injury; and 4) strict record keeping to create a pool of knowledge that can be used for further study and discussion at a later stage, like we are doing now.

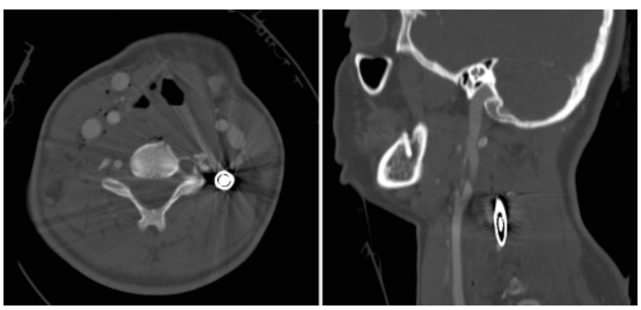

Fig. 7. Case 6. Axial **(left)** and sagittal **(right)** CT scans demonstrating severe cervical soft-tissue injury with penetration of the left jugular vein and fractures of the transverse processes of C5–7 by the bullet.

Conclusions

Even 9 years after toppling the Taliban regime the allied forces must still deal with a strong insurgency, and war in Afghanistan is now bloodier than ever. With the recent arrival of new troops, the balance of military power has shifted south. Presently only 1 neurosurgeon is based in southern Afghanistan. Few ISAF troops have required urgent neurosurgical care, and the majority of treated patients were Afghan Security Forces personnel and civilians injured as a result of military activity. To provide the best neurosurgical care to ISAF troops and their allies, the continuance of this service in southern Afghanistan should be mandatory. The limitation of resources and the possibility of endangering critically ill patients by long flights to a centralized neurosurgical service within the war zone, with the associated tactical limitations and delays, must be balanced. Skilled emergency surgeons should be encouraged to undergo extra training in emergency neurosurgical techniques (bur holes, intracranial pressure monitoring, decompressive craniotomies, and so forth) before their deployment. In close cooperation with the Afghan government the establishment of an Afghan neurosurgical service in the years to come should be considered as a long-term objective. The experience gained in Afghanistan can significantly contribute to the improvement of the neurosurgical techniques used in civilian trauma surgery and in the overall medical management of civilian catastrophic events.

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: MF Eisenburg. Acquisition of data: MF Eisenburg. Analysis and interpretation of data: MF Eisenburg. Drafting the article: MF Eisenburg. Critically revising the article: MF Eisenburg, M Christie, P Mathew. Reviewed final version of the manuscript and approved it for submission: MF Eisenburg. Statistical analysis: MF Eisenburg. Administrative/technical/material support: MF Eisenburg.

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Address correspondence to: Markus F. Eisenburg, M.D., Department of Surgery, Division of Neurosurgery, Klinikum Harlaching, Ludwig Maximilians University, Sanatoriumsplatz 2, Munich, 81545 Germany. email: mbusz@hotmail.com.

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Neurosurgery in Afghanistan during "Operation Enduring Freedom": a 24-month experience

Brian T. Ragel, M.D.,[1] Paul Klimo Jr., M.D., M.P.H.,[2] Robert J. Kowalski, M.D.,[3] Randall R. McCafferty, M.D.,[3] Jeannette M. Liu, M.D.,[4] Derek A. Taggard, M.D.,[4] David Garrett Jr., M.D.,[3] and Sidney B. Brevard, M.D., M.P.H.[5]

[1]Department of Neurological Surgery, Oregon Health & Science University, Portland, Oregon; [2]Wright Patterson Air Force Base, Ohio; [3]Department of Neurosurgery, Wilford Hall Medical Center, Lackland Air Force Base, Texas; [4]Department of Neurosurgery, David Grant Medical Center, Travis Air Force Base, California; and [5]Department of Surgery, R. Adams Cowley Shock Trauma Center, University of Maryland Medical Center, Baltimore, Maryland

Object. "Operation Enduring Freedom" is the US war effort in Afghanistan in its global war on terror. One US military neurosurgeon is deployed in support of Operation Enduring Freedom to provide care for both battlefield injuries and humanitarian work. Here, the authors analyze a 24-month neurosurgical caseload experience in Afghanistan.

Methods. Operative logs were analyzed between October 2007 and September 2009. Operative cases were divided into minor procedures (for example, placement of an intracranial pressure monitor) and major procedures (for example, craniotomy) for both battle injuries and humanitarian work. Battle injuries were defined as injuries sustained by soldiers while in the line of duty or injuries to Afghan civilians from weapons of war. Humanitarian work consisted of providing medical care to Afghans.

Results. Six neurosurgeons covering a 24-month period performed 115 minor procedures and 210 major surgical procedures cases. Operations for battlefield injuries included 106 craniotomies, 25 spine surgeries, and 18 miscellaneous surgeries. Humanitarian work included 32 craniotomies (23 for trauma, 3 for tumor, 6 for other reasons, such as cyst fenestration), 27 spine surgeries (12 for degenerative conditions, 9 for trauma, 4 for myelomeningocele closure, and 2 for the treatment of infection), and 2 miscellaneous surgeries.

Conclusions. Military neurosurgeons have provided surgical care at rates of 71% (149/210) for battlefield injuries and 29% (61/210) for humanitarian work. Of the operations for battle trauma, 50% (106/210) were cranial and 11% (25/210) spinal surgeries. Fifteen percent (32/210) and 13% (27/210) of operations were for humanitarian cranial and spine procedures, respectively. Overall, military neurosurgeons in Afghanistan are performing life-saving cranial and spine stabilization procedures for battlefield trauma and acting as general neurosurgeons for the Afghan community. *(DOI: 10.3171/2010.3.FOCUS09324)*

Key Words • Afghanistan • neurosurgery • Operation Enduring Freedom

Operation Enduring Freedom is the US-led war effort in Afghanistan in its global war on terror. The International Security and Assistance Force is NATO's operation to rebuild Afghanistan and provide security. United States military neurosurgeons are a part of the International Security and Assistance Force, commanded by the acting US general in Afghanistan. The CJTH at Bagram Airfield, Afghanistan, is the military's primary trauma center for the entire country; its mission is to "preserve the fighting force" by caring for injured coalition soldiers (NATO and Afghan military and security forces [AMSF]), as well as to provide care for war-injured enemy combatants and Afghan civilians.[2,3,7,8,18,21,29,36] A secondary humanitarian mission is to provide care for the local community.[3,18,29]

In September 2007, a decision was made to provide continuous neurosurgical coverage to Bagram Airfield by sending a single Air Force neurosurgeon for a 4- to 6-month deployment in support of the dual missions/roles. Surgical and personal experiences and lessons learned are dependent on the role being fulfilled. The types of combat-related injuries to coalition forces and the management of those injuries are similar to those previously reported in Afghanistan and Iraq.[3,11,14,16,19,21,24–26,28–30,32–34,36] However, it is in the context of a secondary

Abbreviations used in this paper: AMSF = Afghan military and security forces; CJTH = Heathe N. Craig Joint Theater Hospital; GSW = gunshot wound; ICP = intracranial pressure; IED = improvised explosive device; MVC = motor vehicle collision; NATO = North Atlantic Treaty Organization; RPG = rocket-propelled grenade; VB = vertebral body.

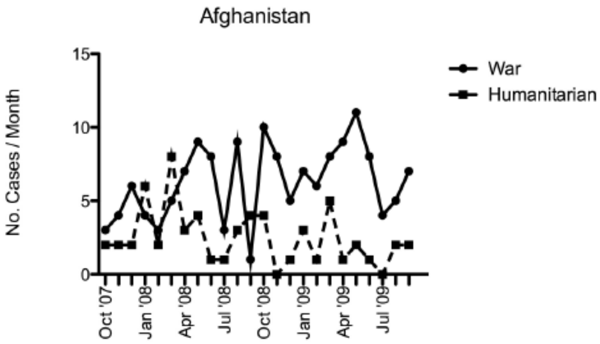

Fig. 1. Line graph depicting number of war and humanitarian neurosurgical operative cases performed per month in Afghanistan during Operation Enduring Freedom between October 2007 and September 2009. Note: The capacity for neurosurgical caseload at CJTH was approximately 8 cases per week. Thus, as wartime operations increased, the ability to accommodate humanitarian cases decreased.

role that neurosurgeons have encountered unique challenges and experiences.

Afghanistan has been at war for the last 30 years, from the occupation by the former Soviet Union in the late 1970s, through fighting between various warlords after the withdrawal of Soviet forces, to the current conflict over the past 8 years. Noncombatant Afghans have been injured as a result of collateral damage from active fighting, millions of past and present land mines, and ongoing placement of IEDs.[3,5,6,18,29] The Afghan health care system is woefully inadequate and rudimentary at best, and few Afghans can afford medical care.[15,18,20] Widespread lack of both running water and waste disposal contribute to the high rate of malaria, intestinal tapeworms, and tuberculosis. Malnourishment abounds, which has direct impact on immediate surgical factors such as prolonged coagulation studies (for example, prothrombin times) and long wound-healing times after surgery.[12]

In this manuscript, we report the types of cases performed by US Air Force neurosurgeons in Afghanistan between October 2007 and September 2009 and detail the lessons learned.

Methods

War Records

At the onset of the neurosurgical mission in Bagram, neurosurgeons kept track of their personal surgical case war records. Data collected included: diagnosis, mechanism of injury if applicable, operation performed, and complications, as well as the patient's sex, age, and country of origin. Mechanism of injury was classified as gunshot wound (GSW), IED, rocket-propelled grenade (RPG), land mine, motor vehicle collision (MVC), or fall from height. For mechanism of injury analysis, IEDs, RPGs, and land mines were combined into one category called "explosive devices." Country-of-origin was classified as NATO (US, Canada, and United Kingdom) or non-NATO (AMSF, enemy combatant, and local Afghan civilians).

Neurosurgical procedures were categorized as major or minor and as battlefield injuries or humanitarian missions. Minor procedures included placement of an ICP monitor, ventriculostomy, cervical spine clearance by active flexion-extension under fluoroscopy, lumbar drainage or puncture, halo orthosis placement, and placement of Gardner-Wells tongs for cervical traction. Major neurosurgical procedures were defined as taking place in the operating room under general anesthesia (for example, craniotomy, placement of spinal instrumentation).

Battlefield injuries were defined as injuries sustained by soldiers while in the line of duty or civilian casualties. Civilian battlefield injuries were injuries caused by weapons of war (for example, GSW, IEDs). Humanitarian work consisted of routine civilian trauma cases and elective procedures. Routine trauma was defined as injuries sustained by local Afghan civilians while performing normal daily activities (for example, MVC or fall from height). Humanitarian elective cases were non–trauma-related neurosurgical cases (for example, myelomeningocele closure, discectomy).

Results

Two-hundred and ten neurosurgical operations were performed in 185 patients at CJTH between October 1, 2007, and September 30, 2009, by 6 neurosurgeons (Fig. 1). Neurosurgeons performed an average of 8.7 operations per month (range 4–14 cases). On average, the number of neurosurgical procedures performed for battlefield injuries and humanitarian work were 6.2 (range 1–11) and 2.5 (range 1–8) per month, respectively (Fig. 1).

One hundred and forty-nine neurosurgical operations for battlefield injuries were performed in 128 patients, including 26 operations in 25 NATO soldiers, 71 operations in 61 AMSF soldiers, 10 operations in 10 enemy combatants, and 42 operations in 32 Afghan civilians who sustained injuries from weapons of war (Table 1). Neurosurgical humanitarian cases accounted for 34 procedures in 31 patients for routine trauma and 27 elective operations in 26 patients (Table 1). Overall, 71% (149) of the 210 surgical procedures performed by military neurosurgeons in Afghanistan were for the treatment of war-related injuries and 29% (61) were considered humanitarian work (Table 1).

Operations for Wartime Trauma

Twenty-five NATO soldiers required 26 neurosurgical interventions for trauma, including 20 cranial procedures (13 craniotomies, 6 decompressive hemicraniectomies for uncontrolled ICP, and 1 decompressive hemicraniectomy for hemispheric stroke secondary to penetrating cervical intracranial artery injury). Two soldiers required spine procedures (1 for a penetrating injury and 1 for blunt trauma). Two soldiers underwent nerve graft repairs (1 for segmental median nerve loss and 1 for a transected peroneal nerve). One soldier required closure of a complex scalp wound. One soldier with neurofibromatosis Type 1 underwent elective surgery for removal of subcutaneous scalp neurofibromas. All NATO soldiers undergoing neurosurgical operations for trauma at CJTH were medically evacuated to a US military hospital in Germany (Landstuhl Regional Medical Center) when medically stable

TABLE 1: Neurosurgical procedures performed by US military neurosurgeons in Afghanistan in support of Operation Enduring Freedom*

			No. of Cranial Procedures			No. of Spinal Procedures		
Category	No. of Pts	No. of Cases	Craniotomy	DHC	Other	Stabilization	Other	No. of Misc Cases
war trauma	128	149	76	30	0	19	6	18
NATO	25	26	13	7	0	1	1	4
AMSF	61	71	36	16	0	13	3	3
EC	10	10	6	1	0	1	0	2
AL	32	42	21	6	0	4	2	9
humanitarian†	57	61	20	6	6	12	15	2
trauma	31	34	17	6	0	9	0	2
elective	26	27	3	0	6	3	15	0
total	185	210	96	36	6	31	21	20

* Between October 2007 and September 2009, 210 operations were performed in 185 patients for war-related injuries and humanitarian work by 6 neurosurgeons. Abbreviations: AL = Afghan local; DHC = decompressive hemicraniectomy; EC = enemy combatant; Misc = Miscellaneous; Pts = Patients.
† Surgical procedures involving treatment of local Afghan civilians.

(usually 12–24 hours after surgery). The US soldiers were subsequently transported back to the US 3–4 days after injury.[2,21]

Sixty-one Afghan soldiers required 71 neurosurgical operations, including 52 cranial procedures, 16 spine procedures (13 spine stabilizations, 1 dural repair after penetrating injury, and 2 partial sacrectomies), and 3 miscellaneous operations (2 incision and drainage of scalp wounds and 1 incision and drainage of lumbar wound). Ten enemy combatants required 7 cranial surgeries, 1 spinal stabilization, and 2 complex scalp wound closures. Forty-two operations were performed in 32 local Afghan citizens, including 27 cranial surgeries, 6 spine surgeries (4 spine stabilizations and 2 dural repairs after penetrating injury), and 9 miscellaneous surgeries (5 closures of complex scalp lacerations, 3 peripheral nerve repairs, and 1 neck exploration).

Operations for Humanitarian Work

Neurosurgical humanitarian work consisted of routine trauma and elective cases. Thirty-one Afghan patients had 34 neurosurgical operations for trauma sustained during normal daily activities. This included 23 craniotomies, 9 spine stabilization surgeries, and 2 complex scalp closures. One patient sustained a non–combat-related indirect GSW to the head while attending a wedding celebration. Twenty-six Afghans underwent 27 elective surgeries, including 3 craniotomies for tumor, 6 miscellaneous cranial procedures (4 ventriculoperitoneal shunt placements, 2 arachnoid cyst fenestration), and 18 spine procedures (12 basic spine surgeries, 4 myelomeningocele closures, and 2 spine operations for tuberculous spondylitis).

Mechanism of Injury

For injuries sustained by NATO soldiers, the mechanism of injury was GSW in 38% of cases (9/24), explosive device in 54% (13/24), and accident in 8% (2/24). In AMSF, the mechanism of injury was GSW in 33% (20/61) of cases, explosive device in 56% (34/61), and accident in 11% (7/61). In Afghan civilians, the mechanism of injury was GSW in 23% (15/63), explosive device in 27% (17/63), and accident in 49% (31/63) (Table 2).

Minor Procedures

One-hundred and fifteen minor procedures were performed over the time studied. These consisted of 85 procedures for battlefield injuries and 30 procedures for humanitarian cases. Minor procedures for wartime cases included 51 ICP monitor placements, 15 ventriculostomies, 10 lumbar punctures or drain placements, 8 cervical spine clearances by flexion-extension under fluoroscopy, and 1 halo orthosis placement. Minor procedures for humanitarian cases included 15 ICP monitor placements, 5 ventriculostomies, 6 instances of lumbar puncture or placement of lumbar drain, 3 flexion-extension studies of the cervical spine under fluoroscopy, and 1 placement of Gardner-Wells tongs for cervical traction.

Complications

No surgery-related complications were noted in NATO forces prior to transfer to Germany. However, these patients were transferred within 1–2 days of surgery and were lost to follow-up to the authors. The authors report only their personal war records, which did not include patient identifiers. Additionally, the US Armed Forces do not track medical outcomes on non-US NATO soldiers. However, the following complications were noted in non-NATO patients: 2 deaths during craniotomy for trauma from pulmonary embolus and uncontrollable bleeding from the sagittal sinus, 1 postoperative death from sepsis after delayed closure of open myelomeningocele, 1 wound revision 5 days after craniotomy for penetrating head injury with debridement of necrotic brain, 2 bone flap expansions after decompressive hemicraniectomy to prevent herniation of brain over bone edges, 1 case of increased paraparesis after thoracic anterior vertebral body reconstruction for tuberculous spondylitis, 4 cases in which incision and drainage of previously closed complex scalp wounds was required, and 2 wound revisions.

TABLE 2: Mechanisms of injury in 210 neurosurgical procedures in an inpatient wartime hospital*

		Mechanism of Injury (%)		
Patient Category	No. of Patients	GSW	Explosive Devices†	Accidents
NATO	24‡	38	54	8
AMSF	61	33	56	11
Afghan civilian	63§	23	27	49

* Surgery performed by 6 neurosurgeons between October 2007 and September 2009 at CJTH. The 210 operations were performed in 185 patients for treatment of war-related injuries and as part of the humanitarian mission.

† Includes IEDs, RPGs, and land mines.

‡ Excludes 1 soldier who underwent an elective procedure.

§ Includes all local Afghan civilians who were treated for either wartime trauma (32 patients) or non–war-related trauma (humanitarian work, 31 patients).

Case Illustrations

Case 1—Decompressive Hemicraniectomy for Penetrating Head Injury

This 23-year-old male Afghan soldier sustained a low-velocity GSW to the right parietal region (Fig. 2). His Glasgow Coma Scale score was 5T, and a head CT scan showed the bullet resting in the right parietal cortex with imploded bone fragments along the bullet path (Fig. 2). The patient underwent a right decompressive hemicraniectomy with wound debridement; the bone flap was stored in a freezer. Three months postoperatively, the patient was conversant and ambulatory on examination. Four months after the decompressive craniectomy, the patient underwent successful autologous cranioplasty with a good cosmetic result.

Case 2—IED Injury to the Eye

This 14-year-old Afghan boy had been struck by a roadside IED and was brought to the CJTH with a large retained metal fragment projecting through the right orbit and into the frontal lobe (Fig. 3). It took over 4 days for him to reach the hospital from his village in western Afghanistan. During this time, the boy was kept moderately sedated with intravenous medication. On arrival, he was awake, alert, and had no focal signs of deficit except for blindness in his left eye. A CT angiogram revealed no evidence of vascular injury. The patient underwent a bifrontal craniotomy to expose the distal end of the fragment (part of a bomb casing), which was then removed in a controlled fashion. The frontal lobe was debrided, a duraplasty was performed, and the frontal fossa floor was repaired with bone and titanium microplates. Ophthalmologists then performed a formal enucleation. Post-

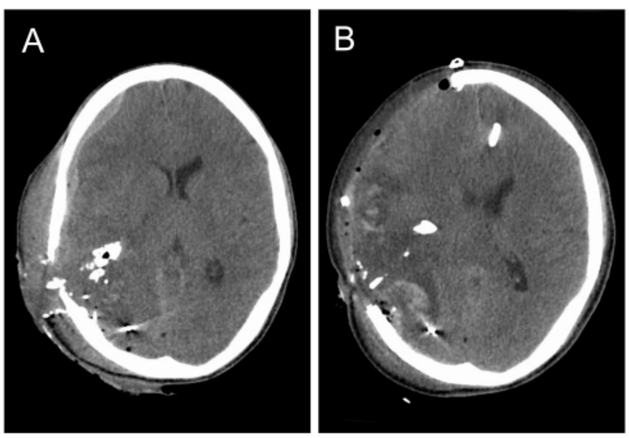

Fig. 2. Illustrative Case 1. **A:** Axial CT image depicting GSW to the head in which the bullet entered the right parietal bone causing implosion of bone fragments inward along the bullet track. The low-velocity bullet penetrated approximately 3 cm before stopping in the right parietal cerebral cortex. **B:** Axial CT after placement of left external ventricular drain and right decompressive hemicraniectomy for debridement of GSW. Note: Because of brain swelling, the bone flap was left off and stored at 30°F until cranioplasty with autologous bone flap.

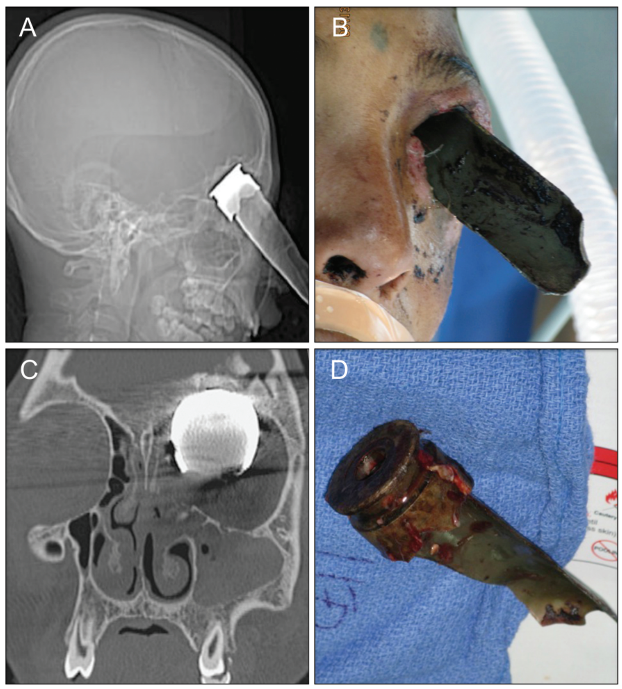

Fig. 3. Illustrative Case 2. **A and B:** Lateral skull radiograph **(A)** and photograph **(B)** depicting metal pipe fragment from an IED that impacted the patient's left eye. **C:** A CT coronal reconstruction showing the blunt portion of the metal fragment located within the left orbit. **D:** Photograph of the metal pipe fragment after removal.

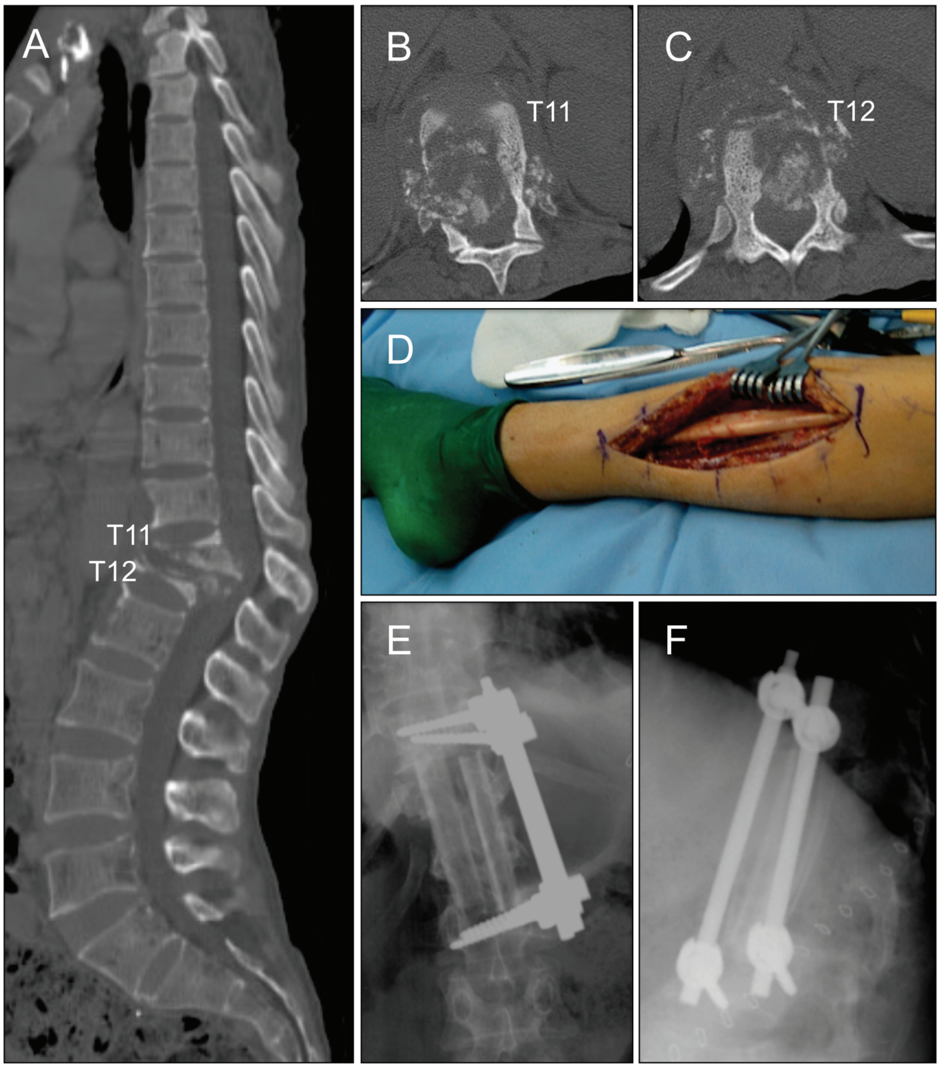

Fig. 4. Illustrative Case 3. **A:** A CT sagittal reconstruction of tuberculous spondylitis eroding the T-11 and T-12 VBs with retropulsion of a caseating granuloma–bone fragment mass into the spinal canal. **B and C:** Axial CT images of the T-11 **(B)** and T-12 **(C)** VBs showing approximately 50% spinal canal narrowing. **D:** Photograph of left fibula exposure prior to harvesting for "double-barrel" autologous bone grafting for T11–12 anterior VB reconstruction. **E and F:** Lateral **(E)** and anterior-posterior **(F)** radiographs of the final anterior VB reconstruction with double-barrel fibular strut grafts and lateral VB pedicle screw and rod construct.

operatively, the patient made an excellent recovery aside from his unilateral blindness.

Case 3—Tuberculous Spondylitis With Anterior VB Reconstruction

This 60-year-old woman with known tuberculosis presented with a 2-year history of worsening lower extremity paraparesis. She had been wheelchair bound for the past year. An examination showed a kyphotic deformity at the thoracolumbar junction and lower extremity strength of 3 out of 5 throughout (Fig. 4). A spine CT revealed severe erosion of T-11 and T-12 with 50% canal compromise (Fig. 4). The patient underwent a left thoracotomy with removal of a caseating granuloma at T11–12. Anterior VB reconstruction was accomplished with double-barreled autologous fibular strut graft and lateral VB rods and screws.[27] The patient was able to walk with assistance at the 2-month follow-up examination.

Discussion

Military neurosurgeons in Afghanistan serve a dual role of providing care to soldiers and to the local Afghan community.[3,18,29] Interestingly, the surgical challenges of today's conflicts are similar to those of previous wars, with limited hospital beds, supplies, and personnel.[38] A war-zone medical facility must quickly transfer wartime injured soldiers out of the country (usually, NATO forces) or to local hospitals (typically, Afghan Army) in order to maintain the ability to treat the newly wounded. Thus, economic use of personnel and hospital resources mandated prompt operative decision-making to balance

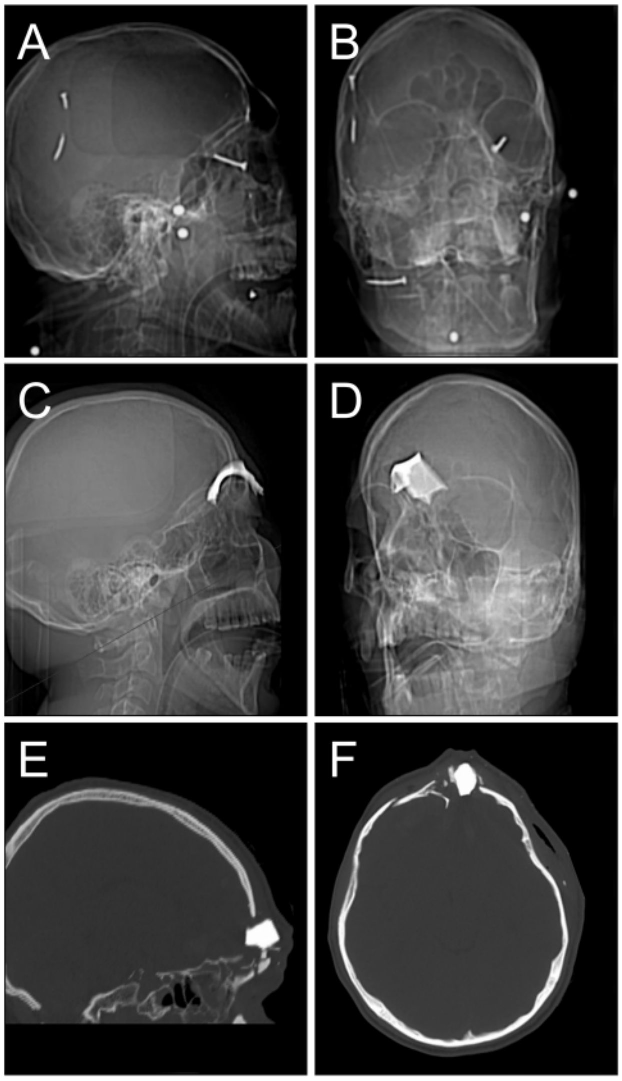

Fig. 5. Examples of penetrating head injuries from IEDs. **A and B:** Lateral **(A)** and anterior-posterior **(B)** CT scout images obtained in a soldier attacked by roadside IED packed with nails and ball bearings. **C and D:** Lateral **(C)** and anterior-posterior **(D)** CT scout images obtained in a soldier attacked by IED with a metal fragment "hooked" into frontal sinus. **E and F:** Sagittal **(E)** and axial **(F)** head CT images obtained in a soldier attacked by IED with rock impacting the left frontal bone.

patient outcome with rapid, safe transfer of patients. For example, decompressive craniectomy evolved to be the treatment of choice for recalcitrant ICP elevation because it allowed for the safe transfer of patients on long medical flights, as well as to local hospitals lacking intensive care units. Humanitarian work was also limited by the local Afghan medical system's ability to care for patients needing either high-end nursing care (for example, care of quadriplegic patients) or advanced treatment modalities (for example, chemotherapy). Therefore, neurosurgeons tended to focus humanitarian surgical efforts on disease states that did not require advanced care or therapies.

Mechanism of Combat-Related Injuries in Soldiers and Civilians

A difference in the proportion of surgeries for soldiers in comparison with Afghan citizens was observed. The proportion of GSW victims who required neurosurgery for their wounds was between 33 and 39% for soldiers and 47% for Afghan locals. We attribute this difference to the wide use of helmets and body armor by soldiers.[3,29] The proportion of NATO soldiers requiring neurosurgery is higher than the overall injury rates previously reported in the literature.[3,14,16,19,25,26,28–30,32,36,37] A recent report noted 6609 injuries in 1566 US soldiers during combat in Iraq and Afghanistan.[26] In that study, the proportions of injuries caused by GSW and explosions were 18 and 78%, respectively.[26] The authors attribute differences in the data they present (38 and 54%, respectively, Table 2) to the different preferences in enemy tactics in Afghanistan (use of direct- and indirect-fire weapons) and Iraq (use of IEDs). Also, our data reflect the caseload at an inpatient wartime hospital rather than overall wartime soldier injury patterns. Interestingly, military neurosurgeons are asked to provide forensic information to aid in the analysis of evolving enemy tactics.

Lessons Learned in the Operative Management of Penetrating Head Injuries From IEDs

The opposing fighters use IEDs to incapacitate or destroy personnel and equipment. These devices are usually constructed from conventional military high-explosive weapons (e.g., artillery shells) attached to a detonating mechanism.[7,13,14,22,24] Such IED attacks in Afghanistan and Iraq are common, accounting for 48% (2560/5283) and 65% (23,650/36,222) of all US soldier deaths and injuries, respectively.[1] Our experience with penetrating cranial injuries due to IED blast reveal cranial injuries from ball bearings, nails, metal fragments, and rocks (Cases 1 and 2; Figs. 2, 3, and 5).

Several issues were important in the management of these patients. Patient hemodynamic stabilization was a priority in these cases, with treatment of life-threatening bleeding attended to prior to or in conjunction with the craniotomy. Without access to magnetic resonance (MR) imaging equipment, CT angiograms proved valuable for evaluation of intra- and extracranial vascular injury due to a roughly 30% incidence of cerebrovascular injury.[4] Aggressive surgical management was warranted in all cases not believed imminently fatal. Large craniotomies were performed in the event of need to convert to a decompressive hemicraniectomy. There was a low threshold to perform decompressive hemicraniectomies for those cases in which the neurosurgeons believed intracranial hypertension was highly likely, this is because of long transport flights where neurosurgical care and intracranial monitoring were not available (Case 1).[4] Particular attention was paid to making the craniotomy as large as possible to diminish the risk of any postoperative ICP issues and also to prevent herniating brain tissue from becoming lacerated and ischemic at the cut bone edges. Intraparenchymal injuries were debrided without being overly aggressive with deep and small bone or foreign fragments, and large hematomas were evacuated. The first surgery often represented "damage control" surgery with an emphasis on quick removal of mass lesions, homeostasis, and quick decision on decompressive hemicraniectomy; deep imploded bone fragments and foreign bodies were not chased.[4] Second or third operations were sometimes necessary for further debridement of necrotic brain tissue, and it was found that deep imploded bone fragments and foreign bodies would often deliver themselves to the surface at this time.

Lessons Learned in Bone Flap Management

Bone flap management for soldiers being transported on an 8-hour flight to Germany without subzero freezers, as well as proper handling and storage of autologous bone flaps of Afghan patients without cryogenic freezers presented unique challenges in cases requiring decompressive hemicraniectomy. Three scenarios of managing decompressive bone flaps were encountered, depending upon the patient's country of origin. For US soldiers, bone flaps were routinely discarded because of fear of infection and our excellent cosmetic results from 3D methylmethacrylate prosthetic implants.[21] For all patients from other NATO forces, bone flaps were placed in a subcutaneous abdominal pocket, preferably on the left lower quadrant to avoid contamination by feeding tube placement and to decrease the chance of later confusion with an appendectomy scar. Finally, for injured Afghans, bone flaps were washed with bacitracin irrigation, sterilely wrapped, and stored at 30°F (Case 1, Fig. 2). To date, no postoperative cranioplasty infections have been noted. One 4-year-old patient required cranioplasty revision with mesh and methylmethacrylate at 8 months postoperatively because of autograft resorption.

Lessons Learned in Humanitarian Work

The Afghan health care system has been devastated due to the 3 decades of constant military conflict.[5] Many medical professionals fled the country in the 1980s and 1990s resulting in a halt in the training of new health care professionals. In the early 2000s Afghanistan had 11 physicians and 18 nurses per 100,000 population, with 1 medical facility for every 27,000 people.[5] Most of the current health care is provided by humanitarian aid, with roughly 25% of the population having no access to medical care.[5] Between 250 and 400 patients daily at an Egyptian hospital at Bagram Airfield, with patients needing neurosurgical care referred to the CJTH. Patients were often within driving distance, but some were known to walk for weeks before reaching the Egyptian hospital. The decision to treat neurosurgical disorders was complex and imperfect. Due to lack of ancillary services, the neurosurgeons were unable to treat any disease process that would require prolonged hospitalization, or further high-end therapies (for example, chemotherapy). Treated patients were cared for until well enough to transfer to the Egyptian inpatient service or home.

Neurosurgeons undertaking humanitarian work in Afghanistan report observations similar to those reported by other workers in war-torn countries: horrific wounds from years of war, lack of adequate local health care, malnourishment, long travel times for patients, and lack of postoperative tertiary care (for example, tracheostomy care).[9,10,23,32,39] Overall, US military neurosurgeons performed a broad spectrum of general neurosurgical procedures including myelomeningocele closures, microdiscectomies, spine stabilization for tuberculous spondylitis, craniotomy for tumor, and general neurosurgical trauma care for Afghans injured during normal daily activities.[31] Several lessons were learned in treating malnourished patients, as well as patients with tuberculosis.[17]

The general nutritional health of the average Afghan civilian is poor because of a combination of inadequate nutritional intake and endemic intestinal parasites (for example, ascarids). The 2 major surgical issues attributed to malnourishment were prolonged coagulation studies and poor wound healing. Preoperative administration of vitamin K would usually correct mildly elevated coagulation studies within 24 hours.[12] Attempts to enhance wound healing were made by treating patients with an antihelminthic medication (usually mebendazole) in hopes of increasing nutritional absorption in the short term. In addition, incision staples were left in for at least 14 days because earlier removal often resulted in wound dehiscence. Tuberculosis is also endemic in Afghanistan and untreated patients were required to complete at least 2 weeks of an antituberculosis regimen (typically rifampin and isoniazid) prior to being allowed into the hospital to undergo elective surgery.[17]

Lesson Learned in Case of Probable Early Fatal Pulmonary Embolus After IED Attack

We would like to draw attention to one particular case of a soldier who died in the operating room of a presumed pulmonary embolus. This 25-year-old Afghan soldier was a passenger in a car attacked by an IED, and sustained a right open tibia–fibula fracture and depressed frontal sinus fracture with embedded bone fragment in the left frontal lobe. A CT angiogram showed no vascular injury. The patient was taken to the operating room for simultaneous below-the-knee amputation and bifrontal craniotomy for skull fracture elevation. Shortly after the leg was removed and the bifrontal craniotomy performed, the patient went into cardiac pulseless electrical activity and his oxygen saturation dropped to 40%. Cardiopulmonary resuscitation was instituted. Intraoperative maneuvers included covering the sagittal sinus with wet packs, placement of bilateral chest tubes, aspiration of the right ventricle with a long central line, replacement of the bone flap, and closure of scalp wound. Epinephrine and blood products were administered. Upon return of his pulse, the patient was transferred to the intensive care unit where an echocardiogram revealed a hypokinetic heart without evidence of air embolus. The cardiac rhythm was again lost and the patient died after bedside exploratory laparotomy and thoracotomy for open cardiac massage. An autopsy was not performed due to local Afghan customs requiring the deceased to be buried within 24 hours.

We believe blast injuries prime the vascular system for deep vein thrombosis and venous thromboembolism by damaging vascular endothelium and upregulating procoagulation factors (such as thromboxane A2).[7,13] This, combined with extremity bone fractures, rapid infusion of blood products, and possible activated factor VII administration, may increase the chance of early deep vein thrombosis with subsequent fatal pulmonary embolus.[35] Although in this case fatal air embolus cannot be excluded, we believe primary embolus is more likely due to isolated reports of similar intraoperative deaths in Iraq after attack by IED (personal communications) and the negative echocardiogram. After this case, only life-saving craniotomies were immediately performed on patients sustaining polytrauma from IED attack.

Conclusions

Military neurosurgeons in Afghanistan perform life-saving cranial operations and spine stabilization procedures for wartime injuries and act as general neurosurgeons to the local Afghan community. The lessons learned with regard to combat-related injuries are similar to those learned in Iraq and other conflicts. Military neurosurgeons are also asked to provide forensic information to aid in the continual assessment of evolving enemy tactics. We experienced unique issues when treating the local Afghan population. As the neurosurgical mission continues in Afghanistan, undoubtedly lessons will continue to be learned and measures implemented that will hopefully further endeavors to provide the best care for all patients.

Disclosure

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

The opinions and assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of the US Air Force, the Department of Defense, or the Department of Veterans Affairs.

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Address correspondence to: Brian T. Ragel, M.D., Department of Neurological Surgery, Oregon Health & Science University, Mail Code CH8N, 3303 SW Bond Avenue, Portland, Oregon 97239. email: brian.ragel@gmail.com.

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Use of neurosurgical decision-making and damage-control neurosurgery courses in the Iraq and Afghanistan conflicts: a surgeon's experience

Richard J. Teff, M.D.

Division of Neurosurgery, Brooke Army Medical Center, Fort Sam Houston, Texas

A shortage of Coalition neurological surgeons in the Iraq conflict prompted a creative approach to standardized neurosurgical care in 2007. After formulation of theater-wide clinical pathway guidelines, a need for standardized triage and neurological resuscitation was identified. The object was to establish a simple, reproducible course for medics, forward surgical and emergency room personnel, and other critical care providers to quickly standardize the ability of all deployed health care personnel to provide state-of-the-art neurosurgical triage and damage-control interventions. The methods applied were Microsoft PowerPoint presentations and hands-on learning. The year-long project resulted in more than 100 individuals being trained in neurosurgical decision making and in more than 15 surgeons being trained in damage-control neurosurgery. At the year's conclusion, hundreds of individuals received exceptional neurosurgical care from nonneurosurgical providers and a legacy course was left for future deployed providers to receive ongoing education at their own pace. *(DOI: 10.3171/2010.2.FOCUS1017)*

Key Words • **wartime neurosurgery** • **penetrating brain trauma** • **neurosurgical decision making** • **damage-control neurosurgery**

Wartime neurosurgery has been provided by neurosurgeons since World War I. Prior to this, and subsequently as an adjunct to formal neurosurgical care, general surgeons and other nonneurosurgeons have done the best they could with existing supplies to treat head-injured casualties during every wartime conflict. The Iraq and Afghanistan conflicts have not been exceptions. By the 4th year of the Iraq-Coalition conflict, 6 American combat support hospitals provided advanced surgical care to all arriving casualties. Despite this, only 2 neurosurgeons were stationed in a single theater hospital to provide all of the definitive neurosurgical care for both Iraq and Afghanistan. Casualties from other locations were evacuated to the neurosurgical providers in Iraq or the evacuation hospital in Landstuhl, Germany, or simply cared for by the providers on the ground at that moment. Though some nonneurosurgeons took the initiative to seek additional training in neurosurgical techniques, the vast majority of providers remained untrained and incapable of delivering even basic neurosurgical care to head-injured casualties. The formation of a Joint Theater Trauma System and Clinical Pathway Guidelines established basic principles of care for patients after stabilization in the intensive care unit. Triage and damage-control principles for neurosurgical patients were not distributed until 2006.

Description

While stationed in Balad at the Air Force Theater Hospital, neurosurgeons MAJ Hans Bakken and LTC Richard Teff identified several patients evacuated from Baghdad and Basra who had undergone damage-control craniotomies prior to evacuation for definitive neurosurgical care (Figs. 1 and 2). Among these were patients with malpositioned and inadequate decompressive craniectomies who received no benefits from the operations they had undergone. Dozens of other patients suffered from triage and management errors that placed the patient or providers at unnecessary risk.

Initial attempts toward reconciliation of these problems established better lines of communication and joint decision making. Telephone number rosters and pagers were distributed to more quickly connect the theater neurosurgeons and the Combat Support Hospital providers. Better Internet connections and advanced radiology software allowed CT scans to be quickly and routinely sent between hospitals. Despite this, patients were frequently evacuated emergently when outlying providers felt overwhelmed by head-injured patients. Countless medevac missions were created for patients with mild head injuries, frequently placing helicopter personnel at needless risk. At the other end of the triage spectrum, many moribund patients were flown at great risk and cost, only to receive palliative care when they arrived in Balad.

Further attempts toward education were difficult. Transportation of neurosurgeons to provide standardized triage teaching to providers at each Combat Support Hospital was risky to the neurosurgeons and left Balad without key providers. After redeployment of MAJ Bakken, MAJ Donny (Mark) Melton and LTC Teff set out to establish a triage course that could be delivered via the Internet to any provider in any location at any time. The

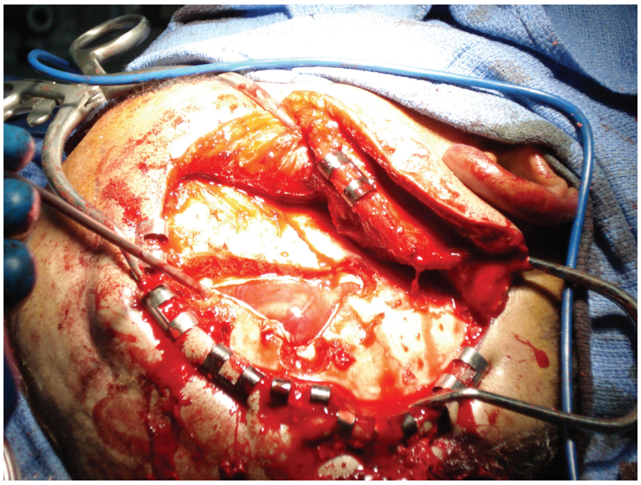

Fig. 1. Intraoperative photograph showing an example of a misplaced right craniotomy incision that resulted in a decompression too small to achieve any meaningful therapeutic result.

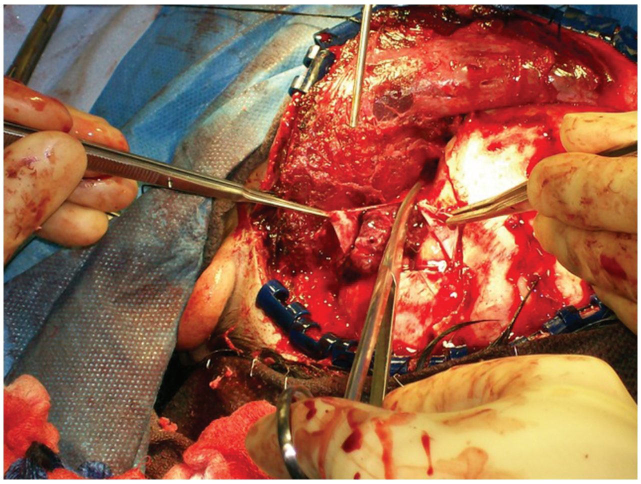

Fig. 3. Intraoperative photograph showing the dura mater being opened by MAJ Kenneth Yu during a damage-control temporal craniectomy in a child in Afghanistan.

course was divided into 2 major sections: the Neurosurgical Decision Making Course for medics, nurses, and nonsurgical physicians; and the Damage Control Neurosurgery Course for select surgeons who would be stationed at the Combat Support Hospitals outside Balad.

The first individuals to receive Neurosurgical Decision Making training were the providers at Ibn Sina Hospital in Baghdad, Iraq's busiest military trauma hospital. Selected members of the 28th Combat Support Hospital viewed 6 PowerPoint presentations as follows:

1. Introduction to Neurosurgical Decision Making
2. The Essential Neurological Exam
3. Interpretation of the Non-Contrast Head CT
4. Abnormal CT Findings and Neurosurgical Decision Making
5. Intracranial Pressure Monitoring
6. Neurosurgical Clinical Pathway Guidelines

After demonstrating proficiency with these principles, interested individuals received hands-on training in the placement and use of Codman strain gauge intracranial pressure monitors. These providers were taught how to use ICP monitoring to guide advanced interventions used in the reduction of intracranial pressure.

Finally, selected surgeons with exceptional understanding of the decision-making principles were taught how to perform a damage-control craniectomy in patients who would benefit from the intervention. Lieutenant Colonel James Frizzi, a general surgeon stationed with the 28th Combat Support Hospital at Ibn Sina Hospital, was the first to hone his skills from simply performing craniectomies to adequately decompressing the brainstem, saving multiple lives with his interventions.

After the successful training of the Baghdad providers, priority was turned to a select surgeon deploying to Afghanistan. With no American neurosurgeon available, he would be the only damage-control provider for the first 24 hours of Coalition neurosurgical casualty care. Major Kenneth Yu, US Air Force otolaryngologist, reluctantly underwent the decision-making and damage-

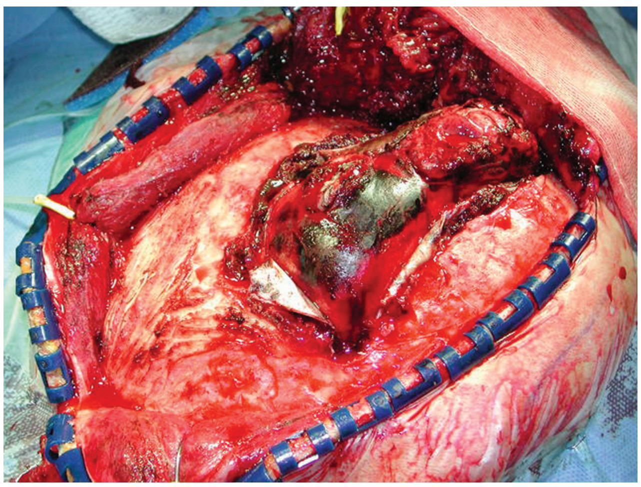

Fig. 2. Intraoperative photograph showing an example of an inadequate left hemisphere craniectomy placed too high on the patient's skull, resulting in strangulation of herniating brain tissue.

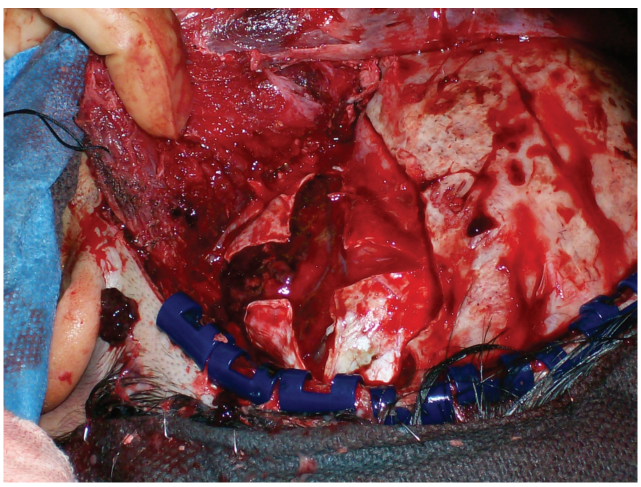

Fig. 4. Intraoperative photograph obtained later during the same procedure as shown in Fig. 3, showing a satisfactory left temporal decompressive craniectomy result achieved by a nonneurosurgeon.

Fig. 5. Postoperative photographs of the child treated by MAJ Yu (Figs. 3 and 4). These photographs were obtained 2 weeks after the damage-control craniectomy. The child walked out of the hospital a week later.

control training, then proceeded to Bagram to perform multiple successful cranial debridements and damage-control craniectomies. Among MAJ Yu's most rewarding outcomes was an Afghani child who would not have survived but for his timely intervention (Figs. 3–5).

After the redeployment of MAJ Melton, MAJ Jon Martin and LTC Teff trained multiple surgeons at Balad to place at least one "damage-control neurosurgeon" at each Combat Support Hospital in Iraq and Afghanistan. Subspecialties of the candidates ranged from obstetrics and gynecology to thoracic surgery. Lieutenant Colonel Teff also recorded the narrative portions of each decision-making lecture to complete the series of 6 for wide distribution via the Internet. Every provider entering Iraq and Afghanistan was given the hypertext link to download these lectures and view them at each individual's own pace during a time of his or her choosing. Today the lectures may be downloaded from Army Knowledge Online (https://www.us.army.mil.) or obtained directly from Dr. Teff at Brooke Army Medical Center.

Outcome

The main focus of this project was wide dissemination of neurosurgical triage and acute management skills to every Coalition health care provider in or entering Iraq or Afghanistan. Today the Neurosurgical Decision Making Course remains available to any individual with Internet access and an interest in developing these skills. The Damage Control Neurosurgery Course has been restricted to and reserved for exceptional surgeons who master the decision-making principles and demonstrate an ability to tackle the complexities of penetrating wartime brain injuries. The Damage Control Neurosurgery Course is presented in Advanced Trauma Life Support (ATLS)–like 2-day fashion and includes both didactic and hands-on skills. The laboratory portion of the course is usually performed with cadaver heads.

Discussion and Conclusions

The need for a Neurosurgical Decision Making Course arose from in-theater observations that most providers are either uncomfortable with or incapable of independently performing triage on wartime casualties with head injuries. War medicine experiences have demonstrated the value of mastering Advanced Trauma Life Support principles and performing trauma resuscitations in a systemic fashion with teams of experienced professionals. Repetition improves individuals' skills, but individuals redeploy and are replaced by new, inexperienced providers who must either reinvent the wheel or learn from the experiences of others. The lack of neurosurgical expertise could not be remedied by simply sending more neurosurgeons into Iraq and Afghanistan. A worldwide need for military neurosurgeons stretches thin the ranks of eligible deployers. Our solution to a lack of neurosurgeons in Iraq and Afghanistan was to train nonneurosurgeons to "hold the line" until patients can be transported to those available in Balad and Landstuhl. The Damage Control Neurosurgery Program was not a perfect solution, but it did standardize the care that was previously provided by trial and error. In the end, lives were preserved and saved lives were improved, if only a little more than in previous conflicts.

The military Damage Control Neurosurgery model cannot be easily extrapolated to underserved areas of civilian America. Needs are similar, but medical standards of care are different. Some will argue that when neurosurgeons are not immediately available, other providers may need to step forward and perform life-saving damage-control interventions. Timely neurosurgery for select individuals does save lives and improve outcomes. This is an evolving focus of modern Acute Care Surgery fellowship programs. Although curricula currently emphasize only neurosurgical decision making, intracranial pressure monitoring, and medical management of patients with head injuries, a growing number of general surgeons are seeking the surgical skills needed to intervene when no neurosurgeon is available.

Those who argue that only neurosurgeons can provide emergent neurosurgical care are challenged to maintain enough neurosurgical providers to willingly cover every American hospital that accepts trauma. As it stands today, deployed American soldiers and underserved American regions are both facing a growing problem in need of definitive solutions.

Disclosure

The author reports no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Address correspondence to: Richard Teff, M.D., Division of Neurosurgery, Brooke Army Medical Center, 3851 Roger Brooke Drive, Fort Sam Houston, Texas 78234. email: richard.teff@yahoo.com.

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Management of neurotrauma by surgeons and orthopedists in a military operational setting

Uwe Max Mauer, M.D., and Ulrich Kunz, M.D.

Department of Neurosurgery, German Armed Forces Hospital of Ulm, Germany

There is a considerable discrepancy between the potential demand for neurosurgeons and the actual availability of such specialists not only in civilian settings but even more so in military operational environments.

For this reason, the Department of Neurosurgery at the German Armed Forces Hospital in Ulm conducts courses for surgeons and orthopedists on the management of patients with neurotrauma. Twelve such courses have already taken place. Each course lasts 1 week. Participants can expect to gain the theoretical knowledge and practical skills they need to provide initial surgical care for patients with traumatic brain injuries and/or spinal trauma. Surgical techniques are practiced above all in pig and human cadavers. At the end of the course, participants with previous surgical knowledge should be able to independently perform a craniotomy, from the planning of the procedure to the closure of the wound. Former course participants have successfully used their neurosurgical knowledge in countries of deployment where they managed patients during teleconsultation sessions and helped repatriate, or even provided surgical treatment to, patients with traumatic brain injuries. In these situations, it was particularly helpful when the physician deployed abroad and the neurosurgeon in Germany knew each other personally. In the future, efforts will be made to combine telemedicine and neuronavigation in an attempt to further improve direct support for physicians under military deployment conditions. *(DOI: 10.3171/2010.1.FOCUS09328)*

Key Words • **neurosurgery course** • **craniotomy** • **trauma surgeon** • **orthopedist**

In civilian settings, generalist surgeons have become obsolete and are being replaced by specialists for all branches of surgery. Neurosurgery was one of the first surgical specialties to emerge as an independent discipline. In 1999, for example, the German Regulations on Continuing Medical Education were changed to the effect that general surgeons are no longer required to learn how to perform a craniotomy. In 2006, these regulations were changed again and now no longer require orthopedists and trauma surgeons to acquire the ability to perform this procedure. For this reason, only a small number of trauma surgeons today perform craniotomies on a regular basis.

Despite this trend toward specialization, however, many patients who require conservative treatment for a TBI are not directly managed by a neurosurgeon. One reason is the sparse availability of neurosurgeons even in Western industrialized countries. It should be noted, however, that many patients actually do not need the specific expertise of a neurosurgeon.[5] A study that was conducted on the basis of the United States National Trauma Data Bank revealed that only 1% of a total of 730,000 trauma patients and 3.6% of all head-injured trauma patients underwent craniotomy.[2] When a neurosurgeon is unavailable in a civilian setting, a trauma surgeon can and must provide emergency surgery for patients with TBI.[7]

The same problem can, of course, arise when medical and surgical care is provided to soldiers under military deployment conditions. During Operation Iraqi Freedom II, for example, intracranial injuries were seen in only 13% of more than 100 patients. The majority of these patients obviously did not require surgery.[8] During deployments, a neurosurgeon cannot be present at all times and at all places to treat a potential patient. For this reason, it is even more likely in a military environment than in a civilian setting that a nonneurosurgeon must operate on a patient with TBI.

To this end, the Department of Neurosurgery at the German Armed Forces Hospital in Ulm has already conducted 12 neurotrauma courses for surgeons since 1995

Abbreviation used in this paper: TBI = traumatic brain injury.

Fig. 1. Practical training using a plastic skull.

Fig. 2. Practical training using a human cadaveric calvarium.

and for orthopedists since 2002 to provide these physicians with the required knowledge and skills. The course was developed on the basis of the experience we gained from the "Ulm Spine Week," which is an instructional course in spine surgery, and from our long-standing course in microsurgery.

At present, there are 12 neurosurgeons who work at 5 German Armed Forces hospitals. These hospitals are fully integrated into the German health care system for the civilian population. Rescue helicopters are stationed at most German Armed Forces hospitals. In these hospitals, which provide the services of a trauma center, neurosurgeons and trauma surgeons regularly cooperate in the management of trauma patients.

Course Objective

It is not the objective of the course to qualify surgeons as neurosurgeons in a brief period of time. If patients are operated on by surgeons who overestimate their abilities in the field of neurosurgery, the consequences could be devastating. Rather, the objective of the course is to give surgeons and orthopedists the knowledge and skills they need to provide simple acute care for patients who are in a life-threatening situation. Surgeons must accept that they can only provide initial care and that patients must be repatriated to their home country for definitive care. Another no less important objective of the course is to make participants understand when no intervention is indicated and when they must simply wait for the repatriation of a patient.

When a surgeon believes that surgery is urgently required because cranial CT scanning demonstrates the presence of bleeding, the consequences can be disastrous if the surgeon is unable to provide appropriate postoperative care. Such a situation is particularly unacceptable when surgery might have been postponed for 24 or 48 hours. For this reason, one of the main objectives of the course is to make surgeons aware of TBI dynamics. After cranial CT, there is usually enough time for a teleconsultation because most patients with a TBI that has a fulminant course cannot be managed surgically due to severe primary brain damage. There is no specialized intervention that can save the life of a patient who does not survive this initial phase from hospital admission to surgery. This knowledge enables every course participant to provide care to a patient with a TBI in accordance with the patient's needs and the surgeon's skills.

Course Program

The course is an official training course offered by the German Armed Forces under the title "Neurotrauma Course for Surgeons and Orthopedists" (No. 803 809 in the German Armed Forces Course Catalog).

Participants can expect to gain both the practical skills and theoretical knowledge they need to provide initial surgical treatment for patients with TBI and/or spinal trauma. Surgical skills are practiced above all on pig and human cadavers.

Each course lasts 1 week and is limited to 20 participants. Sunday is the day of arrival. A course day starts at 8:00 a.m. and finishes around 6:00 p.m. Theoretical sessions, which comprise lectures and seminars *(Appendix)*, take place in the morning. Lectures are given not only by specialists from the German Armed Forces but also by invited speakers of national or international reputation. The small size of the course enables course participants and speakers to engage in dialogue and discussion. While the focus of the lectures is on basic principles underlying the management and especially the diagnosis of patients with TBI, one morning is dedicated to the treatment of spinal injuries.

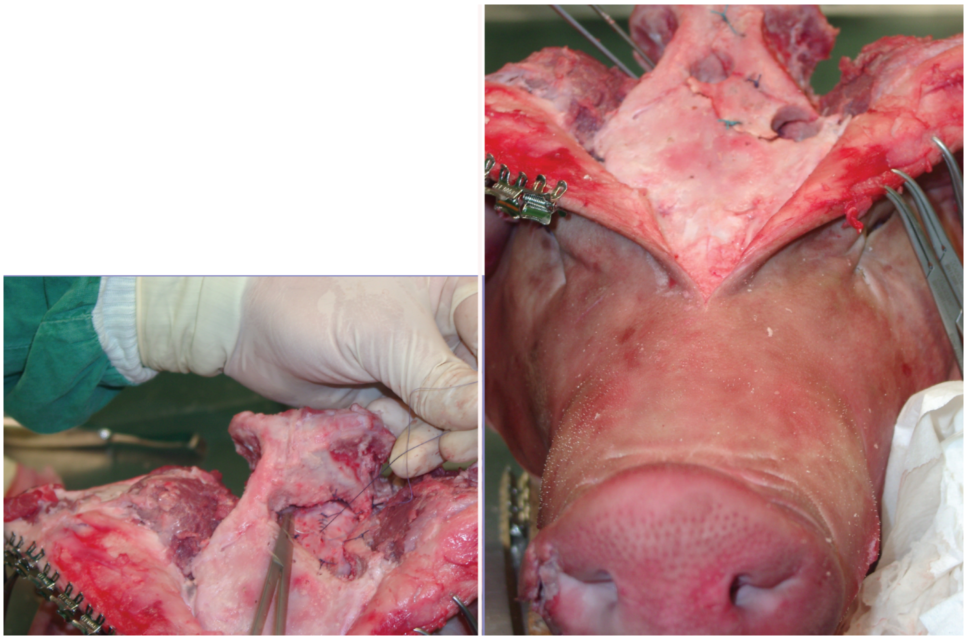

Fig. 3. **Left and Right:** Practical training using fresh porcine skulls.

Parallel to the seminars, craniotomies are performed in the operating room every morning. Two course participants are given an opportunity to assist a surgeon during a craniotomy and to perform part of the procedure themselves. These surgical procedures are broadcast live into the seminar room. During the most important stages of a craniotomy, lectures or discussions are interrupted and images from the operating room, which can be seen permanently on a computer in the seminar room, are projected onto a larger screen for the benefit of the audience.

Practical sessions take place in the afternoon. In a first step, course participants train on plastic skulls (Fig. 1). They practice how to perform a craniotomy and how to replace a bone flap. A balloon filled with air or water is used to simulate the dura mater. At the end of this extensive practical training session, the plastic skulls cannot be reused and may be kept as souvenirs by course participants. In a second step, participants can apply their newly acquired skills and use human cadaveric calvaria and underlying dura for further training (Fig. 2).

In a third step, course participants are trained on fresh porcine skulls (Fig. 3 left). These skulls allow participants to learn and practice how to perform dural sutures and dural tenting sutures, which are used to prevent secondary epidural bleeding and to control primary epidural bleeding (Fig. 3 left). The replacement of a bone flap can also be practiced on porcine skulls (Fig. 3 right), although this is not always an objective of initial surgical care.

In a final step, craniotomies are performed in human cadavers fixed in formalin or, more preferably, using the Thiel method. These cadaver skulls allow course participants to practice the newly learned techniques under relatively realistic conditions. In addition, the practical sessions permit surgeons to study and understand anatomical structures of particular interest to them. All practical training sessions take place in the dissecting room of the Department of Anatomy at the University of Ulm, which is a 5-minute walk from the German Armed Forces Hospital in Ulm.

In addition, interested participants can gain additional experience working on the neurosurgical service during the week. They thus have an opportunity to test and train their skills in real emergency situations.

During and after lunch breaks, participants can attend clinical ward rounds on the interdisciplinary intensive care unit and the neurosurgical ward of the German Armed Forces Hospital in Ulm where they are shown the armamentarium of a neurosurgeon.

At the beginning of the course, each participant receives a plastic skull and a "Handbook for the Management of Patients with Traumatic Brain Injuries," which has been prepared by the Department of Neurosurgery. At the end of the course, each participant receives a CD containing hundreds of digital images taken during the course, a souvenir group photo and a certificate of course attendance. The neurotrauma course is awarded 36 continuing medical education points by the Medical Association of Baden-Wuerttemberg.

The course not only offers participants an opportunity to gain theoretical knowledge and practical skills in the field of neurosurgery but also provides an important forum for meeting colleagues and developing contacts during breaks and after sessions.

Strictly speaking, the neurotrauma course is only the first stage of the training program. Following completion of the course, participants spend 1 week in the department of neurosurgery to apply and extend their knowledge and skills in everyday clinical practice. During this week, they assist in providing medical and surgical care especially to emergency patients. In addition, they take part in planned surgical procedures in neurosurgical cases in which patients have brain tumors or vascular malforma-

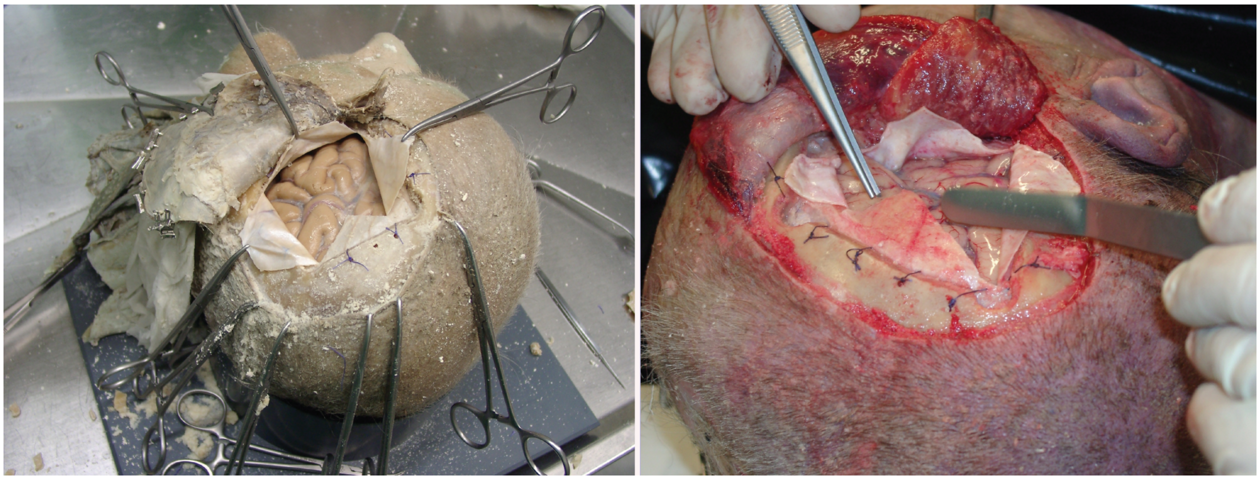

Fig. 4. Practical training using human cadavers fixed in formalin **(left)** or using the Thiel method **(right).**

tions, and they perform craniotomies that are no different from craniotomies in trauma patients. We arrange a time for this second stage of training with each participant on an individual basis.

Accrued Experience

All participants have invariably been highly motivated. Once they know exactly how they should take care of patients with CNS injuries and how much time they have for the management of these cases, their initial fear of treating these patients subsides.

At the end of the course, participants with previous surgical knowledge are able to independently perform craniotomies, from the planning of the procedure to the closure of the wound. Participants with only little surgical knowledge take the opportunity to learn and practice new skills. Similar experience is rarely reported in the literature. In New York, Ko and Conforti[3] established a program for training nonneurosurgeons to perform ventricular catheter placement under the guidance of neurosurgeons using teleradiology. The reported results and the complication rates were similar to those of neurosurgeons. In his damage-control neurosurgery concept, Rosenfeld[6] presented a course for military and civilian surgeons performing urgent surgery in remote environments. This course appears to be broadly similar to the course described here. Recent years have shown that teleconsultation with the specialist at home and the organization of repatriation are particularly effective when the remote expert and the on-site nonspecialist know each other personally and when they share relevant theoretical knowledge.

In 2 cases, former course participants successfully managed patients with an open TBI in the country of

Fig. 5. Management of a gunshot wound to the skull by a former course participant in Afghanistan.

Fig. 6. Management of a subdural hematoma by a former course participant in Afghanistan.

deployment. The first case was a patient in the former Yugoslavia who had an open and depressed fracture of the skull. The second case was a patient in Afghanistan who had sustained an open gunshot wound at a time when neurosurgeons were not yet available in the country of deployment (Fig. 5). Other course participants successfully treated 2 patients with acute subdural hematomas (Fig. 6). In 2 cases, further treatment was provided by one of the German Armed Forces hospitals in Germany that actively contributed to the neurotrauma course. The clinical course was good in both cases. Because the other 2 patients were referred to hospitals in their home countries, no information on their further course is available. Their initial clinical course in the country of deployment was unremarkable.

Unfortunately, recent years have also shown that former participants tend to forget some of what they have learned in the course since they do not see patients with TBIs or spinal trauma in their everyday work and thus lack practice. For this reason, we recommend that former participants spend 1 week in the department of neurosurgery every 2 years to refresh their skills. Likewise, former participants can also repeat the course, as some colleagues have done in the past. They thus remain up to date with the latest guidelines that are issued by relevant specialist societies and which are reflected in the course program. In addition, the chosen topics and speakers vary every year so that the course remains interesting and relevant to new and former participants alike.

Outlook

The principles underlying the management of patients with open[1] and closed brain injuries and spinal trauma[4] continue to be further developed and adapted to the special requirements of military operational settings. The neurotrauma course presented here offers an excellent forum to spread knowledge and encourage constructive dialogue between neurosurgeons and nonneurosurgeons.

In the next few years, we will concentrate our efforts on increasing the availability of telemedicine and neuronavigation so that we can provide telemedical support in emergency cases requiring immediate surgical attention. The underlying idea is that the use of a neuronavigation system with a camera in the country of deployment allows the neurosurgeon at home to use a light pointer to indicate anatomical landmarks, the location of bur holes and critical areas in the region of the surgical site. In doing so, we will benefit from our many years of experience with neuronavigation and telemedical support both in military and civilian hospitals. Since as early as 1989, our department has used telemedical systems to link with civilian hospitals in the vicinity. In the beginning, images were taken using a simple digital camera and a light box. They were then transmitted via a computer system and a conventional telephone line to the target hospital. This form of communication with civilian hospitals has been optimized over the years.

Initial pilot projects are being planned and will be implemented in cooperation with neurosurgeons from the French Armed Forces.

Conclusions

Surgeons and orthopedists who attend the 1-week neurotrauma course presented here can expect to acquire the basic knowledge they need for the surgical management of patients with a TBI and/or spinal trauma. The wider use of telemedicine will enable neurosurgeons to provide specialist support in an increasing number of cases.

Authors' Note

The human bodies used in our neurotrauma courses are donated by people who declared during their lifetime that their bodies should be made available after their death for medical research and education at the University of Ulm.

All porcine heads are obtained from a slaughterhouse in Ulm. These pigs are killed in accordance with applicable guidelines and regulations.

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: both authors. Acquisition of data: UM Mauer. Analysis and interpretation of data: UM Mauer. Drafting the article: UM Mauer. Critically revising the article: U Kunz. Administrative/technical/material support: UM Mauer. Study supervision: UM Mauer.

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Address correspondence to: Uwe Max Mauer, M.D., Lt. Col. (MC), Department of Neurosurgery, German Armed Forces Hospital, Oberer Eselsberg 40, D-89070 Ulm, Germany. email: UweMaxMauer@bundeswehr.org.

Appendix: Course program (example)

Neurotrauma Course for German Armed Forces Surgeons and Orthopedists, No. 803 809

Course convenors: U. Kunz, M.D., Assistant Professor, Col. (MC), Director, Department XII (Neurosurgery), German Armed Forces Hospital, Ulm; U. M. Mauer, MD, Assistant Professor, Lt. Col. (MC), Senior Physician, Department XII (Neurosurgery), German Armed Forces Hospital, Ulm

All times are exact times but may be subject to change for organizational reasons.
Parallel to the seminars, practical training takes place in the operating room.

Monday	
8:30 a.m.	Welcome
8:45 a.m.	Introduction
9:00 a.m.	Anatomy for craniotomy & spinal injuries
10:00 a.m.	Pathophysiology of brain & spinal injuries
11:00 a.m.	Indications for urgent surgery in patients w/ TBI – Part 1
12:00 noon	Lunch break
2:00 p.m.	Indications for urgent surgery in patients w/ TBI – Part 2
3:00 p.m.	Planning & performing a craniotomy
4:00 p.m.	Becoming familiar w/ neurosurgical instrumentation
	Practical training using plastic skulls
6:00 p.m.	End of Day 1
Tuesday	
8:00 a.m.	Preclinical treatment of patients w/ brain & spinal injuries
9:00 a.m.	Conservative treatment of patients w/ TBI
10:00 a.m.	Diagnostic imaging of patients w/ TBI
11:00 a.m.	Intracranial pressure monitoring
12:00 noon	Lunch break
1:30 p.m.	Clinical ward round
2:00 p.m.	Complications & late sequelae of TBIs
3:00 p.m.	Practical training in craniotomy using plastic or porcine skulls
6:00 p.m.	End of Day 2
Wednesday	
8:00 a.m.	The role of TBI in polytrauma patients
9:00 a.m.	Otorhinolaryngology: effects of injuries & principles of treatment
10:00 a.m.	Oral & maxillofacial surgery: effects of injuries & principles of treatment
11:00 a.m.	Ophthalmology: effects of injuries & principles of treatment
12:00 noon	Lunch break
1:30 p.m.	Clinical ward round
2:00 p.m.	Practical training in craniotomy using cadaver skulls
6:00 p.m.	End of Day 3
Thursday	
8:00 a.m.	Current aspects of telemedicine
9:00 a.m.	Diagnostic imaging of patients w/ spinal injuries
10:00 a.m.	Surgical treatment of lumbar & thoracic spine injuries
11:00 a.m.	Surgical treatment of cervical spine injuries
12:00 noon	Lunch break
1:30 p.m.	Familiarization w/ Crutchfield tongs & halo traction
2:00 p.m.	Comprehensive care according to Sir Ludwig Guttmann
3:00 p.m.	Practical training in craniotomy using human cadavers
6:00 p.m.	End of Day 4
Friday	
8:00 a.m.	Neuronavigation: modern computer-assisted technologies in neurosurgery
9:00 a.m.	The role of TBIs in a military operational setting abroad
10:00 a.m.	Managing gunshot injuries of the skull
12:00 noon	End of course & presentation of certificates

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Intercontinental aeromedical evacuation of patients with traumatic brain injuries during Operations Iraqi Freedom and Enduring Freedom

Raymond Fang, M.D.,[1] Gina R. Dorlac, M.D.,[2] Patrick F. Allan, M.D.,[1] and Warren C. Dorlac, M.D.[2]

[1]*Landstuhl Regional Medical Center, Landstuhl, Germany; and* [2]*United States Air Force Center for the Sustainment of Trauma and Readiness Skills, University of Cincinnati, Ohio*

Traumatic brain injury contributes significantly to military combat morbidity and mortality. No longer maintaining comprehensive medical care facilities throughout the world, the US military developed a worldwide trauma care system making the patient the moving part of the system. Life-saving interventions are performed early, and essential care is delivered at forward locations. Patients then proceed successively through increasingly capable levels of care culminating with arrival in the US. Proper patient selection and thorough mission preparation are crucial to the safe and successful intercontinental aeromedical evacuation of critical brain-injured patients during Operations Iraqi Freedom and Enduring Freedom. *(DOI: 10.3171/2010.2.FOCUS1043)*

Key Words • **critical care** • **traumatic brain injury** • **military medicine** • **war** • **wounds and injuries**

The "mobile patient" is a reality.[5] No longer capable of indefinitely maintaining comprehensive medical care facilities throughout the world, the US military developed a worldwide trauma care system focused on making the patient the moving part of the system. Life-saving interventions are performed early, and essential care is delivered at forward, austere locations. Patients then proceed successively through increasingly capable levels of care, culminating with arrival at permanent facilities in the US for definitive care and rehabilitation. The safe and successful movement of critical brain-injured patients is an extremely challenging system requirement for the medical support of OIF/OEF.

Wartime TBI

Traumatic brain injury contributes significantly to military combat trauma morbidity and mortality. A published query of the Joint Theater Trauma Registry—the DoD's trauma registry for data on all care rendered by the military trauma care system—showed that 8% of all war-related wounds occurred to the head. Explosions accounted for 79%, gunshots for 19%, and motor vehicle collisions for 2% of all combat wounds.[8] Exposure to an explosive blast with penetrating fragments is the most common mechanism of brain injury sustained in OIF/OEF. By DoD regulation, Walter Reed Army Medical Center and the National Naval Medical Center at Bethesda in the National Capital Region receive nearly all US casualties with moderate to severe TBI. A review of neurosurgical consultations at these 2 centers during the 5-year period between 2003 and 2008 revealed a mechanism of injury distribution of 56% blast/fragments, 21% gunshot wounds, and 9.6% vehicle collisions for 408 patients with TBI.[2] The current Kevlar helmet protects the head well from ballistic injury, but it is not as effective in preventing injury from primary blasts and blunt force trauma. Even with high compliance and proper helmet and individual body armor wear, the head, face, and neck must remain somewhat exposed during combat to allow soldiers to maintain not only mobility but also sensory awareness of the surrounding environment. Risk assessment, potential threat identification and injury avoidance are much more effective at mitigating primary brain injury than bulkier, more restrictive personal protective equipment.

Following injury, battlefield medical care rendered by fellow soldiers and combat medics is classified as Level I care. The first priority of Level I care is establishing scene security to avoid additional injury to either the injured individual or the caregivers. Subsequent Level I care includes hemorrhage control frequently using extremity tourniquets, airway establishment, field dressing

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Abbreviations used in this paper: CCATT = Critical Care Air Transport Team; CPP = cerebral perfusion pressure; C-STARS = Center for the Sustainment of Trauma and Readiness Skills; DoD = Department of Defense; DVT = deep vein thrombosis; ICP = intracranial pressure; OEF = Operation Enduring Freedom; OIF = Operation Iraqi Freedom; TBI = traumatic brain injury.

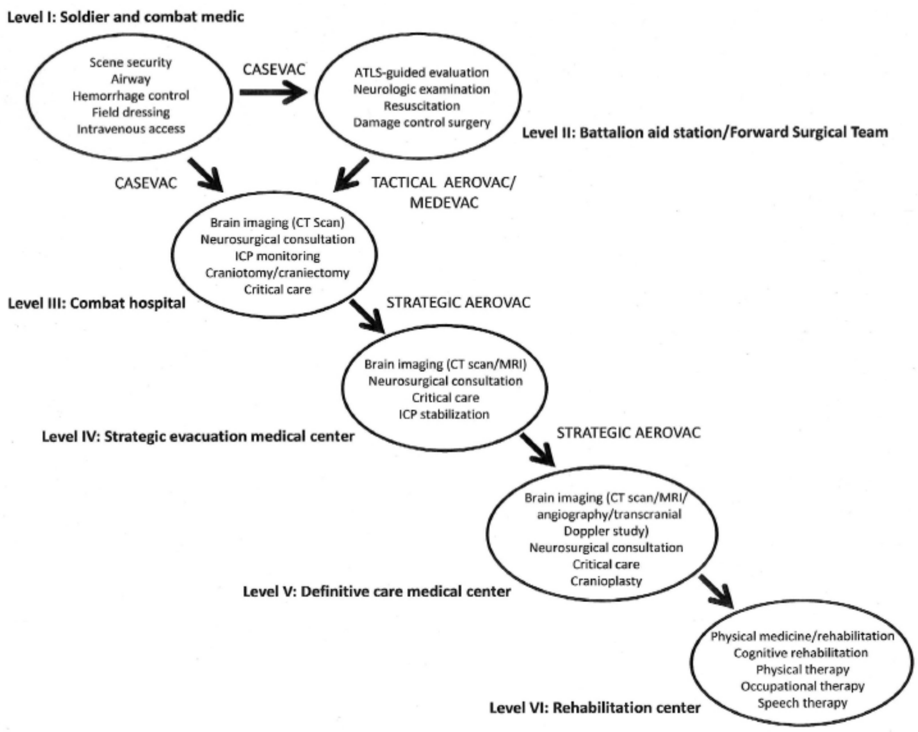

Fig. 1. Military levels of care for TBIs: casualty evacuation (CASEVAC) is transport from battlefield to military medical facility; medical evacuation (MEDEVAC) is rotary-wing patient movement between medical facilities; aeromedical evacuation (AEROVAC) is fixed-wing patient movement between medical facilities; tactical refers to in-theater missions; and strategic refers to intertheater missions.

application to protect wounds from continued contamination, and intravenous access to initiate fluid resuscitation. Casualty evacuation from the scene occurs as rapidly as the tactical situation allows to Level II or III medical facilities by rotary wing aircraft, typically a UH-60 Blackhawk helicopter, or ground transport ambulance. Arrival of the injured individual at higher levels of care within the "golden hour" after injury is a DoD priority.

Post-injury resuscitation continues at Level II and III facilities where the casualty enters the formal military health care system. Evaluation and treatment follows protocols as described by the American College of Surgeons Advanced Trauma Life Support Course. Early identification of casualties with significant penetrating head injuries may be dramatic and straightforward, but blunt blast injuries frequently manifest in a more delayed and subtle fashion. Documentation of a brief, thorough initial neurological examination is of crucial importance because many severely injured patients will subsequently progress through the evacuation chain intubated and pharmacologically sedated. Forward deployment of surgical resources to Level II facilities allows for the performance of limited "damage-control surgery" by general and orthopedic surgeons so that casualties can then be evacuated to the more comprehensive, deployed Level III facilities. The capability to perform CT scanning of the brain is generally limited to Level III facilities where specialized neurosurgical expertise may be available.

Prevention of secondary brain injury is the goal of surgical and critical care management strategies in TBI with emphasis on control of ICP and avoidance of hypotension and hypoxemia. Hyperthermia, anemia, and hypoglycemia also potentially worsen outcomes. At select Level III facilities, a multidisciplinary Head and Neck team frequently collaborates on the surgical management of these patients due to the complexity of the wounds. The surgical team includes neurosurgeons, ophthalmologists, otolaryngologists, and maxillofacial surgeons operating side-by-side.[7] The neurosurgical operative approach to patients with severe TBI in OIF/OEF is to perform aggressive decompression through a generous craniectomy, to remove devitalized brain and easily accessible foreign bodies, and to attempt watertight dural closure.[10] Ventricular drains are preferred over fiberoptic ICP monitors because ventriculostomies allow for both pressure measurement and therapeutic CSF drainage. Stabilization at Level III facilities is followed by intercontinental aeromedical evacuation to a Level IV facility, outside the combat zone, in Germany. Ultimately, critical care casualties evacuate to one of 3 Level V military medical centers in the US: Walter Reed Army Medical Center, National Naval Medical Center at Bethesda, and Brooke Army Medical Center (Fort Sam Houston in San Antonio, TX) requiring a second intercontinental movement (Fig. 1).

United States Air Force CCATT

Development of the US Air Force CCATT Program in the early 1990s was driven by a new DoD requirement

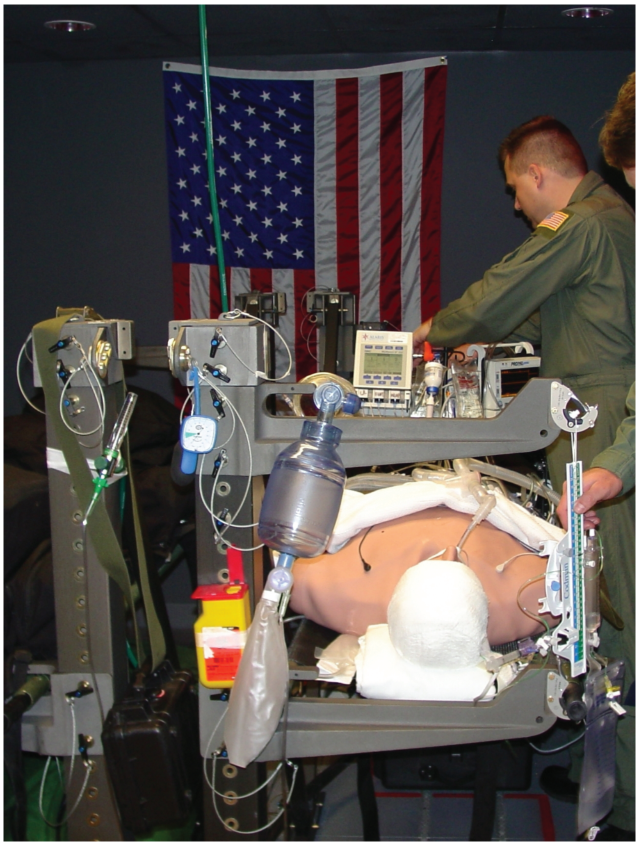

Fig. 2. Patient care simulator at the US Air Force Center for the Sustainment of Trauma and Readiness Skills.

to effectively evacuate critically ill and injured patients in potentially large numbers from austere forward locations rearward through the levels of care to the US.[2] The CCATT concept is the capacity to transport stabilized, intensive care patients who have undergone initial management by ground-based medical personnel. A "stabilized" patient is operationally defined for aeromedical evacuation as having 1) the airway secured, 2) accessible hemorrhage controlled, and 3) extremity fractures immobilized. Physiological stability, although preferred, is not implied in the definition, and the patient may be undergoing continued resuscitation and stabilization en route depending on the circumstances at the sending location.

The CCATT is a specialized 3-person team comprising a physician with critical care experience, a critical care nurse, and a respiratory therapist. By doctrine, each team can care for 3 high-acuity, ventilated patients (or 6 lower-acuity, nonventilated patients) for a presumed mission duty day of 16 hours. In most hospital intensive care units, nurse-to-patient ratios are 1:1 or 1:2. In the CCATT environment, cross-functionality is essential so that the physician and respiratory therapist routinely assist with critical care nursing responsibilities. Patient care in CCATT begins with evaluation and preparation at the sending facility and ends with successful hand-off to the receiving medical team at the destination facility. Depending on the timeliness and fidelity of the electronic medical record, the CCATT may also need to convey in detail the patients' entire preceding treatment course to the receiving caregivers.

Since the inception of the US Air Force CCATT Program in 1994, a formal selection and training process has evolved. US Air Force medical commanders nominate prospective CCATT members to meet deployment manning requirements. Candidates must pass a flight physical qualifying them for in-flight duties. A clinical validation committee composed of mission-experienced CCATT members in the same team role as the applicant reviews the candidate's clinical training and experience. Validated candidates then undergo initial CCATT training at the US Air Force School of Aerospace Medicine located at Brooks City-Base (San Antonio, TX). This 2-week course covers operational concepts, flight physiology, flight safety, and the CCATT equipment and supply allowances. For the majority of personnel, this will be their first exposure to the US Air Force aeromedical evacuation system. When subsequently given orders for deployment, team members must then attend the CCATT Advanced Course located at the US Air Force C-STARS, at the University of Cincinnati. This 2-week course serves 3 functions: 1) to review concepts taught at the CCATT initial course, 2) to provide 60–80 hours of supervised critical care experience in a busy civilian Level I trauma center with a dedicated neurosurgery intensive care unit, and 3) to incorporate recent clinical "lessons learned" from ongoing operations into the training experience. For example, focused training on ventricular drainage systems was added to the curriculum following feedback from the field and observations of prior C-STARS students. The course challenges students with a realistically simulated aircraft environment utilizing high-fidelity electronic human patient simulators and the actual CCATT equipment and supply allowance. Scenarios include trouble-shooting a faulty ventricular drain as well as managing refractory intracranial hypertension in a patient with TBI (Fig. 2). This course serves as a final predeployment "check ride." The CCATT members who, in the judgment of the C-STARS faculty, are not adequately prepared for mission success are not deployed until completing a remediation plan that may include repeating the course.

By the end of 2007, CCATTs performed more than 2000 casualty evacuation in support of OIF/OEF.[3] From an analysis of the CCATT Performance Improvement Database for the 18-month period between January 2007 and June 2008, 12% of CCATT patients had a diagnosis of TBI. Of these head-injured patients, 80% underwent mechanical ventilation, and in 35% ICP monitors were in place throughout transport.[6]

Intercontinental Aeromedical Evacuation

Patient Selection, Mission Preparation, and Movement

As in any complex patient intervention, mission planning and preparation are crucial for maximizing the potential for CCATT mission success. Because no dedicated aeromedical evacuation aircraft exists in the US Air Force inventory, missions are flown on "aircraft of opportunity" with no intrinsic medical capability. Most commonly, cargo aircrafts such as the C-130 Hercules for tactical missions (short-range, within a theater of

Fig. 3. Photograph of a patient with TBI during aeromedical evacuation. A ventriculostomy drain hangs at the head of the bed and intensive care monitors are loaded at the foot.

operations) and the C-17 Globemaster III for strategic missions (long-range, between theaters of operation) are used. After cargo and passenger off-load, these aircraft can be rapidly reconfigured for patient movement. The CCATTs must be aware of aircraft-specific variations such as patient litter positioning and accessibility, oxygen and electrical supply, airspeed, flight range, and cabin temperature regulation. The C-17 Globemaster III can be configured to accommodate 54 ambulatory and 36 litter patients with 360° access. The aircraft cabin is relatively comfortable and well lit and the aircraft's on-board systems deliver pressurized medical oxygen at 50 psi and 60 Hz AC electrical power through standard 110-V outlets. It flies at a speed of 450 kn at 28,000 feet and has an unlimited range with aerial refueling.[1] During flight, available clinical expertise, medical equipment, and supplies to include medications are limited to those brought aboard by the CCATT itself (Fig. 3). Nonstandard medications such as hypertonic saline solutions (3% or 23.4%), desmopressin, and phenobarbital must be obtained from the sending facility prior to departure.

The first crucial decision in CCATT mission planning is the timing of patient movement. Besides the austere aircraft environment, physiological effects of flight may have deleterious effect on the acutely injured patient with TBI. Military aircraft cabins are generally pressurized to an altitude of 8000 ft above sea level, which is typically well tolerated by normal individuals. However, the reduced barometric pressure is still associated with a decreased partial pressure of oxygen compared with sea level. Because hypoxia is a major contributor to secondary brain injury, patients with TBI with significant oxygenation support requirements at baseline may be intolerant of flight even when mechanically ventilated. Cabin pressurization to lower altitudes consumes additional fuel, decreases flight range, and lengthens mission time especially if refueling becomes necessary. Additionally, decreased atmospheric pressure causes gases to expand according to Boyle's law so that trapped intracranial air may significantly increase in volume at altitude and lead to a potential intracranial mass effect. Trapped gas expansion in the sinuses and gastrointestinal tract may also increase patient discomfort. While patients with TBI are ideally maintained in darkened, low-stimuli environments to minimize ICP reactivity, the aircraft environment is one of constant noise, vibration, and surrounding activity. The movement of other injuries (for instance, extremity fractures, and laparotomy incision) further agitates the patient, increasing sedative and analgesia requirements during flight. Low ambient humidity at altitude leads to increased insensible fluid losses during aeromedical evacuation and necessitates increased fluid intake to avoid intravascular hypovolemia and decreased cerebral perfusion. Accelerative forces during take-off, landing, and combat flight maneuvers can also impact cerebral blood flow and ICP. Risks of flight, resource constraints at the sending facility, urgency of specialty care only available at the destination, military operational tempo, weather conditions, and aircraft availability must all be weighed in the decision to transport a patient. With peak brain edema occurring during the postinjury Days 3–5, transfer is avoided during this time window if ICP remains problematic. If the situation allows, the provision of several days of ICP stability is strongly preferred because CCATT management is limited to maximizing medical therapy. In flight, the CCATT is unable to repeat brain CT imaging or to intervene should a surgically correctable lesion exist.

Once a patient with TBI has been designated for strategic aeromedical evacuation, the CCATT must complete a thorough patient evaluation. They must also develop a mission plan, one that anticipates potential in-flight complications and one that acts to prevent these complications if possible.

Neurological. While close-interval, serial neurological examinations during sedation breaks are possible in an intensive care unit setting, CCATTs may require other surrogate indicators of neurological status. Increased sedation requirements related to noise, vibration, and other continuous external stimulation frequently obviate clinical examination. Sedation breaks also increase the risk for inadvertent in-flight dislodgment of therapeutic devices. Thus, an invasive ICP monitor may be necessary to detect deleterious neurological changes and to ensure that cerebroprotective measures are followed. Propofol is the most common sedative agent used for patients with TBI due to its extremely short half-life facilitating neurological examinations in an intensive care unit setting. The CCATTs routinely continue propofol infusions for sedation during aeromedical evacuation. While propofol also decreases cerebral metabolism, it comes with the potential drawback of inducing systemic hypotension. Patients with severe head injuries receiving high-dose infusions are at increased risk of developing propofol infusion syndrome, a rare, potentially lethal, complication of its use.[11] An increase in serum creatine phosphokinase levels or the development of rhabdomyolysis, metabolic acidosis, or cardiac dysrhythmias should prompt suspicion for the syndrome and immediate cessation of the propofol infusion.[9]

The prevention of secondary brain injury by targeting ICP less than 20 mm Hg and CPP greater than 60 mm Hg remain principal post-TBI management goals. Simple bedside maneuvers promoting cerebral venous drainage include head of bed elevation if the thoracolumbar spine is cleared, maintaining the head midline, and loosening or removing of the cervical collar if the patient is sedated, immobile, and the cervical spine has been radiographically cleared. A standard algorithm for ICP elevations should be understood by the CCATT members (that is, assess level of sedation, evaluate function/accuracy of ICP monitor, determine CPP, institute therapeutic measures [bolus sedation, drain CSF, consider osmotic therapy with 250 ml 3% saline, 20 ml 23.4% saline, or 0.5–1.0 mg/kg mannitol and/or titrate vasopressor support of mean arterial pressure depending on the patient's intravascular status and drug availability]). Empirical pharmacological seizure prophylaxis needs to be continued with appropriate therapeutic serum drug levels confirmed prior to flight.

The C-17 Globemaster III flies with a slight nose-up attitude that is steeper during take-off and landing when accelerative forces are also most pronounced. Standard aeromedical evacuation litter positioning places the patient's head rearward, reducing the benefits of the head-of-bed elevation and placing the head in a somewhat dependent position for the flat supine patient. For this reason, CCATT patients with TBI are instead loaded head forward.

Spinal Clearance. Cervical spine clearance requires both the radiographic exclusion of osseous injury by fine-cut CT scans with multiplanar reconstructions (axial, sagittal, and coronal views) as well as evidence of ligamentous integrity. In patients with TBI without a reliable clinical examination, MR imaging to diagnose potential ligamentous injury is contraindicated if retained metallic fragments are present. Consequently, patients may remain immobilized in cervical collars throughout their journey back to the US. The thoracic and lumbar spines can be cleared by radiographic exclusion of injury using adequate CT scanning as previously described. Patients with thoracic and lumbar spinal instability are either surgically stabilized at the Level IV facility prior to evacuation or flown immobilized while lying on a transport spine board (Vacuum Spine Board, Med Tech Sweden, Inc.), which was introduced into the aeromedical evacuation system in 2009.

Cardiovascular. An invasive arterial catheter facilitates both continuous mean arterial pressure monitoring (goal > 70 mm Hg or as required to maintain CPP > 60 mm Hg) as well as arterial blood sampling. Central venous catheters help monitor intravascular volume status by displaying central venous pressure measurements (goal > 10–12 mm Hg) as well as provide reliable intravenous access for medication administration. Vasoactive agents such as phenylephrine, norepinephrine, and vasopressin should be premixed and readily available should CPP sustaining infusions be required.

Respiratory. Extubation is avoided in the interval immediately preceding air transport. The hypobaric aircraft environment may potentiate hypoxia and worsen secondary brain injury. In the absence of an artificial airway, short-term hyperventilation to manipulate PCO_2 and to dampen acute ICP elevations is no longer an option. An aircraft is also an extremely challenging location to attempt emergency intubation without backup expertise or equipment. Verification of endotracheal tube position is difficult without the ability to obtain a chest radiograph, visualize the airway with a fiberoptic bronchoscope, or auscultate breath sounds. Closed tube thoracostomies should not be removed within 24 hours of flight to minimize the risk of in-flight reaccumulation of an occult pneumothorax resulting in hypotension and hypoxemia. Chest tubes are carefully inspected to confirm patency, placement, and function. Review of a recent (< 12 to 24–hour) chest radiograph is mandatory prior to departure to verify endotracheal tube and chest tube placements in patients for whom these tubes were required. Continuous end-tidal CO_2 measurement and in-flight arterial blood gas sampling (Portable Clinical Analyzer Model 200, Abbott Point of Care, Inc.) are useful tools to ensure adequacy of mechanical ventilation.

Infectious Disease. Patients receive prophylactic antibiotics for ventriculostomy drains and penetrating brain injuries (1 g cefazolin intravenously every 8 hours), but not for fiberoptic ICP monitors. For malaria prophylaxis, doxycycline (100 mg intravenously/nasogastrically/orogastrically) is administered daily for patients evacuated from OEF. Other antimicrobials are administered depending on associated traumatic injuries or microbial culture results. Ventilator-associated pneumonia–prevention practices continued in-flight include head-of-bed elevation, oral care, caregiver glove wear, and in-line tracheal suctioning. Because febrile episodes increase cerebral metabolism, cooling measures are initiated for temperatures exceeding 99.5°F.

Prophylaxis. Pantoprazole (40 mg intravenously) is given daily for stress gastritis/ulcer prevention. With once-daily dosing regimens, a medication dose administered prior to departure will not need to be repeated by the CCATT during transport. If CT demonstrates no progression of intracranial pathology at 48 hours from time of injury, enoxaparin (30 mg subcutaneously twice daily) is started for DVT prophylaxis in this high-risk population. All patients also undergo duplex ultrasound surveillance to exclude preexistent DVT. In patients deemed to be persistently at too high a risk for pharmacological prophylaxis or found to have a preexistent DVT, placement of an inferior vena cava filter is performed. In 2009, the US Air Force approved a mechanical sequential calf compression system for patient use on US Air Force aircraft (Kendall SCD Express Compression System, Covidien). This new option for DVT prophylaxis will reduce the need for inferior vena cava filter placement in high-risk patients with a contraindication to pharmacological DVT prophylaxis.

Research

With CCATTs currently transporting large numbers of patients in support of OIF/OEF, research to improve processes and patient outcomes is ongoing at multiple organizations. The DoD designated the US Army Institute for Surgical Research as the Joint Center of Excellence for Battlefield Health and Trauma. A main research division of this organization is the En Route Care Research Center, which is focused on improving all aspects of patient movement from point of injury to arrival in the US. Furthermore, the US Air Force C-STARS is collaborating with its hosts at the University of Cincinnati to perform bench research on the effects of aeromedical evacuation on TBI patients. The Landstuhl Regional Medical Center Trauma Program is also involved with CCATT-related clinical research from its central position in the evacuation chain.

During flight, ICP is a continuous variable that is generally measured and documented each hour. Hourly measurements are insufficient to truly demonstrate dynamic responses related to in-flight events. An ongoing, simple observational research project involves the real-time continuous collection of ICP and mean arterial blood pressure measurements throughout transport to gain insight on how different phases of flight and in-flight events impact ICP. Not unexpectedly, initial observations of patients with severe TBI transported from OIF/OEF demonstrate early spikes in ICP at the time of take-off and these spikes persisted for variable durations.

The systemic inflammatory response to TBI is increasingly acknowledged as a contributor to the severity and progression of primary and secondary head injury. Primary brain injury causes a breakdown in the blood-brain barrier, allowing an influx of inflammatory mediators into the injured brain originating from the initial trauma-primed immune response. This may subsequently contribute to both tissue hypoxia and cerebral edema. The physiological impact of aeromedical evacuation on systemic and intracranial inflammation is unknown.[6] In healthy individuals, rapid ascent to relatively low altitudes (8000 ft) have led to mild hypoxemia, which may be responsible for symptoms of high-altitude illness and a concomitant systemic inflammatory response. The initial injury inflicting the primary TBI may prime the body for a second hit triggered by early, postinjury aeromedical evacuation. Researchers at the University of Cincinnati studied a murine TBI model subjected to simulated flight in a hypobaric chamber.[4] Early (3-hour), but not delayed (24-hour), exposure to the hypobaric environment increased the neuroinflammatory response to injury in these animals. It is possible that an ideal time for transportation of patients with TBI may be identified by awaiting the resolution of the acute neuroinflammatory response, provided that the patient can be supported at the forward location.[6]

Conclusions

Intercontinental aeromedical evacuation of combat casualties with significant TBI early after injury is a requirement for the military medical support of OIF/OEF. The austerity of the aircraft environment and physiological stressors of flight can be detrimental to the casualty during transport. Critical Care Air Transport Team member selection and training in concert with diligent mission planning and preparation mitigate these potential risks. The mortality rate for OIF/OEF patients who survived initial neurosurgical stabilization in the war zone and 2 subsequent intercontinental transports to Germany and then the US was approximately 4.4%.[3] This result compares favorably with that of a similar casualty population during the Vietnam War while the time of transfer to the US decreased from an average of 45 days to less than 5. The modern population likely reflects higher overall injury severity as many evacuated patients would not have been candidates for movement in the past and would have died of their wounds in the combat theater. Current research targets improved understanding of aeromedical evacuation's impact on TBI, and determining the optimal timing of TBI patient movement.

Disclosure

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

The views and opinions expressed in this manuscript are those

of the authors and do not reflect the official policy or position of the US Air Force, US Army, US Navy, Department of Defense, or the US Government.

Author contributions to the study and manuscript preparation include the following. Conception and design: R Fang. Acquisition of data: R Fang. Analysis and interpretation of data: R Fang, GR Dorlac, WC Dorlac. Drafting the article: R Fang, GR Dorlac, PF Allan, WC Dorlac. Critically revising the article: R Fang, GR Dorlac, PF Allan, WC Dorlac. Reviewed final version of the manuscript and approved it for submission: R Fang, GR Dorlac, PF Allan, WC Dorlac. Administrative/technical/material support: R Fang.

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Address correspondence to: Raymond Fang, M.D., Division of Surgery, Landstuhl Regional Medical Center, 402 Box 506, APO, AE 09180-0506. email: Raymond.Fang@amedd.army.mil.

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Military aeromedical evacuation, with special emphasis on craniospinal trauma

Joseph Reno, M.D.

95th Aeromedical and Dental Squadron, Edwards Air Force Base, Edwards, California

This brief intends to educate civilian neurosurgeons on the structure and function of the US military aeromedical evacuation (AE) system, with special focus on the role of the military neurosurgeon. It highlights the thought process required to participate as a surgical provider in the AE system. It further clarifies the expanded role the AE system plays in nonbattle evacuation. *(DOI: 10.3171/2010.2.FOCUS1023)*

Key Words • **military aeromedical evacuation** • **casualty** • **trauma** • **traumatic brain injury**

The natural cost of war is casualties. Previously these were treated near the front lines in abbreviated fashion and in cramped conditions, due to the inherent difficulty in moving severely injured patients, especially when that transportation was rough, slow, and limited. These latter conditions no longer apply, and casualty evacuation is possible to an unprecedented degree with respect to speed and distance. This is due to more than the rapid global reach of modern airlift; the current golden age of quick and long-distance casualty evacuation owes much to clinical advancements in the quick stabilization of severe injuries.

What is Military AE?

The US military uses its AE system for flexible movement of casualties. "Casualty" is a practical term including anyone needing evacuation; it implies a mismatch between medical capability at the place of injury and the degree of injury—or illness. Battle casualties must be airlifted out, but so too must US soldiers with other diseases and nonbattle injuries, such as a herniated disc thrown out during an impromptu football game. The US AE network routinely transports coalition forces and even enemy combatants requiring medical treatment. The AE system moves sick and injured refugees and humanitarian crisis survivors. In short, AE provides relief for more than just battle injuries and to more than just US soldiers.

Abbreviations used in this paper: AE = aeromedical evacuation; AF = Air Force; CAR = cabin altitude restriction; CASF = Contingency Aeromedical Staging Facility; CCAT = Critical Care Air Transport; ICP = intracranial pressure; ICU = intensive care unit.

The Stages of Patient Movement

Combat casualties are sent rearward in stages. Immediately following the injury, a soldier is trained to apply "self-aid," followed by squad mates providing "buddy care." On-scene evacuation occurs via a helicopter or ground vehicles (known as Vehicles of Opportunity) close at hand. The patient is taken to the first echelon of care, the first medical provider. This person may be a company medic, or in some cases a forward surgical team. The forward surgical team is a 4-person squad: trauma surgeon, orthopedic surgeon, anesthesiologist, and operating room technician or nurse. They carry portable operating supplies in backpacks and can perform several operations before resupply. Frequently they work in any shelter available, even under trees or in bombed-out buildings. As soon as practical, the patient is sent on to the nearest true field hospital with an airfield adjoining; this will be the first stop if a helicopter evacuation is available from the scene of injury. Field hospitals are usually within 30–90 minutes' helicopter time from the front lines. Once at a field hospital, the patient enters the official AE system. Administrators coordinate the patient's movement request with logisticians and aircrew supervisors overseeing the entire theater's situation. Patients can be requested for "urgent," "priority," or "routine" evacuation (Table 1). Meanwhile, the trauma and/or orthopedic surgeons who staff these field hospitals will assess and stabilize the patient to prepare him or her for air evacuation to the major theater hospital, which will have surgical subspecialization, including neurosurgery and a CT scanner.

Travel from a field hospital to one of the main theater hospitals (Balad base, Iraq, or Bagram base, Afghani-

TABLE 1: Patient movement precedence

Requested Precedence	Expected Time to Movement
routine	<72 hrs
priority	<24 hrs
urgent	as soon as possible

stan) can be via helicopter, but is often via C-130, C-12, or C-21. Flight times vary, but are typically 30–90 minutes by plane. Further surgical or intensive stabilization is provided at the theater hospital; if the injury can be definitively corrected, it will be. Most patients need further specialized care, recuperation, or staged procedures; they are moved to Germany (in the case of casualties generated in Central Asia or the Middle East), to the regional medical center at Landstuhl. This involves a 5- to 7-hour flight in either a C-17 or a KC-135 transport. Once there, a patient may stay weeks, days, or only hours before setting off to the continental US, which takes 7–8 hours to Maryland, for the Army and Navy hospitals in Washington, DC; or 10 hours to Texas, for the military burn and trauma center in San Antonio. Each of these military treatment facilities is connected by air routes; at each of these stops the patient is reevaluated. The goal is to take the patient as far as required, as fast as required. As with civilian patient transfers from hospital to hospital, the patient remains the responsibility of the relinquishing physician until the gaining physician takes over. Unlike normal civilian transfers, however, air evacuation is a multistepped, frequent, and high-volume exodus of casualties. Coordination among the multiple players is the crucial step.

Participants and Roles

The AE system depends on four types of clinical teams to shuttle severely injured patients safely and promptly across continents (Table 2). The provider—who is often a trauma surgeon or an orthopedic surgeon until the theater hospital level of care—evaluates and sets the treatment plan for the patient. Immediate or planned stabilization follows, and the surgeon uses any intervening time to ensure that the patient is ready for transport. This entails understanding the unique stresses of flight and adapting the clinical orders to care for the patient in flight as well as on the ward or in the unit.

The flight surgeon provides guidance to coordinate the aviation and clinical situations. His contribution is to verify that the patient meets criteria for flight and that safety measures have been ordered. Each patient will have orders written by the provider and reviewed by the flight surgeon—especially with regard to the need for oxygen, pressure-related precautions, and in-flight comfort. The flight surgeon's presence is the final step needed to clear the patient to leave the hospital and fly to the next echelon of care. All flight surgeons fly in military aircraft frequently as nonpilot aircrew. They are trained to understand physiological and pathological conditions related to altitude, speed, and military aviation environments. This skill set enables them to ensure that a stabilized patient will fly with the typical risks of altitude and flight mitigated.

Working with the flight surgeon are the nurses, technicians, and pharmacists of the Aeromedical Staging Facility (in contingency/wartime operations this is called a CASF). This team expedites the gathering of supplies and preparation of the patient to be ready and loaded onto the mission aircraft in an orderly, safe, and expeditious manner. Moving even one patient can present a nightmare in keeping together all the supplies, medications, dressings, additional equipment, records, and personal effects; the CASF team ensures continuity during transfer to and from the aircraft of all the many patients moving simultaneously at all hours of the day and night. Also, they can provide an overnight ward level of care for patients passing through on a short layover.

Once the patient gets to the aircraft, the on-board AE team takes over. These are flight nurses and flight medical technicians who will provide a ward level of care for patients in flight. They are highly trained to be self-sufficient in handling the rare emergencies and other spur-of-the-moment issues that arise. Similarly to civilian medical flight crews, they are handpicked for their seniority, experience, and clinical maturity. There is no physician present on routine AE flights. In the cases in which a patient must be transported at an ICU level of care, a special team of medical attendants will care for the patient in transit. This is the CCAT team; this team is composed of an ICU-certified physician (usually a pulmonologist, cardiologist, or emergency room physician, because the surgeons are occupied in the field hospitals), an ICU nurse, and a cardiopulmonary technician. Because CCAT teams care for ICU-level patients en route, close communication between the CCAT team attending physician, who is not a surgeon, and the relinquishing surgeon is vital. With the advent of CCAT teams, regular and safe evacuation of ICU patients has become feasible. This is the highest example of the coordination among the different clinical teams flying the evacuation missions.

TABLE 2: Participants and roles*

Team/Participant	Role(s)
primary surgeon	assess, stabilize, define Tx goal, request air evacuation & precedence, write orders for transfer
flight surgeon	review case, clear pt to fly, act as consultant for primary surgeon, coordinate CASF & AE efforts
CASF	ensure pt prepared for flight, screen pt for security, deliver pt to/from aircraft
AE medical flight crew	in-flight medical care per orders (ward level)
CCAT team	deliver ICU pts to/from aircraft, in-flight ICU-level care

* pt = patient.

TABLE 3: Aircraft types involved in AE*

Aircraft	Description	Phase of AE
UH-1 “Huey”	Army helicopter, Vietnam-era	front lines to field hospital
UH-60 “Blackhawk”	Army et al. helicopter	front lines to field hospital
C-9 “Nightingale”	AF medical transport	NA (retired)
C-17 “Globemaster III”	AF large jet transport, bare field capability, long-distance craft	theater to regional hospital (Central Asia to Germany), regional hospital to CONUS (Germany to MD or TX)
KC-135 “Stratotanker”	AF jet air refueler/tanker, long-distance craft	theater to regional hospital
C-130 “Hercules”	AF turboprop, medium-sized, medium-distance, bare field capability, loud & rough ride	field to theater, (rarely) theater to regional hospital
C-12	AF turboprop, small-sized	field to theater, (rarely) theater to regional hospital
C-21 Learjet	AF small jet	as needed
KC-10	AF large jet refueler/tanker	as needed
C-5 “Galaxy”	AF very large jet transport	as needed

* CONUS = continental US; MD = Maryland; NA = not applicable; TX = Texas.

The USAF is the main branch of the armed forces providing aircraft and manpower for AE. The Army does provide helicopters for the early stages of evacuation before arrival at a fixed facility; these are the venerable UH-1 “Huey” or the UH-60 “Blackhawk” helicopters (Table 3). In past years, AE relied primarily on the C-9 “Nightingale,” heavily modified jets with their sole use as medical transports. More recently, the military has adopted a more generalized and flexible philosophy; any aircraft that can physically accommodate litters and/or ambulatory patients can be used. In practice, however, there are several common aircraft. The C-17 transport is a large 4-engine cargo jet with a long range and the ability to land on dirt runways. It can hold several dozen patients of both litter-bound and ambulatory types. The slightly smaller C-130 is a medium-sized 4-engine propeller aircraft with less range but more flexibility in landing in less improved places. It is legendarily loud, slow, and useful for all transport missions, including AE. The third most common airplane is the KC-135, which is primarily an air-to-air refueling tanker with some cargo capacity. Other less commonly used aircraft in AE include the small C-21 Learjet, the smaller C-12 (twin-engine propeller plane), and the enormous C-5 “Galaxy,” which is nearly too big to carry people efficiently. The KC-10, another tanker with some cargo space, is occasionally used too. The clinician does not control which type of aircraft is used; it rarely matters much. There is a set list of generalized stressors of flight that must be considered, no matter the aircraft type.

Stressors of Flight and General Clinical Considerations

Flight surgeons exist because the aviation environment is notably different from that at altitude sea-level and speed zero. Flight poses unique stressors (Table 4). The first and greatest risk is hypoxia. Half the atmosphere is below 18,000 feet; above that there is simply less air, and less air means less oxygen. With increasing altitude, the partial pressure of oxygen decreases; this is the Dalton law. Even in a normally pressurized commercial aircraft cabin, the effective altitude is 8–10,000 feet. This rarely causes noticeable hypoxia in resting, healthy airline passengers, but it can adversely affect ill patients. Comorbid conditions can worsen the risk of hypoxia. The greatest danger with hypoxia is that it can affect individuals in highly unique ways, and it usually has a very subtle onset. Altitude can cause other blood gas disorders. Altitude “bends” (that is, decompression sickness) or even arterial gas embolisms are possible, although they rarely occur without inadvertent decompression of the cabin above 18,000 feet in altitude.[2] These disorders occur because gas solubility changes with decreased pressure at altitude. These are the worst and most feared possible pressure-related side effects, and fortunately they are rare. Another barotrauma effect involves the Boyle law, which describes the volume expansion of gas with increased altitude (that is, decreased pressure). Besides flatulence and discomfort in ears and sinuses, this can cause damage to the tympanic membrane, rupture of sinuses, distension of the diaphragm, and altered thoracic hemodynamics. If there are traumatic or iatrogenic air pockets in vital structures like the eyeball or brain or chest, the normal operating altitude-related increase in volume can cause catastrophic effects. Additionally, barotrauma is a unique and easily forgotten source of pain, which may be especially dangerous in cases of head trauma with tenuous ICP control.

Additional stressors of flight include temperature shifts, vibration, noise, decreased humidity, and g-forces.[2] Despite rudimentary environmental controls, the cabin pressurization system causes refrigeration of the air. A typical military transport is either too cold or too hot: frequently it is both on the same flight, and there are frequent oscillations between the two. Unlike helicopter transfers, fixed-wing aircraft cannot taxi as close to the medical center, so more in-transit exposure to the elements (hot and cold) occurs. Airplanes that are propeller driven, like the C-130, tend to have high vibration loads. Any patient situated near the bulkheads (walls) or ramp will be subjected to total body vibration. With vibration comes gen-

TABLE 4: Stressors of flight and their management*

Stressor	Management/Prevention
hypoxia	supplemental oxygen, CAR, assign additional medical attendant
barotrauma (to ears, sinuses, abdomen, chest, pneumocranium)	CAR
decompression sickness, arterial gas embolism	rare w/o cabin decompression above 18,000 ft
temp shifts	provide blankets, assess pt & temp regularly
vibration	position pt away from bulkheads, verify that litter is buffered
noise	earplugs
decreased humidity	fluids (oral/IV); assess eyes, breathing, & hydration
g-forces	positioning: feet forward, HOB 30°, notify aircrew via flight surgeon
air sickness	antiemetic provided as needed
cumulative fatigue, pain	sedate if necessary, regularly assess for comfort, keep pt oriented, ambulate/ range-of-motion exercises

* HOB = head of bed; IV = intravenous; temp = temperature.

eralized muscle stimulation and increased metabolism. Sound also can be highly uncomfortable, detract from rest, and increase stress. Vibration, noise, and dry air make the cabin tiresome at best. Routine air exchange is integral to maintaining pressurization and breathability, but it does cause a loss of moisture. A 2-hour flight will drop the cabin humidity to 5%; a 4-hour flight can see the humidity at or below 1%. This can cause breathing problems and can exacerbate clearing ears and sinuses of pressure. It can also worsen dehydration. The movement of body fluids touches on another stress of flight: g-forces. Most transports, even in combat zone landings and takeoffs, do not sustain high g-forces (> 2–3 times gravity's force). Most of the impetus is in the fore-aft direction, and is usually worse with takeoff than landing. However, this is a stress that easily slips the mind of a provider on the ground writing orders for a patient soon to be spending hundreds of miles and hundreds of minutes in the air.

Neurosurgical Patient Care in AE

In recent wars, the pattern of injury has changed away from the torso—relatively—and increasingly to the extremities and head. Although spine injuries are still frequent, head trauma from improvised explosive devices (IEDs) and rifle fire is nearly ubiquitous. Due to the varying types of casualties evacuated, neurosurgeons may indeed encounter diseases and nonbattle injuries requiring evacuation too. In light of the generalized stressors of flight mentioned earlier, the neurosurgeon must consider additional facts. Hypoxia in a patient with existing traumatic brain injury should be actively avoided as well as warned against; a single episode can be catastrophic. Pneumocranium should be expected with skull or facial fractures. Similarly, barotrauma in sedated or unconscious patients may result from their inability to release the pressure via swallowing or a forced Valsalva technique. Also, the normal aviation stopgap techniques for dealing with ear block or sinus pain are a forced Valsalva maneuver to clear ears or sinuses, or as a last resort a Politzer bag, which forcibly injects air to reverse the eustachian seal. Both the Valsalva technique and Politzer bag can dangerously increase ICP and/or fracture craniofacial bones.

The safest alternative is to prevent barotrauma with CAR.[2] The physician can order the cabin altitude to be at or below a certain level to prevent pressure-related trauma to vital structures. Even flying over the mountains out of Afghanistan, CARs can be used. With a cabin altitude of 2000 feet, a C-17 can still climb up to nearly 24,000 feet before the pressure gradient across the plane's bulkhead is too steep. Below this, the cabin altitude can be set to even lower levels. Most cases of CAR are to 4–8000 feet, which permits transports to fly as high as they need to. For another example, vibration in a neurosurgical patient can cause motion sickness; emesis will elevate ICP. Antiemetics consequently must be prepared for use whenever ICP is a concern. Patients with hypothalamic involvement may be at greater risk to temperature swings. Dehydration can damage exposed mucus membranes and the cornea in patients without intact blinking.

For patients with problems controlling ICP, a ventriculostomy may be safely used on board. The AE team will close the stopcock for patient movement, for takeoff, and for landing. They are trained to ensure that it is not closed longer than 15 minutes; they also have training and written guidance in troubleshooting basic ventriculostomy failures. For evacuation of ICP cases such as severe head injury, the patient is loaded in the reverse of the normal feet-forward position.[2] The takeoff g-forces will draw down pressure intracranially with the patient in the feet-aft position. Even AE crews are qualified to use mannitol, drain fluid from a ventriculostomy, perform hyperventilation in the patient, and follow arterial blood gas levels with portable on-board diagnostic equipment. Head of bed elevation, via a litter-backboard, and "head midline" are routine orders for severe head injury/ICP cases. All these capabilities are included in basic AE crew training.[1]

Further care is available via the ICU staff of the CCAT team. Under their expertise, hypertonic saline is available, mainly 3% but occasionally 23%, for either drip or bolus at the instruction of the relinquishing surgeon and depending on the familiarity of the en-route ICU physician. On the other hand, few AE teams will have encountered spinal or deep brain stimulators. If a patient with one of these devices is being transported, the neurosurgeon must make clear to the CASF and AE teams that routine antihijacking screening must not include handheld devices or detectors, which may interfere with the implant(s). In cases of spine instability, patients can be transferred on vacuum boards, in Halo braces, or on hard backboards. These patients are prepared with special instructions for hand loading, and the litter is locked into place on the cabin floor to ensure maximal rigidity during flight. In-flight deteriorations are rare with spine cases; we know this because any complication of flight is tracked and investigated by the safety branch of the Global Patient Movement Requirements Center at Scott AF Base, near St. Louis. Once all preparations are done, and the patient has flown off, the neurosurgeon can be comforted that in the event of a sudden change in status or other crisis, radio communication can connect the medical crew members with a specialist. In this case, the aircraft's pilot plans to immediately lower cabin altitude (the term for cabin pressure and the altitude to which that pressure corresponds; the pilot will also lower the aircraft altitude if practical), and will consider diverting to an airfield with neurosurgical and radiographic capabilities. The key to anticipating modifications required by head, spine, and peripheral nerve cases during transit is to remember the stresses inherent in flight.

Conclusions

Routine AE takes sick and injured people and places them in transit in an inhospitable environment. For neurosurgical patients aboard an AE flight, this involves spending hours minimally mobile in a locked metal room that is loud and shaking, too cold and too hot and too dry, with constant exposure to less oxygen and more gas in the body cavities than is normal or comfortable. That so many do so well bears witness to the flexibility and preparedness of neurosurgeons and their associated AE colleagues.

Disclosure

The author reports no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Address correspondence to: Captain Joseph Reno, M.D., 95th Aeromedical and Dental Squadron, Edwards Air Force Base, 55 North Wolfe Avenue, Edwards, California 93524. email: joseph.reno@edwards.af.mil.

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The French mobile neurosurgical unit*

Renaud Dulou, M.D.,[1] Arnaud Dagain, M.D.,[1] Jean-Marc Delmas, M.D.,[1] Evelyne Lambert, M.D.,[2] Eric Blondet, M.D.,[1] Olivier Goasguen, M.D.,[1] Bruno Pouit, M.D.,[1] Guillaume Dutertre, M.D.,[1] François de Soultrait, M.D.,[1] and Philippe Pernot, M.D.[1]

[1]Service de Neurochirurgie, Hôpital d'Instruction des Armées du Val-de-Grâce, Paris; and [2]Service d'Anesthésie-Réanimation, Hôpital d'Instruction des Armées Percy, Clamart, France

The authors present the French concept of a mobile neurosurgical unit (MNSU) as used to provide specific support to remote military medicosurgical units deployed in Africa, South America, Central Europe, and Afghanistan. From 2001 to 2009, 15 missions were performed, for 16 patients. All but 3 of these missions (those in Kosovo, French Guyana, and Afghanistan) concerned Africa. Eleven patients were French soldiers, 3 were civilians, and 2 were Djiboutian soldiers. The conditions that MNSUs were requested for included craniocerebral wounds (2 cases), closed head trauma (7 cases), spinal trauma (5 cases), and spontaneous intracranial hemorrhage (2 cases). In 5 of the 16 cases, neurosurgical treatment was provided on site. All French soldiers and 2 civilians were evacuated to France. The MNSU can be deployed for timely treatment when some delay in neurosurgical management is acceptable.
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Key Words • **mobile team** • **French neurosurgery** • **war surgery**

The first MNSUs were created by Hugh Cairns during World War II.[7] Their aim was to provide specific treatment for head injuries (total removal of bone fragments under direct vision, wound closure, and air evacuation) close to the fighting with sufficient mobility to be redeployed "where the need was greatest."[16] The units initially included 1 neurosurgeon, 1 neurologist, and 1 "anaesthetist," and paramedical staff trained for neurosurgical casualties, and were provided with sufficient equipment to be able to perform at least 200 operations without replacements.[16] They were serviced by field ambulances attached to a hospital or casualty clearing station located further from the battlefield.[12] Such units were subsequently developed and used by the Canadian Army during World War II and later on by the Eighth US Army during the 2nd year of the Korean War.[10] In their paper, Meirowsky and Barnett[10] emphasized the advantages of such units: mobility, the earliest possible neurosurgical management, and economy (because of reduced morbidity). Enhanced mobility imposed a number of constraints, including portable surgical kits restricted to a variety of instruments necessary to perform craniotomies and/or craniectomies. That is why, according to Meirowski and colleagues, only experienced neurosurgeons could be deployed in MNSUs, not only because of their specific knowledge of intracranial injuries, but also because of their surgical know-how.

Abbreviations used in this paper: medevac = medical evacuation; MNSU = mobile neurosurgical unit.

After this period, the management of wartime neurosurgical casualties changed for several reasons:

1. Logistics. During the Vietnam War, evacuation of patients greatly improved with the development of air ambulances: the UH-1D (Huey) was able to transport 6–9 patients at a time within 30–35 minutes following injury.[8] Patients were evacuated to facilities such as evacuation hospitals where a neurosurgeon was present on the surgical staff.[17]

2. Techniques. The evolution of surgical instruments (surgical microscope), neuroradiological tools (CT), and resuscitation facilities improved the management of neurosurgical casualties. Many of the advances were associated with an increase in the size, weight, and complexity of equipment, however, and were not suitable for use in mobile structures such as Level 2 medical field units (Table 1).

3. Indications. Treatment of penetrating head injuries evolved with the widespread acceptance of more conservative surgical treatment proposed by some authors.[1,3,4,9]

With these developments, neurosurgical capability became fixed in Level 3 facilities. The neurosurgeon lost his mobility and capacity to operate close to the front line, paradoxically because of the improvements in his practice.[11] This situation became controversial because some

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TABLE 1: Theoretical classification of the NATO levels of medical support*

Level	Role & Main Characteristics	Staffing	Force Size†
1	primary health care & immediate life-saving procedures; integrated into the fighting unit (France); no surgical or patient holding capability	1–2 medical doctors (France: 1); 6–2 paramedics (France: 1 nurse)	ranges from a combat company (France: 150 personnel) to a battalion (500–600 personnel)
2	increased medical capability & limited inpatient bed space (4–20 beds); basic field lab & x-ray equipment, blood bank; high mobility (theoretical); examples: Forward Surgical Team, Mobile Field Surgical Team (US), Airborne Surgical Unit (France)	surgical staff (1–3 general/visceral surgeons, orthopedist, anesthesiologist, OR nurse, nurse anesthetic): 20–40 personnel	brigade (>1000 personnel)
3	emergency & definitive medical & surgical management, intensive care; high-level lab & radiological capabilities (including CT), no mobility	15–20 doctors; multidisciplinary staff (including ENT surgeon, ophthalmologist, neurosurgeon, urologist); 80–200+ personnel	>5000 personnel

* Theoretical classification based on information from Department of Defense, 2004, and Seet, 1999. Each service and nation have different types of unit at each level. Abbreviation: ENT = ear, nose, and throat.
† Size of the force to be supported by the level specified.

advocated the presence of a neurosurgeon in Level 2 facilities to shorten the time between injury and surgery.[13]

The current deployment of French Army medicosurgical units outside France involves peace-keeping missions and health care for military personnel. Supporting medical units include Level 2 or Level 2–3 medicosurgical groups in which surgical suites do not allow optimal neurosurgical practice. These conditions are improving with telemedicine, development of telesurgical tools, and the recent deployment of radiological facilities (mobile CT units positioned in Level 2–3 field hospitals based in Chad and Republic of Djibouti). General surgeons are supposed to be trained for neurosurgical emergencies, but in practice, the time devoted to specific education is relatively short.[14,15]

This can be partially explained by the fact that there is no mandatory course in neurosurgery during the education of military general surgeons in France. Specific workshops are held only occasionally, although a significant effort was recently begun in 2007 to implement regular specialized neurosurgical training for general and orthopedic surgeons. The management of the main spinal, head and neck, and neurosurgical emergencies is presented, in order to improve the versatility of these practitioners before their deployment in Level 2 and 3 units.

The establishment of a permanent telephone and Internet link in a single rear structure in Paris, Val-de-Grâce Military Hospital, has greatly improved the quality of communication between neurosurgeons and French remote medicosurgical teams. Remote consultations are generally initiated by telephone, and, when possible, data are transmitted by Internet. The on-call neurosurgeon may contact the radiologist when images are transmitted (no radiologist is deployed outside France because there are very few radiologists in the French Army). Nevertheless image and information transfer systems are still not always available in every location where they might be needed. In 2000, difficulties in sending a neurosurgeon into Sarajevo to operate on a patient with an open craniocerebral wound before his transfer to France led us to propose the creation of a mobile team including neurosurgical and resuscitation staff.

The Modern French MNSU

A complete MNSU consists of 1 active duty military neurosurgeon, 1 general medical nurse, and 1 operating room nurse trained in managing neurosurgical casualties. One anesthesiologist and 1 nurse anesthetist may be added to this unit on demand. Specific surgical equipment is permanently available in our neurosurgical department. It includes cranial and spinal emergency sets, spinal cervicodorsal and lumbosacral osteosynthesis sets, and an intracranial pressure monitoring kit.

The medical units that might have need of an MNSU are remote French military airborne surgical units (Level 2 medical support) and medicosurgical groups (Level 2–3 medical support)[5,18] based in Africa, Central Europe, and Afghanistan.

An MNSU may be requested to take care of civilian or military patients with neurosurgical emergencies. The neurosurgical consultation is initiated by telephone, generally with the presence of the anesthesiologist, and the images may be transmitted using the telemedicine system to the neurosurgical Department of Val-de-Grâce Hospital. The decision to send an MNSU or a single neurosurgeon must be approved by the office of the Surgeon General.

When requested, MNSUs may be carried by light military aircraft based in Villacoublay (approximately 6 miles away from Percy Military Trauma Centre Hospital, Clamart). These aircraft are also used for nonmedical missions and are not permanently equipped for medical transport. These aircraft are able to receive and transport one severely wounded patient with resuscitation equipment (Fig. 1). Regular flights may also be used for patient transport when the case is not an emergency, and regular military or civilian flights may be used when a single neurosurgeon is required.

Summary of Recent Missions

From January 2001 to November 2009, 15 missions were performed (Table 2). They can be summarized as follows:

TABLE 2: Summary of the MNSU activity between 2001 and 2009*

Mission	Date	Pt Age (yrs), Sex	Combat Status	Avalaible Data†	Internet Facilities	Departure	Surgery on Site	Evacuation to France	Outcome
1 (Chad)	Jan 2001	40, F	civilian	traffic accident 6 days previously, incompl lt UE deficit, C4–5 dislocation	yes	delayed, reg military flight	yes	no	favorable, neurol improvement
2 (Cameroon)	Jan 2003	37, M	Fr soldier	severe head trauma, coma, acute SDH?	no	emerg, w/ medevac team	no	yes	death 2 days after arrival in France
3 (Chad)	Feb 2004	8, M	civilian	traffic accident, severe head trauma, coma	no	emerg, w/ medevac team	no	yes	death 21 days after arrival in France
4 (Djibouti)	May 2004	34, M	Djib soldier	traffic accident, quadriplegia, C5–6 dislocation	yes	delayed, reg civilian flight	yes	no	death 13 months after trauma
5 (Djibouti)	Nov 2004	44, M	Fr soldier	open craniocerebral wound, neurol deterioration	yes	emerg, w/ medevac team	yes	yes	favorable, neurol recovery, cranioplastly 1 yr postinjury
6 (Djibouti)	Feb 2006	21, M	Fr soldier	ICH, posterior fossa AVM, hydrocephalus?, GCS 14	no	emerg, w/ medevac team	no	yes	favorable, AVM embolization
7 (Djibouti)	Jan 2008	25, M	Fr soldier	traffic accident, severe head trauma, intracranial contusions, GCS 14, secondary agitation & sedation	no	emerg, w/ medevac team	no	yes	favorable, conservative management
8 (Djibouti)	Oct 2008	44, M	Fr soldier	craniofacial trauma, GCS 12, lt hemiparesis, rt intraparenchymal frontotemporal contusions	no	emerg, w/ medevac team	yes	yes	favorable, neuropsych sequelae
9 (Gabon)	Nov 2008	40, M	Fr soldier	cervical trauma (parachuting injury), UE paresthesiae, C4–5 instability?	no	emerg, w/ medevac team	no	yes	favorable, conservative treatment
10 (Gabon)	Jan 2009	22, M	Fr soldier	severe closed head trauma, bifrontal intraparenchymal contusions, vault fracture, GCS 14	yes	emerg, w/ medevac team	no	yes	favorable, mild neuropsych sequelae
11 (Kosovo)	May 2009	52, M	Fr soldier	ICH, posterior fossa AVM, hydrocephalus GCS 7	no	emerg, w/ medevac team	yes	yes	favorable, AVM embolization
12 (Fr Guyana)	Aug 2009	23, M	Fr soldier	penetrating craniocerebral knife injury, GCS 13	yes	emerg, w/ medevac team	yes	yes	favorable
13 (Djibouti)	Oct 2009	25, M	Djib soldier	traffic accident, quadriplegia, C6–7 dislocation	yes	delayed reg civilian flight	yes	no	stable
14 (Djibouti)	Oct 2009	5 mos, M	Fr civilian	severe closed head injury, epidural hematoma, GCS 5	yes	emerg, w/ civilian ped medevac team	yes	yes	favorable, neuropsych sequelae
15 (Afghanistan)	Nov 2009	31, M	Fr soldier	traffic accident, severe closed head injury, GCS 5, acute SDH	yes	emerg, w/ medevac team	yes	yes	severe neuropsych sequelae
		30, M	Fr soldier	traffic accident, spinal trauma, incompl lt UE deficit, C-7 pars articularis fracture			no		favorable, cervical anterior arthrodesis

* AVM = arteriovenous malformation; Djib = Djiboutian; Djibouti = Republic of Djibouti; emerg = emergency; ICH = intracerebral hemorrhage; incompl = incomplete; Fr = French; GCS = Glasgow Coma Scale; neurol = neurological; neuropsych = neuropsychological; ped = pediatric; Pt = Patient; reg = regular; SDH = subdural hematoma; UE = upper extremity.

† Data available before MSNU was sent.

Fig. 1. Photographs showing external views of the Falcon 50 **(A)** and Falcon 900 **(B)**. Internal view of the Falcon 50 (**C**) showing patient positioning. Resuscitation equipment can be seen in the foreground, and the patient is in the background. The medicosurgical staff would be positioned to the right.

1. "Immediate emergency" cases in which data were transmitted by telephone and Internet, there was an indication for surgery, and an MNSU was sent with a medevac team: 5 cases (2 open craniocerebral wounds, 3 severe closed head injuries); Missions 5, 8, 12, 14, and 15 (Figs. 2 and 3).

2. "Immediate emergency" cases in which data were transmitted only by telephone and/or there was failure of communication by Internet, an MNSU was sent with a medevac team, and the indication for surgery was discussed on site: 7 cases (2 spontaneous intracerebral hemorrhages, 3 cases of closed head trauma, 2 spinal trauma cases); Missions 2, 3, 6, 7, 9, 10, and 11 (Fig. 4). It was determined that surgery was not required in 5 of these 7 cases. In the remaining case, placement of an external ventricular drain was required for treatment of intraventricular hemorrhage.

3. "Delayed emergency" cases in which data were transmitted by telephone and Internet, there was an indication for surgery, and a neurosurgeon was sent with appropriate surgical equipment: 4 cases (closed spinal trauma); Missions 1, 4, 5, and 13. Transport was accomplished by regular military or civilian flight.

The time from MNSU activation to takeoff was less than 3 hours for each "immediate emergency" case. Time to operation in-country depended on the time of flight to destination (8 hours for Mission 15, Afghanistan).

Discussion

Neurosurgery represents a small part of the activity of Level 2 and 3 French medicosurgical units deployed outside France. During the civil war in N'Djamena in 1980, the French Military Airborne Advance Surgical Unit received 1484 wounded patients and performed 518 surgical procedures; 27 patients presented with opened craniocerebral wounds, with 14 of these being treated surgically. Two other patients presented with paraplegia (due to war-related vertebromedullary wounds) and died; these patients constituted 1.95% of the casualties, and the procedures related to their care represented 2.7% of the surgical procedures performed.[2] A more recent publication[15] reported that neurosurgical procedures during a United Nations peace-keeping mission in Rwanda represented 2% of the overall interventions. Eleven of these 17 procedures were considered emergencies and 6 were considered elective, including repair of scalp or cranial defects or meningocele and surgical treatment of osteomyelitis or chronic subdural hematoma. These data confirm that the presence of neurosurgeons on site is unnecessary, despite the conclusions of a 2000 report.[9] Many publications emphasize the necessity of serious training in neurosurgery for deployed general surgeons—training that includes management of neurotrauma, infections of the CNS, and indeed congenital pathologies for the pediatric civilian population. This training can be supported and updated by specialized military illustrated manuals or other publications.[6,14,15]

Nevertheless, this training is often limited to the treatment of some chronic subdural hematomas, open cranial wounds, and/or a few acute extradural hematomas, in conditions in which complete neurosurgical facilities are available. The situation is different in remote areas. Telemedicine and telesurgical assistance (limited to surgical coaching by telephone or message in most cases) certainly reduce the stress of isolated and generally young surgeons. This mode of support obviously depends on the availability of adequate computer systems, the quality and reliability of which continue to improve. Two examples of cases in which teleassistance was used are illustrated in Figs. 5 and 6. In both of these cases,

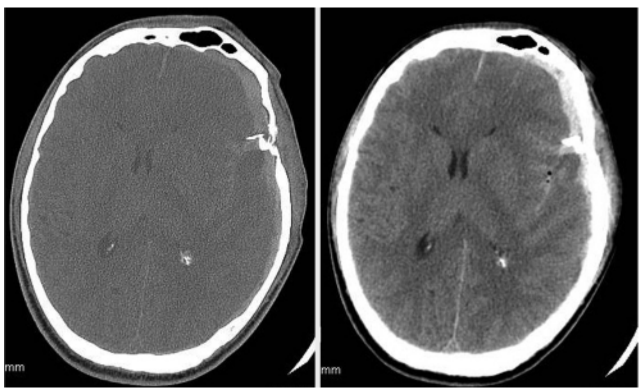

Fig. 2. Case managed during Mission 12. Axial CT scan with osseous **(left)** and parenchymal **(right)** windows. This patient had an open craniocerebral wound with depressed frontal fractures and an acute subdural hematoma.

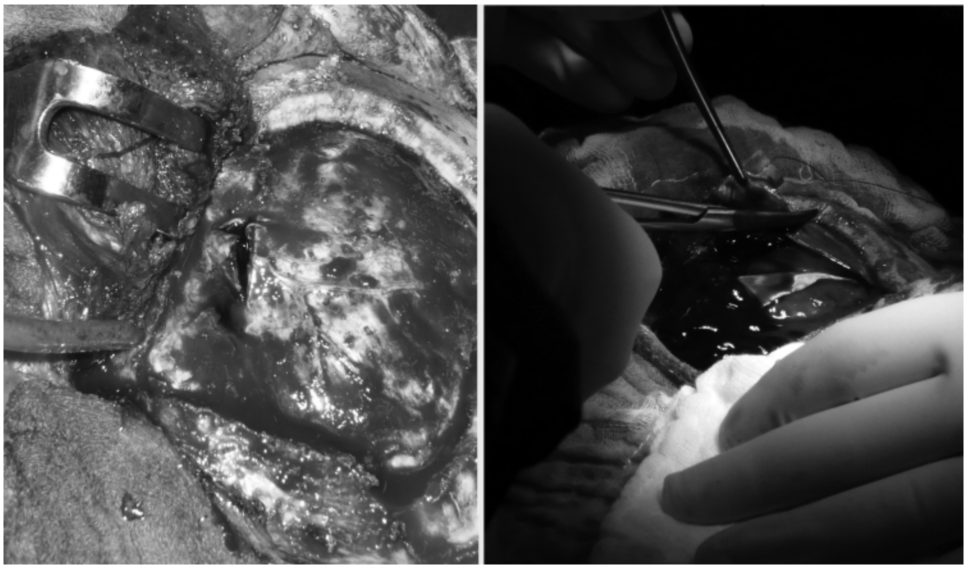

Fig. 3. Case managed during Mission 12. Intraoperative views after removal of the cranial flap with exposure of the lacerated dura **(left)** and after opening of the dura and exposure of the subdural hematoma **(right)**.

the technology allowed appropriate management without deployment of an MNSU. The patient in the first example was a 40-year-old French soldier who was admitted to the French Level 2 medicosurgical unit in Kabul in status epilepticus, which was considered at the time to be due to "posttraumatic contusion." An emergency CT scan performed on site showed a possible cerebral contusion (Fig. 5). There was no radiologist available in Kabul, and the pictures were transmitted to the neurosurgical department at Val-de-Grâce, where the on-call neurosurgeon requested a radiological diagnosis. No diagnosis could be established at this stage, and the patient, who did not require an MNSU, was evacuated to France for further studies (MR imaging) and specific management. The MR images led to a tentative diagnosis of intraaxial right frontal tumor. The final diagnosis after surgery was cerebral ganglioglioma.

The patient in the second example was a 2-year-old boy with severe head trauma resulting from a fall. The child had a Glasgow Coma Scale score of 13, and an emergency CT scan revealed a very large extradural hematoma of the cranial vault. A consultation was conducted via the Internet and telephone (Fig. 6). The on-call neurosurgeon at Val-de-Grâce (R.D.) established the diagnosis of subdural hematoma, and a 3D CT reconstruction was created so that a schematic guide could be prepared for the use of the surgeons on site. Using Microsoft PowerPoint, the neurosurgeon marked the sites for the skin incision, bilateral craniotomies, and dural tack-up sutures for bleeding control and hemostasis directly onto the 3D

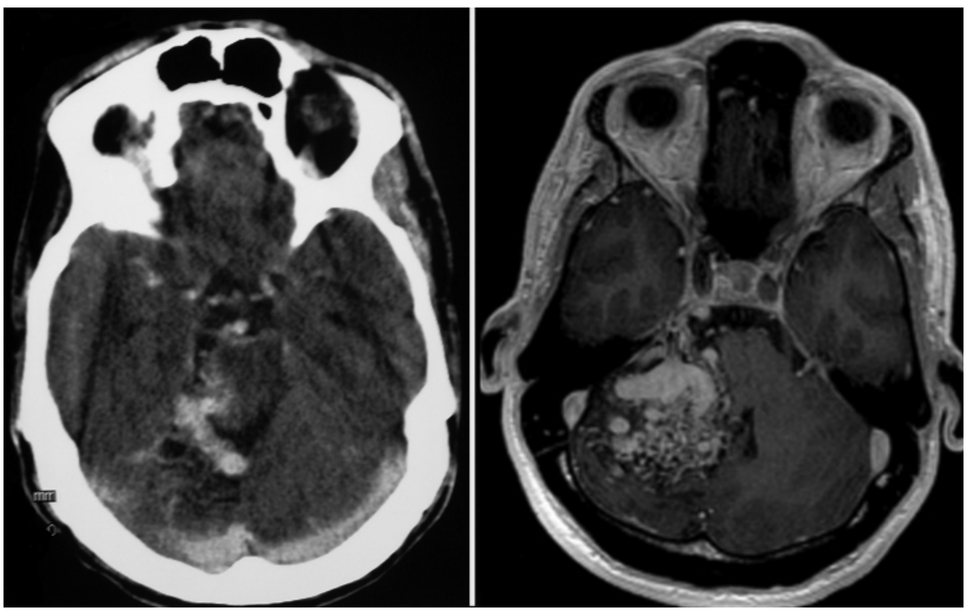

Fig. 4. Case managed during Mission 6. Axial CT scan **(left)** and T1-weighted axial MR image **(right)** showing a large AVM in the right posterior fossa.

Fig. 5. Case managed with image transfer, Kabul, 2007. Axial CT scan (unenhanced) showing a hypodense right frontal lesion without mass effect in a patient who was evacuated from Kabul and non-MSNU. The images were interpreted remotely by means of image transfer, leading to revision of the initial diagnosis. The final diagnosis was ganglioglioma.

CT reconstruction. This guidance permitted the general surgeon and the orthopedic surgeon in Djibouti to successfully perform the surgery. Thanks to the telephone link, the general surgeon was able to report their progress and concerns during and after the surgery. The postoperative course showed dramatic improvement, and the child was rapidly discharged home. The surgeons in Djibouti reported that the indications for the tack-up sutures were of great utility when significant bleeding occurred from the midline as the hematoma was progressively removed.

This was the first such use of this technology by this team and was possible because 3D CT reconstructions were performed and transmitted via Internet. The schematic seemed to be the best way for the neurosurgical consultant in France to explain the surgical procedure to non–neurosurgeons in Djibouti (better than verbal description by telephone). Again, the MNSU was finally not required for this child.

We think MNSUs represent an interesting supplementary tool for remote units for situations in which a delay in neurosurgical management is acceptable. Certainly, there are cases in which the sending of a neurosurgeon turns out to be unnecessary, as we could say with respect to some of the cases in our series, and sometimes the lack of precise and accurate information can result in an MNSU being requested unnecessarily. In our system, evacuation of the severely wounded is a high priority. Including a neurosurgeon in the evacuation team does not pose logistical challenges other than the need to find sufficient space on the airplane, and can be beneficial for the patient, even when no surgery is needed in the final analysis.

Conclusions

Neurosurgical emergencies represent a small part of the activity of remote French Level 2 and 3 medicosurgical units. Training of general surgeons is the basis for the management of these cases, and such training is optimally supplemented with teleassistance. The MNSU is a relatively low-cost tool for providing additional support for these remote units in some cases.

Disclosure

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

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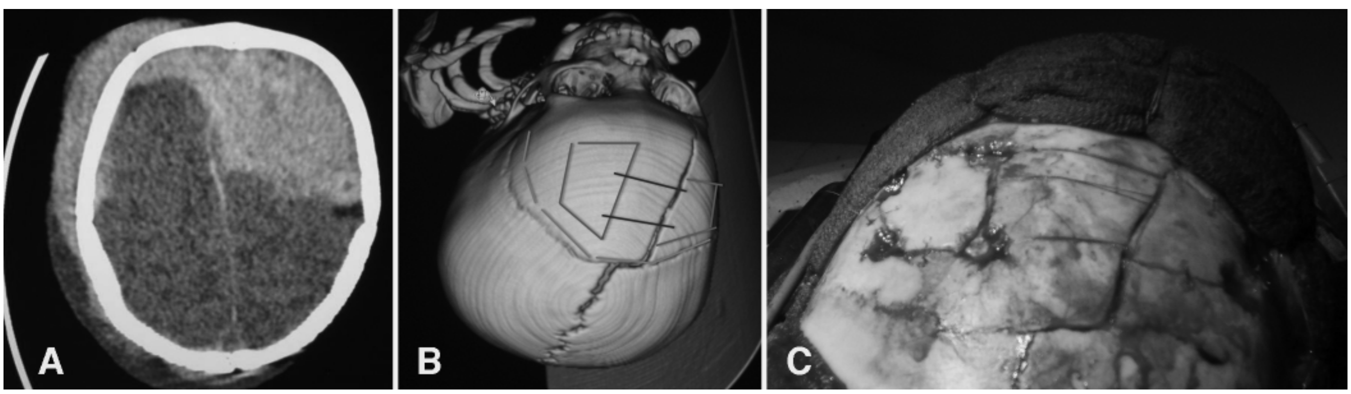

Fig. 6. Case managed surgically with telephone and internet assistance, Republic of Djibouti, 2009. This 2-year-old boy presented with severe head trauma and a Glasgow Coma Scale score of 13. **A:** Axial CT scan with parenchymal window revealing a huge extradural hematoma of the vertex. **B:** A 3D CT reconstruction with the markings made by the neurosurgeon in France, indicating the recommended locations for the skin incision, craniotomies, and tack-up sutures. **C:** Intraoperative photograph showing application of the neurosurgeon's recommendations in the actual surgery.

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An earlier version of this article was published in French. The authors have extended the period covered to include information from more recent conflicts as well as condensing and translating the text. The original paper (Dulou R, et al: Équipe neurochirurgicale mobile: Historique et perspectives. **Médecine & Armées: Revue du Service de santé des armées 37:**29–33, 2009) can be accessed online at http://www.defense.gouv.fr/sante/content/download/149659/1297302/file/MEA_T37_N1_WEB.pdf.

Address correspondence to: Médecin en chef Renaud Dulou, Service de Neurochirurgie, Hôpital d'Instruction des Armées du Val-de-Grâce, 75230 Paris Cédex 05, France. email: renaud.dulou@gmail.com.

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German military neurosurgery at home and abroad

Uwe Max Mauer, M.D.,[1] **Chris Schulz, M.D.,**[1] **Ronny Rothe, M.D.,**[2] **and Ulrich Kunz, M.D.**[1]

[1]*Department of Neurosurgery, German Armed Forces Hospital, Ulm; and* [2]*Department of Neurosurgery, German Armed Forces Central Hospital, Koblenz, Germany*

For many years, the experience of neurosurgeons from the German Armed Forces was limited to the peacetime care of patients in Germany. In 1995, German military neurosurgeons were deployed abroad for the first time. Since the beginning of the International Security Assistance Force mission, there has been a rapidly increasing number of opportunities for military neurosurgeons to broaden their experience during deployments abroad.

Since the first deployment of a neurosurgeon to the German field hospital in Mazar-e-Sharif, Afghanistan, a total of 140 neurosurgical procedures have been performed there. Sixty-four surgeries were performed for cranial or spinal neurotrauma management. During the entire period, only 10 International Security Assistance Force members required acute or urgent neurosurgical interventions. The majority of neurosurgical procedures were performed in Afghan patients who received acute and elective treatment whenever the necessary infrastructure was available in the field hospital. Fifteen patients from the Afghan National Army and Police and 115 local patients underwent neurosurgery. Sixty-two procedures were carried out under acute or urgent conditions, and 78 operations were elective.
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Key Words • **military neurosurgery** • **history of military neurosurgery** • **Afghanistan** • **International Security Assistance Force**

History of German Military Neurosurgery

In Germany, the first surgical procedures involving the nervous system were performed by physicians who had started training in surgery or neurology and who had been influenced by events in World Wars I and II. In 1934, Wilhelm Toennis (1898–1978) established the first independent neurosurgical department in Germany in Wuerzburg. In 1936, he founded the first ever neurosurgical journal. During World War II, he became brigadier general in the medical corps of the German Air Force and was awarded the Knight's Cross with Swords for meritorious service on May 31, 1944. He organized the neurosurgical management of wounded military personnel and the air evacuation of patients with brain injuries from the battlefield to the central hospital for brain-injured casualties in Berlin.

Today the German Armed Forces Medical Service is a separate service similar to the Army, Navy, and Air Force. All 5 German Armed Forces hospitals, which are located in Berlin, Koblenz, Hamburg, Ulm, and Westerstede, have neurosurgical departments and are fully integrated into the German health care system for the civilian population. At present, there are 12 neurosurgeons in the German Armed Forces. The Department of Neurosurgery at the German Armed Forces Hospital in Ulm plays a leading role in German military neurosurgery and is the only neurosurgical department that provides full-scope residency training in neurosurgery. The German Armed Forces Hospital in Ulm is a tertiary care hospital and has a center for head and neck medicine and surgery. A rescue helicopter is stationed at the hospital in Ulm, which provides the services of a Level I trauma center.

After World War II, neurosurgeons of the German Armed Forces were deployed abroad for the first time from 1995 to 1997 in Rajlovac and then from 1997 to 1999 in Trogir when they took part in the United Nations Protection Force (UNPROFOR) and Implementation Force (IFOR) missions (in the former Yugoslavia). During these deployments, it became clear that the German Armed Forces Medical Service did not require the on-site presence of a neurosurgeon to perform its tasks for the Implementation Force and/or Stabilization Force missions. For this reason, neurosurgeons were no longer deployed to the former Yugoslavia after December 1999. On account of the operational spectrum of the German Armed Forces, there was no situation in which a German soldier required on-site neurosurgical treatment. This was also the beginning of the successful use of military telemedicine. Since that time, neurotrauma courses for German Armed Forces surgeons and orthopedists have been conducted and are still being optimized. It is not the objective of these courses to qualify surgeons as neurosurgeons in a brief period of time. If patients undergo surgery performed by surgeons who overestimate their abili-

Abbreviation used in this paper: ISAF = International Security Assistance Force.

TABLE 1: North Atlantic Treaty Organization levels of medical support

Role	Location	Level of Care
1	mobile aid stations	emergency medical care, stabilization for transportation
2	mobile surgical hospitals	initial op
3	field hospitals	further surgical care, acute clinical care
4	hospitals	definitive care, rehabilitation

ties in the field of neurosurgery, the consequences could be devastating. Rather, the objective of the course is to give surgeons and orthopedists the knowledge and skills they need to provide simple acute care for patients who are in a life-threatening situation. Surgeons must accept that they can only provide initial care—similar to damage control surgery—and that patients must be repatriated to their home country for definitive care. Another no less important objective of the course is to make participants understand when no intervention is indicated and when they must simply wait for the repatriation of a patient. At the same time, surgeons and orthopedists can expect to gain the practical skills and theoretical knowledge they need to provide initial surgical treatment for patients with a traumatic brain injury and/or spinal trauma. Surgical skills are practiced above all on pig and human cadavers in the Department of Anatomy at the University of Ulm.

Recent years have shown that teleconsultation and repatriation are particularly effective when the specialist at home and the nonspecialist in the country of deployment know each other personally and when they share relevant theoretical knowledge. In the past, former course participants successfully managed several patients with (open) traumatic brain injuries in the country of deployment.

The ISAF Mission

The question of whether a German contingent that is involved in operations abroad should include a neurosurgeon was not raised again until the beginning of the ISAF mission. Until the summer of 2007, patients with neurotrauma had been treated by surgeons who had completed a neurotrauma course and had received training in a neurosurgery department. Since July 2007, neurosurgical services have been continuously available in the German (Role 3) field hospital (Table 1 and Figs. 1–3) in Mazar-e-Sharif, Afghanistan, and have been provided by neurosurgical specialists from the German Armed Forces and neurosurgeons from the French Army. As a result of this cooperation with the French Army, a pool of approximately 10–15 neurosurgeons ensures the availability of neurosurgical services and the provision of primary care for patients with all types of neurotrauma in the field hospital.

Camp Marmal is located outside of Mazar-e-Sharif in northern Afghanistan, 450 km north of Kabul. It previously housed Dutch forces and was taken over by the German Armed Forces in November 2005. Since then the camp has expanded and now covers an area of 1000 × 2000 m. It includes a field hospital with a size of 4000 m^2, which was completed in 2007. The hospital is located in fixed buildings, and it is managed by a hospital company. Apart from laboratories for clinical chemistry, transfusion medicine, microbiology, veterinary medicine, and food chemistry, the field hospital houses a pharmacy, an emergency unit with 2 resuscitation rooms, a radiological department with a state-of-the-art CT scanner, a surgical unit with 2 operating rooms and a recovery room, which can be used as an extended intensive care unit in a mass casualty situation, as well as an outpatient unit, a modern intensive care unit, and inpatient wards. In the field hospital of Mazar-e-Sharif, patients can receive medical and surgical care not only from a neurosurgeon but also from an internist, a urologist, an otolaryngologist, a dermatologist, a neurologist, a psychiatrist, and a dentist (oral surgeon). Veterinary support is available as well. In addition, the field hospital has a telemedicine system that allows on-site medical professionals to receive support in special cases as well as interdisciplinary advice from remote specialists.

Fig. 1. Field hospital at Camp Marmal in Mazar-e-Sharif.

All the supplies and equipment needed for the complete treatment of patients with neurotrauma are available in the operating rooms of the field hospital in Mazar-e-Sharif. All types of acute operations on the skull such as bur hole trepanations and craniotomies can be performed. The field hospital also meets the technical requirements for cranial reconstructive surgery. Spinal decompression

Fig. 2. An emergency room.

surgery can be performed from the craniocervical junction down to the lumbosacral spine. If required, spinal stabilization by instrumentation is also possible. All necessary instruments as well as halo fixation devices for cervical immobilization and instruments for the management of peripheral nerve lesions are available in the field hospital of Mazar-e-Sharif. In addition, a surgical microscope and mobile radiography units can be used for neurosurgical procedures.

If capacities are available, German medical personnel also provide medical and surgical care to local patients including members of the Afghan National Army and Police, Afghan civilians, and members of governmental and nongovernmental organizations. For example, one of these cases was a 25-year-old patient with a lower leg

Fig. 3. A neurosurgical procedure in one of the operating rooms.

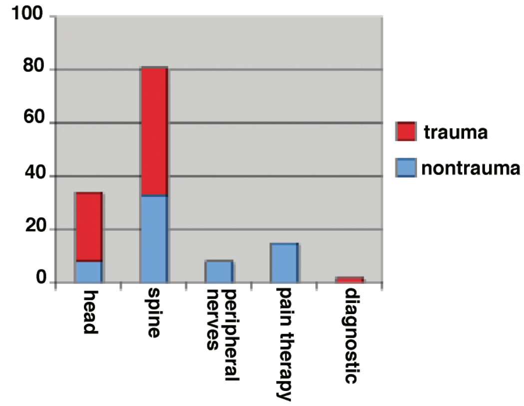

Fig. 4. Neurosurgical procedures in the German field hospital in Mazar-e-Sharif from July 2007 to December 2009.

fracture. The presence of hemiparesis was noted during the initial examination (see Fig. 5). Cranial CT scanning demonstrated a depressed fracture in the central region (see Fig. 6). The Afghan physician who had provided initial care had treated this injury with only a few sutures, which were largely obscured by the patient's hair. After the cranial CT scan, the patient underwent surgery. The hemiparesis improved, leaving only a minimal residual deficit. The postoperative course was otherwise unremarkable. The majority of patients, however, are ISAF members stationed at Regional Command North locations.

Between July 2007 and December 2009, a total of 140 neurosurgical procedures were performed in the field hospital. Sixty-four surgeries were performed for cranial or spinal neurotrauma management (Fig. 4). During the entire period, only 10 ISAF members required acute or urgent neurosurgical interventions. Five of these 10 patients underwent neurosurgical treatment during the last 3 months of 2009. Spinal injuries occurred not only in the cervical but also in the thoracic and lumbar spine. Cervical injuries were managed using iliac crest bone grafting and ventral plate fixation. The ISAF members with thoracic and lumbar spine injuries underwent only dorsal instrumentation and decompression. Definitive ventral treatment was provided by a hospital in the home country. Afghan patients also received ventral treatment involving the placement of interposition grafts (iliac crest bone grafts, rib grafts, or spineoplasty) in the field hospital. Local patients also underwent elective surgical procedures for disc herniation, trigeminal neuralgia, entrapment neuropathy, and other conditions.

Until October 2009, no German soldier had ever required acute neurosurgical care during a military deployment. In November 2009, however, a German soldier underwent an acute neurosurgical intervention for the first time in German history after World War II. This soldier developed an epidural hematoma after having been injured in an attack on a military vehicle.

The majority of neurosurgical procedures were performed in Afghan patients who received acute and elective treatment whenever the necessary infrastructure was available in the field hospital. Fifteen patients from the

Fig. 5. A local patient with a depressed fracture, hemiparesis, and a lower leg fracture.

Afghan National Army and Police and 115 local patients underwent neurosurgery. Sixty-two procedures were carried out under acute or urgent conditions and 78 operations were elective.

Fig. 6. A CT scan of the same patient as in Fig. 5.

The Way Ahead

Major efforts in the near future will focus on centralizing the neurosurgical management of patients in Afghanistan. The objective is to deploy alternately a German and a French neurosurgeon in the newly established French-led field hospital at Kabul International Airport. Reliable casualty evacuation must, of course, be ensured. Should the central deployment of neurosurgical specialists prove successful, other specialist services—for example, vascular surgery, gynecology, or urology—may be centralized in a similar manner.

Since an increasing number of deployments and an increasing "robustness" of mandates are expected, the limited availability of specialist personnel and the wish to provide neurosurgical expertise in as large an area as possible require the optimization of personnel deployment using state-of-the-art information technology and telemedicine. Teleconsultation and even teleteaching facilities are available and in regular use. The provision of services such as teleassistance, telenavigation, and telerobotics requires considerable infrastructural resources not only in the home country but even more so in military operational environments abroad. Working groups of the European Space Agency are currently attempting to establish complex telemedical networks in a multinational setting (including German Armed Forces neurosurgical departments). A system that has proven to be effective in clinical practice and can also meet military operational requirements is not yet available. The long-term objective is to support on-site medical personnel and remote military specialists in neurosurgery who provide advice (teleconsultation) or actively help perform neurosurgical interventions (teleassistance). Teleassistance involves the use of a camera that allows a remote specialist to directly support a surgeon intraoperatively. One major problem is the establishment of an adequate telecommunications infrastructure that ensures live interaction between the patient, the on-site surgeon, and the remote neurosurgeon. Available systems are not yet able to transmit the large amounts of data required for this purpose. For this reason, existing surgical planning and support systems that are based on information technology must be continuously improved and extended at home. Once they have been integrated into everyday clinical practice, these systems (or at least basic components) can be transferred to field hospitals in countries of deployment. As these systems are used in everyday practice and for training purposes and their performance is continually monitored and assessed, they are already being integrated into future deployment concepts.

The definitive treatment of complex head and spinal injuries requires a high level and wide variety of resources that cannot be held available in countries of deployment. For this reason, definitive treatment must be provided in a German Armed Forces hospital in Germany (Role 4). This applies to the ventral treatment of thoracolumbar spine injuries and severe head injuries such as a cranioplasty after osteoclastic trepanation or facial nerve reconstruction. This means that medical health professionals in the hospitals of the German Armed Forces must have state-of-the-art equipment and all the knowledge they need to provide optimal definitive treatment.

The Role of Neurosurgery at Home

Modern neurosurgery that is based on and reflects current knowledge and advances requires the availability of state-of-the-art technical equipment. Only then can a hospital ensure maximum patient safety and maintain a competitive position in the hospital market. The neurosurgical departments of the German Armed Forces hospitals must be able to compete with their civilian counterparts. Whether neurosurgical patients who present with conditions or require procedures that may be of relevance in military operational settings will be treated in a specific neurological department depends on the availability of modern surgical support procedures. Frame-based and frameless stereotactic surgery and neuronavigation have been used for years. The integration of functional imaging, for example, PET, functional MR imaging, and fiber tracking, into a navigation system are likely to become standard for certain types of surgeries in the future. In addition, 5-aminolevulinic acid–induced fluorescence is used for intraoperative guidance of malignant glioma resection. Microscope-integrated indocyanine green angiography is also used during cerebrovascular procedures on a regular basis. For more complex spinal surgery (above all spinal fusion and cervical spine or craniocervical junction fixation), a navigation system is almost always used and enables the surgeon to correctly place the screws. All these modern methods are being used at the Department of Neurosurgery of the German Armed Forces Hospital in Ulm as well as in the other neurosurgical departments operated by the German Armed Forces. Military hospitals must remain competitive with civilian hospitals to ensure the continued availability of a sufficient number of patients requiring intracranial and spinal procedures that are likely to be of relevance in military operational settings and thus to ensure the initial and sustainment training of neurosurgical professionals. In this context, the importance of CT and MR imaging techniques for intraoperative diagnosis should be emphasized. Particular attention must be paid to the clinical application and the further development of these techniques.

Conclusions

After World War II, there was no compelling need for the presence of military neurosurgeons in military operational settings abroad. As a result of the limited availability of civilian neurosurgeons in most countries of deployment, however, neurosurgical treatment is an important—and sometimes even expected—component of the medical care that is offered for the local population and local personnel, provided such care is part of the mission of the medical service.

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: UM Mauer. Acquisition of data: UM Mauer, C Schulz, R Rothe. Analysis and interpretation of data: UM Mauer, C Schulz, R Rothe. Drafting the article: UM Mauer. Critically revising the article: U Kunz. Reviewed final version of the manuscript and approved it for submission: U Kunz. Administrative/technical/material support: UM Mauer, U Kunz.

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Address correspondence to: Uwe Max Mauer, M.D., Lt. Col. (MC), Department of Neurosurgery, German Armed Forces Hospital, Oberer Eselsberg 40, D-89070 Ulm, Germany. email: UweMaxMauer@bundeswehr.org.

Bulgarian military neurosurgery: from Warsaw Pact to the North Atlantic Treaty Organization

Yavor Enchev, M.D., Ph.D.,[1] and Tihomir Eftimov, M.D., Ph.D., LTC, Bulgarian Army[2]

[1]*Department of Neurosurgery, Medical University-Sofia; and* [2]*Clinic of Neurosurgery, Military Medical Academy-Sofia, Bulgaria*

After 45 years as a closest ally of the Soviet Union in the Warsaw Pact, founded mainly against the US and the Western Europe countries, and 15 years of democratic changes, since 2004 Bulgaria has been a full member of NATO and an equal and trusted partner of its former enemies. The unprecedented transformation has affected all aspects of the Bulgarian society. As a function of the Bulgarian Armed Forces, Bulgarian military medicine and in particular Bulgarian military neurosurgery is indivisibly connected with their development. The history of Bulgarian military neurosurgery is the history of the transition from the Union of Soviet Socialist Republics military system and military medicine to NATO standards in every aspect. The career of the military neurosurgeon in Bulgaria is in many ways similar to that of the civilian neurosurgeon, but there are also many peculiarities. The purpose of this study was to outline the background and the history of Bulgarian military neurosurgery as well as its future trends in the conditions of world globalization. *(DOI: 10.3171/2010.3.FOCUS109)*

Key Words • **neurosurgery** • **military neurosurgery** • **battlefield neurosurgery** • **Bulgarian military neurosurgery**

Bulgaria is a middle-range southeastern European country with a territory of 111,000 km^2 and a population of 7.5 million. The history of Bulgarian military neurosurgery is hard to understand without the knowledge of significant historical facts concerning the political state and the military forces in Bulgaria during the communist regime and the ensuing democratic changes up to the present.

Bulgaria in the Communist Era

After Bulgaria was proclaimed a People's Republic in 1946, the military rapidly adopted the Soviet military doctrine and organization. The country received large amounts of Soviet weaponry, and established a powerful domestic military production.

Traditionally Bulgaria had more troops in uniform per capita than the other Warsaw Pact countries. At one time, it had almost as many soldiers as Romania, a country with a population three times as large as Bulgaria's. By the year 1988, the Bulgarian People's Army numbered 152,000 men, serving in four different branches; Land Forces, Navy, Air and Air Defense Forces, and Missile Forces.

At that time the Bulgarian People's Army operated with an impressive amount of equipment for the country's size; 3000 tanks, 2000 armored vehicles, 2500 large-caliber artillery systems, more than 300 combat aircraft, and 33 combat vessels, as well as 67 SCUD missile launchers, 24 SS-23 launchers, and dozens of FROG-7 artillery rocket launchers.

Being geographically isolated from the strategically more important northern-tier countries of the alliance, Bulgaria participated in only a few joint exercises of the Warsaw Pact along the central front opposite the NATO forces in the German Democratic Republic (East Germany) and Czechoslovakia. Participation on that front usually was limited to small contingents. Shield-82, the first major Warsaw Pact exercise in Bulgaria, was conducted in 1982 and involved 60,000 allied troops from the northern-tier Warsaw Pact countries for the first time. The Warsaw Pact conducted the major command and the staff exercise for its Southwestern Theater of Military Operations in Bulgaria in 1984.

Contemporary Postcommunist Democratic Bulgaria

Bulgaria's transition to democracy was relatively smooth. The Bulgarian communist leader Todor Zhivkov was ousted the day after the Berlin Wall fell, and his departure gave impetus to the country's prodemocracy movement. The Communist Party voluntarily gave up its absolute hold on power in February 1990, and the country's first free elections since 1946 were held 4 months later.

Abbreviations used in this paper: BA = Bulgarian Army; BMMC = Balkan Military Medical Committee; NATO = North Atlantic Treaty Organization.

Fig. 1. Portrait of Major-General Professor Gancho Savov.

Fig. 2. Photograph of the building of the Military Medical Academy-Sofia, currently the biggest hospital in the Balkans. The Clinic of Neurosurgery is located on the 10th floor.

Armed Forces Overview

As a new member of NATO since 2004, Bulgaria's chief military goal in the mid-2000s has been conformity with the equipment and practices of its NATO allies, including military medicine. This goal is to be attained in a gradual modernization plan extending through 2015. In 2009 Bulgaria had approximately 39,000 active-duty military personnel, with the eventual goal of 30,000 active-duty personnel. The process of gradual demilitarization has also affected many military doctors, including military neurosurgeons.

Foreign Military Relations

In 1994 Bulgaria became a member of NATO's Partnership for Peace, participating in joint military exercises and generally supporting the NATO missions in the former Yugoslavia. Since 2004, the dominant aspect of foreign military relations has been activity in NATO.

External Threat

In 2009 Bulgaria faced no threat of conventional armed attack.

Military Service

Bulgarian men were eligible for a basic 2-year military conscription, which was reduced gradually to 9 months, and to 6 months for university graduates. Nowadays, the BA is completely professional, without any conscription.

Foreign Military Forces

In 2009 no foreign troops were stationed in Bulgaria. However, as part of its NATO membership, Bulgaria has negotiated the terms for joint training with a small contingent of US troops at four Bulgarian bases.

Military Forces Abroad

In 2005 Bulgaria withdrew all 466 troops that had supported Operation Iraqi Freedom, but it sent a 150-member humanitarian group to Iraq in early 2006. Elsewhere, in 2005 Bulgaria had 250 troops with the International Security Assistance Force in Afghanistan; approximately 500 troops with the United Nations Kosovo Peacekeeping Force in Serbia; and observers with the United Nations forces in Burundi, the Democratic Republic of Congo, India and Pakistan, and the Middle East.

History and Present State of Bulgarian Military Neurosurgery

The Central Military Hospital-Sofia was founded in 1951, following the Soviet model, as a training and research center in the military aspects of the medical sciences, to upgrade the training of military physicians, and to provide medical services for the armed forces.

The first Bulgarian military neurosurgical ward was established during the same year at the Central Military Hospital-Sofia. The founder of Bulgarian battlefield neurosurgery, Major Dr. Gancho Savov, who had trained for 2 years in Leningrad, in the former Soviet Union, was appointed as its head.[2] In 1961 the neurosurgical ward, with a staff of 25 doctors, became a neurosurgical clinic, and along with the clinics of Neurology, Psychiatry, and Maxillofacial Surgery, was integrated into the Department of War-Field Traumatology of the Nervous System at the Higher Military Medical Institute-Sofia. From its foundation until 1986, the neurosurgical clinic and the Department of War-Field Traumatology of the Nervous System had been commanded by Professor Gancho Savov (Fig. 1), who by then had attained the rank of Major General. Professor Savov's scientific interest, work, and numerous publications were focused mainly on the problems of traumatic brain injuries, traumatic subdural hematomas, and neurooncological and vascular neurosurgery. He was a skillful neurosurgeon and a devoted teacher of the next generations of Bulgarian military neurosurgeons.

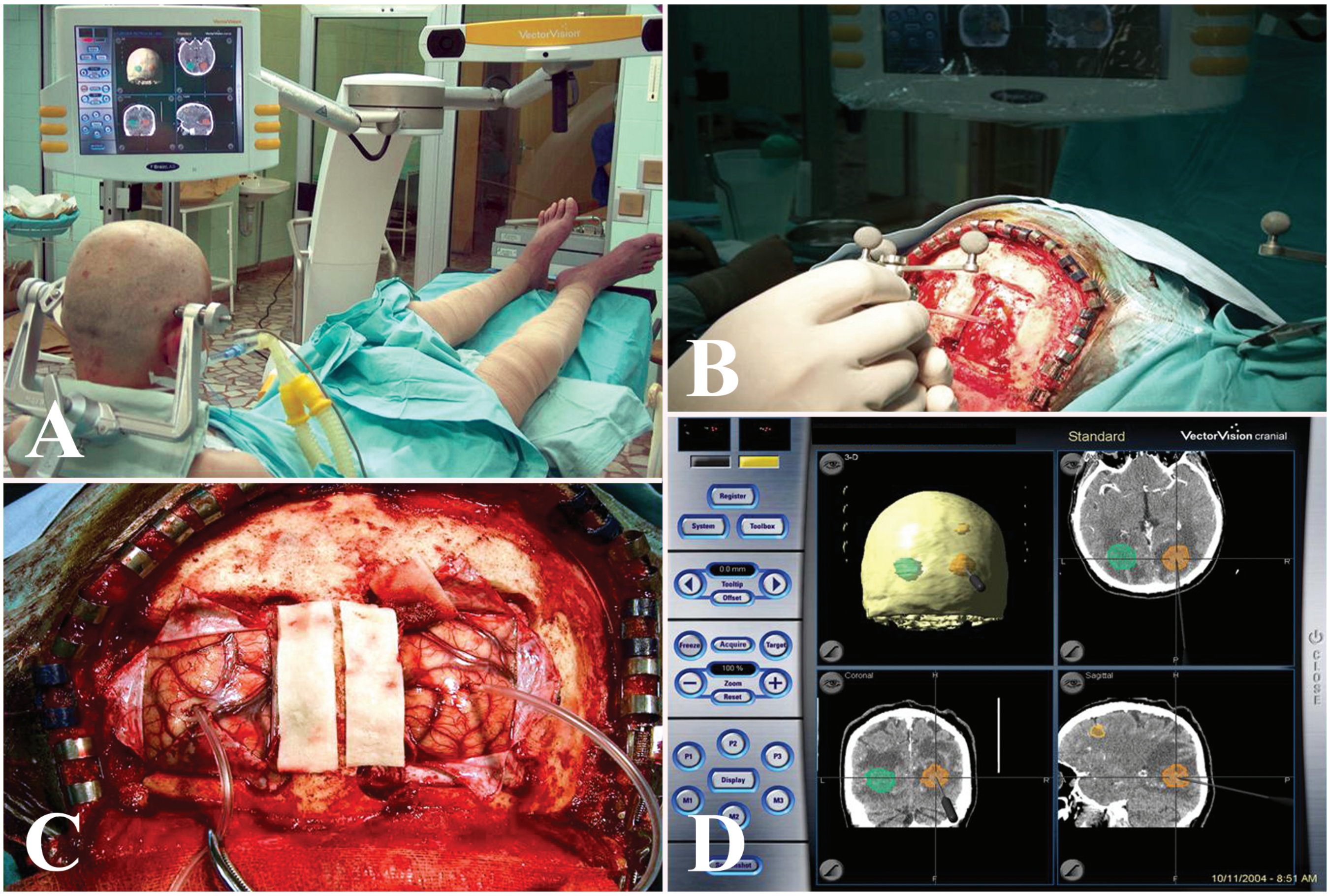

Fig. 3. Intraoperative application of light-emitting diode–based neuronavigation in a 49-year-old patient with 3 metastatic tumors (outlined in *green*, *orange*, and *yellow*). The mirrorlike occipital tumors were removed simultaneously in 1 procedure. **A:** Sitting position of the patient. **B:** Following a bi-occipital skin incision, 2 neuronavigationally outlined occipital craniotomies were performed. **C:** In both metastatic tumors, catheters were inserted neuronavigationally as guides for the localization of the lesions. **D:** Intraoperative screenshot visualizing the localization of the right occipital metastasis.

Throughout the communist era, many Bulgarian military neurosurgeons, as representatives of a Warsaw Pact country, gained significant wartime experience in the numerous world and regional military conflicts and missions in the countries of Latin America, Africa, and Asia.

Following Professor Savov's tenure, the head of the neurosurgical clinic at the Military Medical Academy had been Colonel Professor Todor Stoianchev and Colonel Associate Professor Dimitar Krastev for 4 and 3 years, respectively.

During the period 1993–2004, the head of the neurosurgical clinic was Colonel Associate Professor Alexandar Petkov. In 2004 Petkov retired as a colonel, but up to date has been the head of the Clinic of Neurosurgery and a head of the Department of Neurology and Neurosurgery at the Division of Military Surgery, Military Medical Academy-Sofia (Fig. 2).

In 1995, in the Military Medical Academy, the Clinic of Emergency Neurosurgery was established under the leadership of Professor Manol Vanev and subsequently Associate Professor Nedelcho Gergelchev. At that time the clinic had 20 beds, 7 doctors, and 10 nurses. The priority of the clinic was the patients with neurotraumas, but there was a permanent trend toward increase in the number of patients with neurovascular, neurooncological, and spinal diseases. Due to the reforms in the BA and the processes of demilitarization and restructuring of the Military Medical Academy, however, the Clinic of Emergency Neurosurgery was closed in 2000.

Following the actual membership of Bulgaria in NATO in 2004, the manner of organization of the Military Medical Academy-Sofia and in particular of the neurosurgical clinic has been brought into line with NATO standards.

Nowadays, the neurosurgical clinic has 2 operating rooms, 30 beds, 7 senior neurosurgeons, 4 neurosurgical residents, 10 ward nurses, and 3 scrub nurses. The clinical structure includes 3 wards—general and functional neurosurgery, spinal neurosurgery, and neurooncology. The neurosurgical clinic is supplied with such contemporary high-tech devices as 2 neuronavigation systems (infrared- and ultrasound-based); an ultrasonic aspirator; modern microscopes; neuroendoscopes; many complete sets of microneurosurgical instruments; a digital C-arm; sets of instruments for the anterior cervical approach and for various types of transpedicular screw fixation; a device for intracranial pressure monitoring by intraventricular,

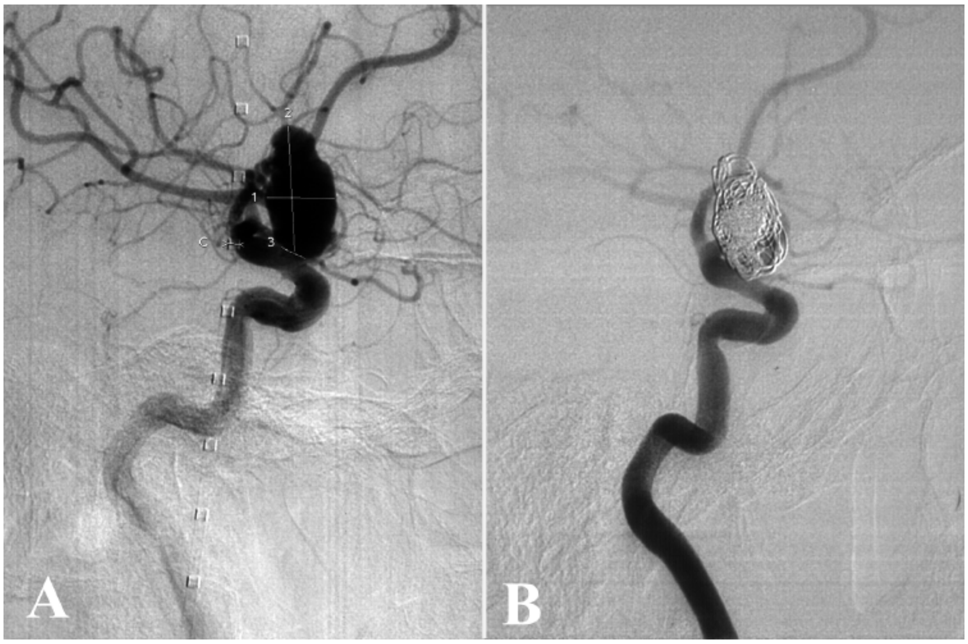

FIG. 4. Endovascular treatment of cerebral brain aneurysm. **A:** Preembolization angiographic study. **B:** Postembolization angiographic study.

intraparenchymal, and subdural transducers; and so forth. Available for neurosurgical purposes are a modern 1-T MR imaging device, a helical CT scanner, and a digital angiograph.

The Clinic of Neurosurgery at the Military Medical Academy-Sofia ensures neurosurgical treatment not only to military personnel and their relatives, but also to all health-insured Bulgarian people and to all emergency neurosurgical patients. The neurosurgical clinic at the Military Medical Academy-Sofia is one of the leading neurosurgical centers in Bulgaria, especially in the field of neurotrauma (cranial, spinal, and peripheral nerves) caused by gunshots, missiles, and so on. The complicated criminal situation during the time of transition to democracy has been beneficial for achieving significant experience with civilian gunshot injuries.

In neurooncology, the surgical activity of the clinic includes microsurgery of glial tumors, metastases (Fig. 3), meningiomas, vestibular schwannomas, craniopharyngiomas, and pituitary adenomas (via a transcranial and/or transnasal-transsphenoidal approach); intraventricular tumors (via a craniotomy or neuroendoscopy); pineal lesions, orbital tumors, brainstem tumors, craniobasal carcinomas, craniospinal chordomas, spinal tumors, and so forth.

Neurovascular pathological entities such as cerebral aneurysms, arteriovenous malformations, cavernomas, carotid–cavernous fistulas, and so on are treated using open neurosurgical procedures or endovascular techniques. In less than 3 years, a rich and unique (for Bulgaria) experience with endovascular embolization of brain and spinal vascular malformations and aneurysms (Fig. 4), as well as with endovascular stenting procedures, has been gained.

The applied functional neurosurgical procedures are epileptic surgery, glycerol rhizolysis, microvascular decompression, and rhizotomy in cases of trigeminal neuralgia, cancer pain surgery, and so on. All possible neuroendoscopic procedures, such as third ventriculostomy, septopellucidotomy, aqueductoplasty, biopsy, and tumor resection are performed in the clinic. Many procedures are neuroendoscopically assisted, profiting by the ability of the endoscope "to look behind the corner."

Spinal neurosurgery is highly developed, including percutaneous vertebroplasty and kyphoplasty and most of the contemporary methods and techniques of spinal instrumentation of the degenerative and traumatically injured spine (Fig. 5).

An experimental direction is the neurosurgical treatment with brainstem cells and neurotrophic growth factors.

The Clinic of Neurosurgery at the Military Medical Academy-Sofia is a referent center for neurosurgical residency not only for the military neurosurgeons. The term of residency is 5 years, and terminates with a Board Examination in Neurosurgery. The examination has three steps. The first part is practical; the resident performs a neurosurgical procedure under the supervision of a senior neurosurgeon. The residents who have passed the first step have a written exam in several neurosurgical areas. The ones who have passed the second then reach the third part—an oral examination in front of the Government Examination Commission, which consists of three professors in neurosurgery, and usually among them is the Head of the Clinic of Neurosurgery at the Military Medical Academy-Sofia.

The Clinic of Neurosurgery at the Military Medical Academy-Sofia is a regular participant in the annual congresses of the BMMC, where actual problems and achievements in the military medicine of the Balkan countries are presented and discussed. The BMMC was established in 1995 based on the idea and initiative of Colonel Associate Professor Alexandar Petkov and with

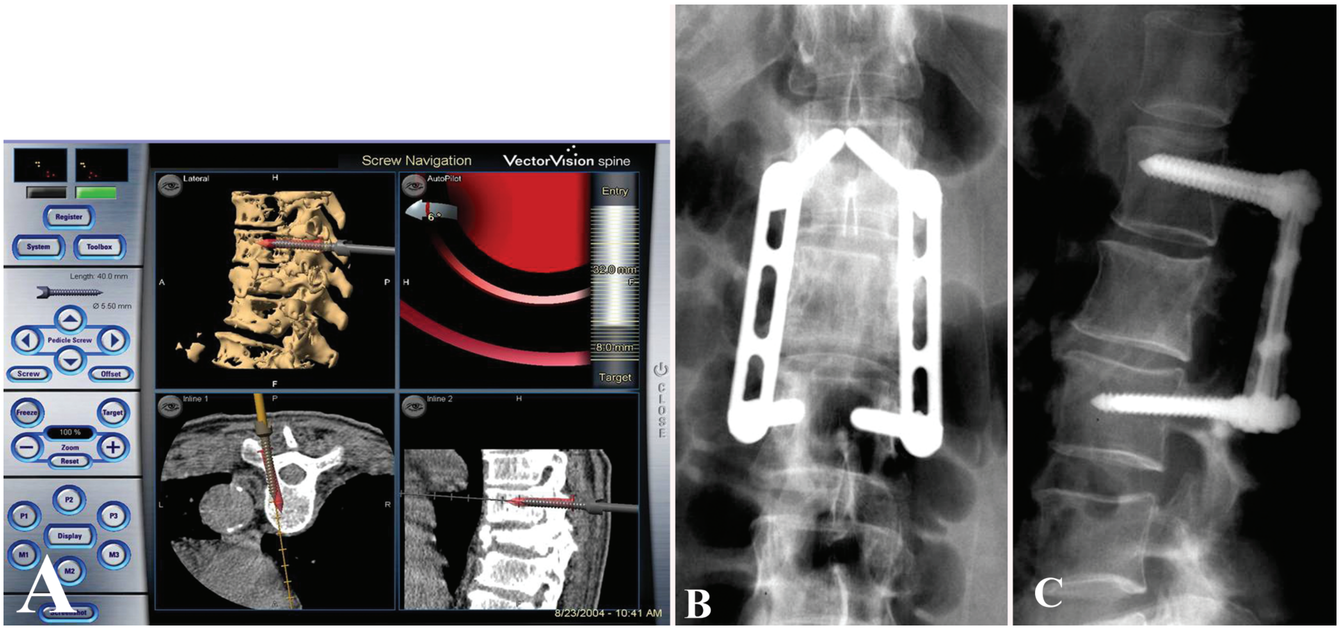

Fig. 5. Neuronavigationally guided insertion of a pedicle screw as part of a spinal stabilization procedure. **A:** Intraoperative screenshot visualizing the positioning of a pedicle screw by using the "autopilot" function of neuronavigation. **B:** Postoperative anterior-posterior radiography study showing the spinal instrumentation in position. **C:** Postoperative lateral radiography study showing the spinal instrumentation in position.

the participation of Bulgaria, Greece, Romania, and Turkey. Nowadays the BMMC is growing, with the association and acceptance of new member countries—Macedonia, Serbia, Croatia, and Montenegro. The participation of Bulgarian military neurosurgeons in military NATO missions is still limited.

Recruitment of Bulgarian Military Neurosurgeons

A professional military career, including that of a military doctor and in particular a military neurosurgeon, has been considered relatively prestigious in Bulgaria, although its prestige has begun to wane in the postcommunist era. Depending on whether nonmonetary benefits like housing and food were considered, an officer's pay was generally 25–50% higher than that offered in civilian positions for neurosurgeons with comparable responsibilities. Only in 1990 did the defense establishment start to address problems familiar to military officers in all countries, however. For example, spouses frequently were unable to find work in the vicinity of military posts. In 1991 a special cash allowance to military families was considered to cover these instances. Day-care and school accommodations often were scarce, and adequate housing was unavailable.

Before becoming a full member of NATO in 2004, the BA started a strict plan for reorganization in accordance with NATO standards. The process of reduction of the number of members in the BA by the gradual demobilization of part of the officers' staff has also affected many military doctors, including military neurosurgeons. Five military neurosurgeons lost their status as military officers and became civilian neurosurgeons.

Training System for Bulgarian Military Neurosurgeons

Military medical training in Bulgaria during the communist regime followed the Soviet model. The medical students willing to become military medical doctors were able to apply for a whole-studies-term military grant. The candidates were subjected to a thorough political examination of their families by the relevant communist organization. The selection was not based on results of medical exams, but on the decision of the communist authorities. The approved medical students signed contracts for 10 years of service as military doctors in the BA without an option to choose their place of work. The military residents in neurosurgery received a substantial monthly grant for the term of residency. In return, after graduation the military neurosurgeons were obliged to fulfill the preliminary contractual duration in military service as medical officers. Following the democratic changes in Bulgaria, the resources for the BA, military medicine, and in particular for military neurosurgery have been significantly reduced. The military neurosurgical residents have lost their privileges, including their financial support by means of monthly grants and nonmonetary benefits. Since the beginning of Bulgaria's membership in NATO, the situation has improved gradually.

Advantages and Disadvantages of a Career as a Military Neurosurgeon in Bulgaria

Nowadays, the salary of Bulgarian military neurosurgeons is equal to or relatively higher compared with that of Bulgarian civilian neurosurgeons, in contrast to the situation with the US military neurosurgeons.[1] Bulgarian military neurosurgeons receive payment from the BA on the one hand as military officers, and from the National Health Insurance Fund on the other hand as medical doctors supplying services to the health-insured citizen. The age of retirement, however, although comparable to that of US military neurosurgeons,[1] is lower by several years compared to that of civilian neurosurgeons. Other advantages are the multiple possibilities for sponsored training and continuing medical education. The patient population is not limited to military personnel and their dependents, but to all health-insured Bulgarian citizens, and even to uninsured emergency patients. In this way, the high case volume of various neurosurgical pathological entities is beneficial for the professional qualification and maintenance of competence. The excellent technical equipment of the military neurosurgical clinic due to NATO's membership financial support is also very attractive. The most appealing aspect of military neurosurgical practice, however, is the opportunity to serve as an officer of the BA and in this way to serve one's country.

The drawbacks of military service are mainly outlined in the signed contract, and include a permanent readiness to be deployed in risk-filled points of military conflict or humanitarian crisis, an impossibility of changing one's workplace of one's own free will, and last (but not least) the prohibition against private neurosurgical practice. The current disadvantages of the career of military neurosurgeon in Bulgaria do not differ significantly from those of US military neurosurgeons.[1]

Future Trends in Bulgarian Military Neurosurgery

The number of the Bulgarian military neurosurgeons will probably increase with the growing number of peacekeeping missions of the BA outside the country. Recently the Military Medical Academy-Sofia became equipped with a modern mobile battlefield hospital, which, although it has not got specific equipment allowing the performance of all kinds of neurosurgical procedures, still includes a mobile CT scanner for neurodiagnosis and is perfectly suitable for wartime neurotrauma cases. The beginning of NATO missions abroad for the Bulgarian military neurosurgeons connected with this hospital are only a matter of a short time. In this way, the currently limited battlefield experience of these neurosurgeons will be augmented in real-time, dangerous situations.

Conclusions

Bulgarian military neurosurgery has a short but very eventful history, reflecting the changes in the political philosophy and military organization of Bulgaria. During the communist era, military neurosurgery was focused mainly on battlefield neurosurgical pathological conditions such as traumatic brain injury, traumatic subdural hematoma, and so forth, which were expected to be caused by the military forces of the Warsaw Pact's enemy countries in NATO. Almost 2 decades after the democratic changes in our country, Bulgaria is a NATO member, and Bulgarian military neurosurgery covers every neurosurgical disease. The prestige of Bulgarian military neurosurgeons has remained consistently high, regardless of the described reforms. The only limitation on the increase of their number is due to the lack of vacancies.

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: Y Enchev. Analysis and interpretation of data: Y Enchev. Critically revising the article: T Eftimov.

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Address correspondence to: Yavor Enchev, M.D., Ph.D., Department of Neurosurgery, Medical University-Sofia, University Hospital "Sv. Ivan Rilsky," 15, Boulevard "Acad. Ivan Geshov," 1431 Sofia, Bulgaria. email: dr.y.enchev@gmail.com.

The evolution of military neurosurgery in the Turkish army

Lt. Col. Yusuf Izci, M.D.

Department of Neurosurgery, Gulhane Military Medical Academy, Ankara, Turkey

The history of neurosurgery in the Turkish army is not long and complex. Neurosurgery was first practiced in the Ottoman army by Cemil Pasha, who was a general surgeon. After the fall of the Ottoman Empire, the Republic of Turkey was established and modern neurosurgical procedures were applied at the Gulhane Military Medical Academy (GMMA). Maj. Zinnur Rollas, M.D., was the founder of the Department of Neurosurgery at GMMA in 1957. A modern neurosurgical program and school was established in 1965 by Col. Hamit Ziya Gokalp, M.D., who completed his residency training in the US. Today, 26 military neurosurgeons are on active duty in 11 military hospitals in Turkey. All of these neurosurgeons work in modern clinics and operating theaters. In this paper, military neurosurgery in the Turkish army is reported in 3 parts: 1) the history of neurosurgery in the Turkish military, 2) the Department of Neurosurgery at the GMMA, and 3) the duties of a military neurosurgeon in the Turkish army.
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Key Words • **military** • **neurosurgery** • **Turkish army** • **Gulhane Military Medical Academy**

Military neurosurgery has a very long and proud tradition of service and innovation that comes to the forefront during periods of peace and war. Modern military surgery in the Ottoman army began with the establishment of Military Medical School in 1827. This school educated and trained the medical students in the European style. This was an evidence-based and secular education without the influence of traditions and religious rules.The history of military neurosurgery in the Ottoman army began with Cemil Pasha (Topuzlu) who was the general surgeon. This history can be divided into 3 consecutive periods: 1) 1890–1908, 2) 1909–1957, and 3) 1957–2009.

History of Neurosurgery in the Turkish Military

1890–1908

After the 17th century, Ottoman medical science began to turn to the West, although until the 19th century it may still be regarded mainly as the continuation of Islamic medicine, which refers to medicine developed in the medieval Islamic civilization and written in Arabic. This medical practice was based on Islamic traditions and religious rules. In the 19th century there were closer medical relations of Turkey with Italy, Austria, and France. Beginning in the second quarter of the 19th century, increasing numbers of physicians from European countries were invited to teach medicine or to be employed in the palace of the Ottoman Emperor or in royal medical institutions. The latter half of the 19th century is considered the formative period of what we now refer to as the era of modern surgical practice. In this era, although probably the most demanding of all the surgical specialties, neurosurgery was nevertheless one of the first specialties to emerge. The first period of military neurosurgery in the Turkish army began with Cemil Pasha. He graduated from military medical school in 1886 as a captain. In 1887, he was sent to Paris for further education and training in surgery. He worked as a resident under Professor Jules Pean, who was France's most famous surgeon at that time. He also worked with other famous surgeons Dr. Verneuil, Dr. Tillaux, and Dr. Guyon before returning to Turkey in 1890 where he became an associate professor in surgery at the Military Medical School in the following year. In 1894, Dr. Pasha became a clinical professor in surgery and the chair of the Department of Surgery. While the developments of surgical techniques, antisepsis, and anesthesia occurred in the Western world, Cemil Pasha was sparking a new era in the history of military surgery in the Ottoman Empire. Starting in 1891, he operated on many patients with brain abscesses, spinal tuberculosis, and traumatic and neoplastic cranial and spinal disorders. He published the list of his cases in *La Gazette Medicale D'Orient* and later in his monograph, *Mémoires et Observations Médicales* in 1905.[2] He published the full texts of operative notes recorded during his years at Military Medical School between 1893 and 1897. He became a general in the Ottoman army in 1905 and then resigned from the army in 1909.[9,12] Dr. Pasha was

Abbreviation used in this paper: GMMA = Gulhane Military Medical Academy.

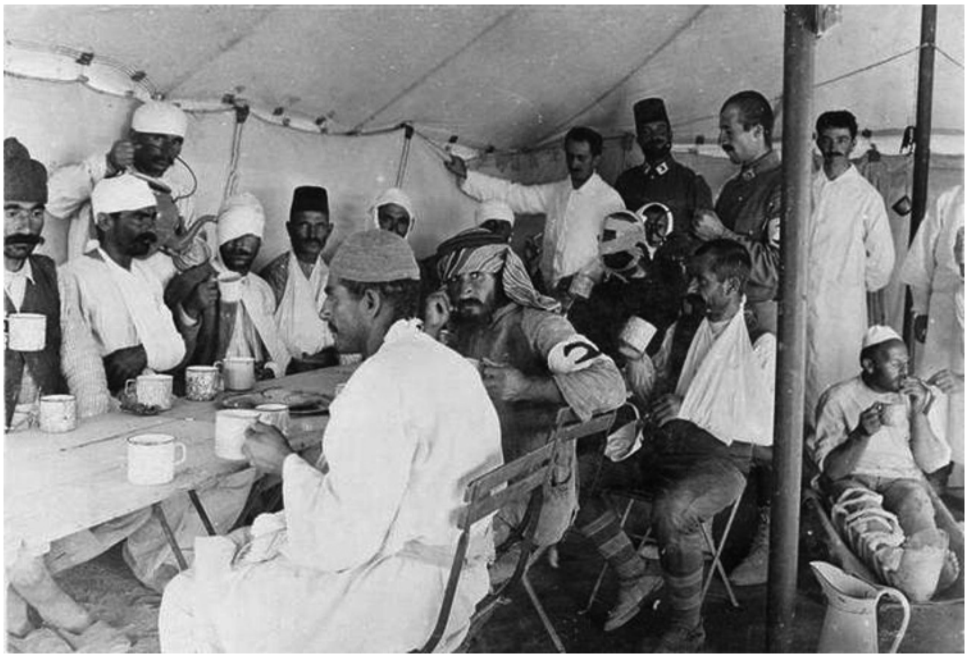

Fig. 1. Phototgraph of dining time in a military field hospital of the Ottoman army during World War I.

one of the pioneers and the founder of contemporary surgery in the Ottoman Empire. His principles became the landmarks of modern surgery in the Turkish Republic.

1909–1957

The next period in Turkish military neurosurgery began with the neurosurgical operations that were performed at GMMA by Dr. Julius Wieting and Col. Mim Kemal Oke. The GMMA was established in 1898 as a training hospital of the Military Medical School. After constitutional rule was reinstalled in 1908, a major reform initiative was started in the Ottoman army. From 1898 to 1914, the German physicians Robert Rieder and Franz Deycke, and following them, Julius Wieting, were the doctors who played a great role in the development of medical education in the GMMA and military hospitals. In 1908, Ottoman physicians were sent to Germany for specialization. In the same year, Dr. Wieting conducted the first Foerster operation, which was the surgical treatment of spastic paralyses by sectioning of the posterior nerve roots, at GMMA. World War I was a disastrous event for the Ottoman Empire. The Turkish army fought against many countries over a large geographical area. During this war, the medical branch of the Ottoman army consisted of doctors, surgeons, veterinarians, pharmacists, dentists, chemists, wound-dressers, and nurses. Armies, corps, and divisions had medical units and the main centers of healthcare were the Red Crescent hospitals, field hospitals, and mobile hospitals (Fig. 1). There were no special facilities for the treatment of head injuries until it was recognized that early operations and the avoidance of slow and distressing evacuations resulted in significantly better surgical outcomes with less infection rates of the wounds. Hospitals located a few miles from the front were therefore designated for the reception of soldiers with head wounds, and postoperative cases remained there for 2 or 3 weeks before being released. There were very few surgeons who were experienced in the treatment of cranial and spinal wounds during the war; however, the need for a thorough exploration and the removal of all bone fragments was slowly appreciated, and meticulous primary closure of the wound prevented herniation of brain into the skull defect and scalp wound. The postoperative mortality rate was approximately 50% but many patients died before reaching a surgeon.

By the end of World War I, Dr. Wieting returned to Germany, and Col. Professor Mim Kemal Öke (1884–1955) became the head of the Department of Surgery in 1918. But the wars were not over for the Turkish army. The Turkish War of Independence is the common name of the multifront political and military struggles that occurred between 1920 and 1922 against the victorious countries of World War I in an effort to protect the Turkish nation and help it flourish. Despite the deficiencies in terms of medical equipment and organization, the humble efforts and endeavors of the military surgeons enabled the Turkish army to receive proper medical care. The Turkish War of Independence stimulated the progress of neurosurgery and taught the surgeon innumerable lessons, which were subsequently applied in civilian practice. Military surgeons were faced with the need to treat large numbers of contaminated wounds in improvised medical facilities, and they performed necrotic tissue debridement; the operations were performed mostly during infectious conditions.

Before 1923, few general surgeons performed neurosurgical procedures at the GMMA, as a result of the influence of European surgeons, especially those from France, Germany, and Switzerland. Among them, Col. Mim Kemal Öke was an especially brilliant surgeon. He wrote the first Turkish brain surgery textbook *Dimağ ve Cümcüme*

Fig. 2. Col. Hamit Ziya Gokalp, who established modern neurosurgical education and practice in the Turkish army.

Fig. 3. Photograph of rapid patient evacuation by helicopter during the Cyprus Peace Operation.

Afetleri ve Tedavileri [*Craniocerebral Disorders and Their Treatment*] in 1924. This book has 2 parts: the first part focused on theoretical information on general neurosurgery, whereas the second part provided an illustrated section on operative brain surgery. The main neurosurgical applications during this period included craniotomies for brain tumors, laminectomies for spinal traumas and infections, surgery for peripheral nerve injuries, surgery for congenital disorders such as hydrocephalus and meningocele, and functional neurosurgical applications for spasticity and trigeminal neuralgia. Between 1917 and 1936, Col. Öke published all of his neurosurgical cases in 14 manuscripts in various medical journals.[11,12]

Among Turkish surgeons who visited western neurosurgical centers, Capt. Mustafa Sakarya was the first to visit the US.[10] He was trained in general surgery, and was then sent to the US for additional neurosurgical training in 1938. Capt. Sakarya was the fellow of Dr. Walter E. Dandy and worked for 9 months at Johns Hopkins Hospital. He wrote his daily observations, operation schedules, information regarding illustrative cases, and some theoretical reviews in his notebook. Capt. Sakarya performed a limited number of neurosurgical procedures for meningioma and neurotrauma. However, he could not work effectively as a neurosurgeon because he was sent to local army hospitals as a general surgeon, as well as to Afghanistan.[10] Between 1940 and 1950, Professors Recai Erguder and Naci Ayral performed many neurosurgical procedures in the Department of Surgery at GMMA. During the Korean War, they treated many patients with cranial and spinal injuries. They removed foreign bodies from the cranium and performed laminectomies for spinal traumas and infections. There were great advances in technique and equipment in the years between the Turkish War of Independence and the Korean War. The mortality rate decreased even more during the Korean War, primarily because surgical personnel were present in forward military hospitals and antibiotics were largely introduced. However, the operative approach was largely the same, that of radical debridement. But neurosurgery remained a very small specialty practiced by men who also had to care for general cases. The main precepts concerned segregation of cranial and spinal injuries, adaptability, and early neurosurgical treatment, including the total removal of bone fragments and decompression of the neural tisuues under direct vision, followed by primary wound closure. These requirements remain for the most part today.

1957–2009

The establisment of the Department of Neurosurgery at GMMA by Maj. Zinnur Rollas, M.D., was the beginning of the third period in the history of Turkish military neurosurgery. After finishing his residency in neurology, Maj. Rollas participated in the Korean War and observed American surgeons who performed neurosurgical procedures for cranial and spinal injuries. After this war, he went to the US and trained with Dr. Harry E. LeFever at Ohio State University between 1954 and 1956. Maj. Rollas participated in approximately 400 neurosurgical operations, and performed 180 operations himself during his residency. He also worked as an instructor of neurosurgery at this university for a short time. After returning to Turkey, he established the Department of Neurosurgery as a separate clinic in June 1957.[18] He performed pneumoencephalographies, angiographies, and neurosurgical operations. Maj. Rollas became the chief of the department and began to practice neurosurgery at GMMA. Maj. Rollas was experienced in treating congenital malformations, hydrocephalus, neurotrauma, and intracranial tumors. Col. Hamit Ziya Gokalp, M.D., was the first neurosurgery resident at GMMA (Fig. 2). He graduated from medical school in 1952 and began his internship at the Department of Surgery. After his work in this clinic, he moved to an air force base in Diyarbakir where he observed many cranial cases and decided to become a neurosurgeon. He returned to GMMA and began his residency in general surgery. He worked with Maj. Rollas who had recently returned from the US. At that time, no accredited residency program in neurosurgery was available at GMMA, and Dr. Gokalp went to the US, where he was trained at the Department of Neurosurgery of Walter Reed Army Medical Center under the supervision of Col. George Hayes and Lt. Col. Ludwig Kempe. He then moved to the George Washington University and became the resident of Professor James Watts. Col. Gokalp performed many neurosurgical procedures at the George Washington University and returned to GMMA after finishing his residency in 1965. He became an associate professor and the head of the department in 1970. Col. Gokalp began to practice stereotactic and functional neurosurgery. After his retirement in 1972, he moved to the University of Ankara and became professor of neurosurgery.[18]

Cyprus has long been a source of conflict in Turkish-

Fig. 4. Photographs showing the main building of the GMMA in Ankara **(upper)** and the Military Medical School on the campus of GMMA **(lower)**.

Greek relations. In 1974 when a military coup in the name of union with Greece took place, the Turkish Peace Operation partitioned the island. Helicopters were used in the casualty evacuation during the Cyprus Peace Operation. Once the principles of military surgery were relearned in this operation and applied to modern warfare, mortality and morbidity were reduced to levels previously unattainable. Surgical specialization and teamwork reached new heights with the creation of units to deal with the special problems of injuries to different parts of the body. But the most revolutionary change was in the approach to wounded soldiers brought about by the use of the helicopter for transportation (Fig. 3). Rapid evacuation of severely injured soldiers from the point of injury provides extreme challenges for neurosurgical teams. Military neurosurgery in the Turkish armed forces, whose capability of diagnosis and treatment continuously increased, proved its power and capabilities once more during the Cyprus Peace Operation. After this war, advances came rapidly, with the initial emphasis on microsurgery. The scope of neurosurgery was further expanded by the introduction of the operating microscope. This introduction brought the benefit of magnification, particularly to neurosurgery. The laboratory of microsurgery was established in the Department of Neurosurgery by Col. Erdener Timurkaynak, M.D., in 1984.[18] This laboratory trained all neurosurgeons in the Turkish army in microsurgery and microsurgical techniques. Today, 26 military neurosurgeons are on active duty in 11 military hospitals in Turkey. All of these neurosurgeons work in modern clinics and operating theaters. The GMMA is the main education center of military neurosurgeons in Turkey.

Department of Neurosurgery at GMMA

The Department of Neurosurgery at GMMA was established in 1957 by Maj. H. Zinnur Rollas, M.D., and is an independent department. The residency program began in 1965 and it has become a nationally recognized center of excellence (Fig. 4). The GMMA Neurosurgery Residency Program is the only neurosurgery training site in the Turkish army. Residency training in neurosurgery at the GMMA is 5 years and the program accepts 1 resident per year. Currently, there are 5 residents and 3 of them are military medical school graduates. The goal of the residency program is to train neurosurgeons who will become leaders in military and academic neurosurgery. The program has a long and proud tradition of training surgeons who have made major clinical and scientific contributions to the field of neurosurgery in Turkey. The philosophy of the program is to expose residents to a large number of high-quality cases spanning the entire range of neurosurgery. As training progresses, residents gain more responsibility in performing surgery and in managing cases. After finishing their residencies, they work only in military hospitals. But military neurosurgeons can work in civilian hospitals after finishing their obligatory military duty, which is 15 years after military medical school. In the Turkish army, all military officers are paid approximately the same for the rank and time in service. Although there is a wide pay gap between the civilian and military physicians in Turkey, it is not difficult to retain neurosurgeons because of the obligatory duty. Most of the military neurosurgeons make their career in the military, especially in GMMA.

The faculty of GMMA specializes in the surgical treatment of adults and children with diseases and disorders related to the brain, spinal cord, and peripheral ner-

Fig. 5. Operating room photograph showing removal of a left thalamic tumor using the neuroendoscope, intraoperative MR imaging, and a neuronavigation system in the operating theater of the Department of Neurosurgery at GMMA.

vous system. Subspecialization among the attending staff fosters broad patient referrals requiring a wide range of surgeries. Nationally renowned areas of expertise exist in neurotrauma, brain tumors, cerebrovascular disorders, pituitary disorders, spinal reconstruction, epilepsy surgery, and neuroendoscopy. The neurosurgeons have expertise in the latest diagnostic and surgical techniques including intraoperative MR imaging and CT, neuroendoscopy, and stereotactic and computer-assisted image-guided neurosurgery. The objectives of the Department of Neurosurgery are to develop special techniques and expertise in neurosurgical procedures and standardize the practice in the Turkish army; to develop the quality and quantity of human resources in the field of neurosurgery for military hospitals; to develop interhospital coordination for activating research/projects such as head trauma, spinal trauma, spine surgery, neurooncology, and neurovascular disorders; to encourage physicians to undertake courses on microsurgery as a part of their training curriculum; and to provide orientation training for neurosurgeons from various medical institutions in Turkey. Most of the patients are from the Turkish army. In addition, approximately 5% of the inpatients are drawn from the civilian population. The Department of Neurosurgery also provides quality emergency and trauma care. The casualty and emergency services are run 24 hours a day, staffed by junior and senior residents and a member of the faculty. Outpatient services for nonemergency cases operate daily from 8 a.m. to 5 p.m. On average about 100 new and returning patients are cared for each day in these services.

To accommodate the patients for admission and surgery there are a total of 56 beds available. There is also a separate 8-bed facility for postoperative patients. A modern fully equipped intensive care facility is available and can treat 16 neurosurgical patients at a time who require respiratory and critical care. This facility also has modern ventilators, monitors, and equipment to monitor intracranial pressure in each patient in all beds, with an ideal nursing staff ratio. Additionally, there is 1 fully equipped operative theater for elective operations, and 1 theater reserved 24 hours a day (every day) only for emergencies. The latter theater has specialized apparatuses and equipment required to deliver quality neurosurgical care (Fig. 5). The list of various instruments includes modern operating microscopes, intraoperative MR imaging for brain surgery, intraoperative CT for spine surgery, intraoperative ultrasonography, intraoperative electrophysiological monitoring for spine and peripheral nerve surgery, fluoroscopy, neuronavigation, neuroendoscopy and skull base instruments, stereotactic apparatus, and an ultrasonic surgical aspirator. Facilities and expertise for the following subspecialties are available in the department: cerebrovascular surgery, cranial base surgery, spinal reconstructive instrumentation, neuroendoscopic procedures, stereotactic procedures, epilepsy surgery, pediatric neurosurgery, and peripheral nerve surgery. Most of the above-mentioned clinical areas have a direct bearing on enhancing patient care and adapting to the particular and specific needs of our soldiers. Thus, the focus of clinical studies is not only to concentrate on various neurosurgical conditions but also to emphasize those conditions common in our army such as landmine explosions, craniocerebral gunshot injuries, spinal injuries, and peripheral nerve injuries due to missile wounds. In addition, we have 1 microsurgical education laboratory that has been developed to perform neurosurgical anatomical dissections, to learn skull base anatomy and other approaches, to train residents and other military surgeons in various microsurgical techniques, to use the drills and microscope for bone and brain dissections, and to perform animal studies. The laboratory has 4 training stations, an operating microscope, and microsurgical instruments.

Duties of the Military Neurosurgeon in the Turkish Army

Neurosurgeons are a small fraction of the health care providers in the Turkish army, but they are distinguished by the unique services that they provide and their unwavering commitment to those they serve. Military neurosurgery in the Turkish army exists as a distinct entity and is not just the practice of neurosurgery in a uniformed service. While there are specific individual operational requirements for all 3 services (Army, Navy, and Air Force), military neurosurgical care is delivered across the 3 branches by individuals, regular and reserve, of any one of the armed forces—for example, army or air force neurosurgeons on land operations.

Military neurosurgery differs from civilian neurosurgery from many points of view. The duties of a military neurosurgeon are too numerous to be mentioned and are mostly suggested by circumstances of war. With slight differences, the duties of the military neurosurgeon during peacetime are almost identical to those of a civilian neurosurgeon, while the duties during war are unique, and therefore deserve a special and closer consideration. Spinal disorders in young recruits, skull and brain tumors, and closed head traumas are the most frequent problems encountered by a military neurosurgeon in the Turkish army during peacetime.[5,7,8,17] Low-back pain is a common complaint of young recruits during basic military training. Low-back pain has a direct (increased medical care) and indirect (loss of workdays) impact on the training of soldiers.[8]

Upon the eve of a battle or an operation, the military neurosurgeon has much to do to prepare the facilities for the treatment of the wounded. The military neurosurgeon should examine the instruments and stores, and should reassure himself or herself that nothing that will be required for the care of wounded has been omitted or forgotten. The military neurosurgeon should also examine the means of transporting the wounded from the place where they are injured to the field infirmary. All the wounded must undergo a thorough examination by the neurosurgeon and all necessary operations must be performed as soon as possible under optimum medical conditions.

Injuries have and will continue to become more complex in military neurosurgery. As we increasingly confront the threat of terrorism and low-intensity conflicts, the battlefield and the enemies are often less well defined. We must anticipate less traditional threats. Military neurosurgeons need to be highly trained and to have experience with complex surgery and trauma. Today, bayonets and lower velocity slugs have been replaced by nuclear, biological, and chemical weapons, and computerized ordinance delivery systems. Craniocerebral trauma is still common during military conflicts.[3,4,6,7,16] Today, with advances in head armor, resuscitation in the battlefield, rapid evacuation, and surgical treatment in the operating theater, patients with traumatic brain injuries have an increased chance of survival, but the majority of patients suffer a penetrating head injury from an explosive blast. Now, landmine explosions cause most of the injuries in terrorist actions and also pose a public health risk.[6,7,15] Additionally, warfare also causes a large number of peripheral nerve injuries.[1,13,14] Despite the considerable progress in diagnosis and treatment of peripheral nerve injuries, morbidity after such injuries is still unacceptably high. This is especially important for war injuries that are frequently associated with severe local damage of soft tissues, blood vessels, and bones. Military grade weaponry has resulted in the highest concentration of peripheral nervous system injuries to the Turkish army since World War I. Injuries that were previously considered expectant are now salvageable secondary to rapid initial interventions coupled with persistent control of secondary injury.

Currently, the practice of military neurosurgery in the Turkish army must respond to meet the new demands and the neurosurgeons must be adequately resourced if lives are to be saved. Preparations are made to combat and respond to a wide variety of terrorist tools, including explosives and weapons of mass destruction. To meet this challenge, military neurosurgery has engaged not only the technological advances well known to the 21st century neurosurgeon, but has also continued to develop and perfect methods to care for the soldier who may be injured in a firefight and must be transported from a remote location. During relatively peaceful times, it is easy for those outside the military to overlook the requirements for providing a surgical capability to the armed forces. However, it is imperative to have a well-trained, competent neurosurgical cadre to provide high-level surgical care for operations. These operations can be of unexpected intensity, requiring the surgical teams to be permanently at a high state of readiness.

Currently, military neurosurgeons are treating casualities of terrorist violence against the Turkish army.[15,16] Most of these casualties have cranial and spinal injuries due to landmine explosions prepared by terrorists near the Iraq border and the patients are primarily treated in local military hospitals. Turkish military neurosurgeons are not deployed and not involved with conflicts today. But, in the past, they were involved in the Cyprus Peace Operation in 1974. Turkish neurosurgeons have not been sent to Kosovo, Iraq, or Afghanistan.

There are some disadvantages to being a military neurosurgeon in the Turkish army. The most prominent disadvantage is the pay gap between civilian and military neurosurgeons, followed by low numbers of patients and operations per neurosurgeon when compared with cilivian neurosurgeons. It is difficult to perform complex surgeries such as those for brain tumors, intracranial aneurysms, and children in military hospitals because of lack of support infrastructure and technology. Low case volume is a major problem for the maintenance of competency in neurosurgery.

Conclusions

Injuries of the nervous system are common during military operations. Currently, blasts and fragmentation from explosive devices are the most common mechanisms of injury for troops serving on the battlefield. Today, military neurosurgeons are proud to serve the troops and help them to better heal both neurologically and emotionally, provide a faster return to normal life, and improve their quality of life after injury by exhibiting immense skill, compassion, and professionalism, continually upholding the core values of the Turkish army.

Disclosure

The author reports no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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Address correspondence to: Lt. Col. Yusuf Izci, M.D., Department of Neurosurgery, Gulhane Military Medical Academy, 06018 Etlik, Ankara-Turkey. email: yusufizci@yahoo.com.

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Management of unilateral cervical radiculopathy in the military: the cost effectiveness of posterior cervical foraminotomy compared with anterior cervical discectomy and fusion

Luis M. Tumialán, LCDR, MC, USN, Ryan P. Ponton, M.D., LT, MC, USN, and Wayne M. Gluf, M.D., CDR, MC, USN

Department of Neurosurgery, Naval Medical Center San Diego, California

Object. To review the cost effectiveness for the management of a unilateral cervical radiculopathy with either posterior cervical foraminotomy (PCF) or anterior cervical discectomy and fusion (ACDF) in military personnel, with a particular focus on time required to return to active-duty service.

Methods. Following internal review board approval, the authors conducted a retrospective review of 38 cases in which patients underwent surgical management of unilateral cervical radiculopathy. Nineteen patients who underwent PCF were matched for age, treatment level, and surgeon to 19 patients who had undergone ACDF. Successful outcome was determined by return to full, unrestricted active-duty military service. The difference in time of return to active duty was compared between the groups. In addition, a cost analysis consisting of direct and indirect costs was used to compare the PCF group to the ACDF group.

Results. A total of 21 levels were operated on in each group. There were 17 men and 2 women in the PCF group, whereas all 19 patients in the ACDF group were men. The average age at the time of surgery was 41.5 years (range 27–56 years) and 39.3 years (range 24–52 years) for the PCF and ACDF groups, respectively. There was no statistically significant difference in operating room time, estimated blood loss, or postoperative narcotic refills. Complications included 2 cases of transient recurrent laryngeal nerve palsy in the ACDF group. The average time to return to unrestricted full duty was 4.8 weeks (range 1–8 weeks) in the PCF group and 19.6 weeks (range 12–32 weeks) in the ACDF group, a difference of 14.8 weeks ($p < 0.001$). The direct costs of each surgery were $3570 for the PCF and $10,078 for the ACDF, a difference of $6508. Based on the 14.8-week difference in time to return to active duty, the indirect cost was calculated to range from $13,586 to $24,045 greater in the ACDF group. Total cost (indirect plus direct) ranged from $20,094 to $30,553 greater in the ACDF group.

Conclusions. In the management of unilateral posterior cervical radiculopathy for military active-duty personnel, PCF offers a benefit relative to ACDF in immediate short-term direct and long-term indirect costs. The indirect cost of a service member away from full, unrestricted active duty 14.8 weeks longer in the ACDF group was the main contributor to this difference. *(DOI: 10.3171/2010.1.FOCUS09305)*

Key Words • anterior cervical discectomy and fusion • cost effectiveness • posterior cervical foraminotomy • cervical radiculopathy

There are distinct implications to the management decisions of a unilateral cervical radiculopathy in active-duty military patients. Whereas anterior or posterior cervical approaches for symptomatic radiculopathy without myelopathy may have equivalent clinical efficacy,[5,6,16] these interventions have their own respective limitations with regard to an individual's capacity to return to unrestricted military service. Governing instructions from the Naval Bureau of Medicine and Surgery, Naval Aerospace Medical Institute, and Naval Undersea Medical Institute collectively establish criteria for the capacity of service members to return to unrestricted full duty after recovering from surgical intervention. Under certain circumstances, the consequences of a surgical approach may delay a return to active duty.

The purpose of this study was to identify the difference in time to return to active duty between a PCF and ACDF. In addition, we sought to examine the cost effectiveness and the clinical outcomes in those patients with unilateral cervical radiculopathy who underwent either ACDF or PCF with or without discectomy in the military. The direct costs of performing the procedure, as well as indirect costs of time away from duty, are examined and compared to determine whether there is a benefit of PCF relative to ACDF in the management of unilateral cervical radiculopathy in the military.

Abbreviations used in this paper: ACDF = anterior cervical discectomy and fusion; PCF = posterior cervical foraminotomy.

Methods

Patient Population

We retrospectively reviewed data obtained in 19 active-duty military patients who were identified to have a unilateral cervical radiculopathy without myelopathy presenting between July 2007 and August 2009. The diagnosis of cervical radiculopathy was made by clinical history, neurological examination, and MR imaging. Review of the imaging studies demonstrated lateral disc herniations or disc osteophyte complexes without central canal impingement. Patients without advanced disc collapse, cervical spondylosis, or segmental kyphosis were preferentially selected for a PCF (19 patients). Four of these patients had soft-disc herniations, and the remaining 15 had disc osteophyte complexes resulting in foraminal stenosis.

The 19 patients in the PCF cohort were matched by age, treatment level, and surgeon with 19 patients identified from our institution's neurosurgical database; these patients had undergone ACDF for unilateral cervical radiculopathy. In the event a patient was unable to be matched for a surgeon, a patient was selected from the senior author's (W.M.G.'s) database. Institutional review board permission was sought and approved to review all outpatient, inpatient, procedural, anesthesia, and radiographic data in the 38 patients included in this study. Hospital records were reviewed for operating room times, estimated blood loss, and length of hospital stay. Clinical records were reviewed for postoperative narcotic medication refills and the time required for return to unrestricted full duty.

All patients underwent a period of nonoperative management including limited duty, physical therapy, antiinflammatory medications, or opioid analgesics. Additionally, all patients underwent MR imaging and had proven disc herniations or disc osteophyte complexes corresponding to the side and level of their clinical symptoms. Exclusion criteria included previous cervical surgery, myelopathy, spinal infection or tumor, and psychiatric illness.

The cost effectiveness of PCF and ACDF was compared by analyzing direct and indirect costs of both procedures, the former associated with the cost of time away from active duty. Direct costs included surgical instrumentation and subsequent hospitalization. Hospital and instrumentation expenses were determined for the PCF cohort and the ACDF cohort using TRICARE military health plan reimbursement figures.

Indirect cost was evaluated by multiplying the service member's monthly salary by the difference in time away from active duty. Monthly salary was based on 2009 fiscal year figures. This monthly salary is composed of base salary, Basic Allowance for Housing, and Basic Allowance for Subsistence. Given the numerous ranks and corresponding salaries within the navy, the authors chose to use the salaries of a junior enlisted service member (E4), a senior enlisted member (E7), a junior officer (O1), and a senior officer (O4) to give a range that would best represent indirect costs.

Diagnostic Imaging

Preoperative imaging studies consisted of anteroposterior and lateral radiographs, flexion-extension radiographs of cervical spine, and an MR images of the cervical spine. A 1.5-T MR imaging system (Signa, General Electric Medical Systems) was used for all studies, and all MR images were obtained at our facility. The MR imaging sequences included axial and sagittal T1-weighted fat-saturation and T2-weighted studies from which the measurements were obtained.

Surgical Technique

Patients underwent either PCF or ACDF performed by 2 neurosurgeons. Intraoperative fluoroscopic imaging was used to confirm the surgical level.

The PCF was performed using either a Frykholm midline open technique or a lateral minimally invasive technique as described by Fessler and Khoo[3] and others.[1,10,12] The anterior cervical fusions were performed using the Smith-Robinson technique with cortical-cancellous allograft and a dynamic plate.

Postoperative management included short periods of light or limited duty when indicated to protect service members from excessively strenuous training exercises. All aviators who underwent ACDF were grounded until they met criteria for a waiver to return to flying status (see below). All special operations personnel who had undergone ACDF were restricted from parachute jumps until there was radiographic evidence of a solid arthrodesis. In all patients who underwent ACDF, anteroposterior and lateral cervical radiographs were obtained between 4 and 6 weeks postoperatively and CT scans were acquired between 3 and 6 months postoperatively. Flexion-extension cervical radiography was performed as part of the criteria to establish a radiographic fusion. Flexion-extension cervical radiographs were obtained in all patients who underwent PCF to rule out abnormal spinal motion.[18]

Outcomes Measures

Successful outcome was determined by return to full, unrestricted active-duty military service within the service member's presurgical military occupational specialty. This includes the capacity to pass a physical readiness test, a combat fitness test (applicable only to the Marines), be cleared for shipboard duty, and be worldwide assignable without restrictions or limitations.

Statistical Analysis

Analysis was based on pairings of patients for demographic variables. Descriptive statistics were frequencies and percentage of occurrence (rate) for categorical variables and mean and range for continuous variables. Differences between PCF and ACDF pair members were tested against a 0 difference using the Wilcoxon signed-rank test.

Results

A total of 21 levels were operated upon in each group (Table 1). The PCF group comprised 17 men and 2

TABLE 1: Summary of data obtained in patients who underwent PCF or ACDF

Case No.	Sex	Age at Op (yrs)	No. of Levels	Op Time (mins)	EBL (ml)	Narcotic Refills	Tobacco	Return to Full Duty (wks)
PCF								
1	M	51	1	180	50	yes	no	6
2	M	43	2	149	50	yes	no	8
3	M	44	2	231	50	no	no	2
4	M	43	1	126	15	no	no	1
5	M	37	1	175	25	no	yes	4
6	M	37	1	197	50	yes	no	4
7	M	37	1	131	20	no	yes	4
8	M	47	1	157	75	no	no	4
9	M	36	1	120	10	no	no	7
10	M	45	1	132	75	no	no	4
11	M	56	1	209	75	no	no	*
12	M	34	1	109	50	yes	yes	8
13	F	27	1	116	10	no	no	4
14	M	54	1	164	75	no	no	2
15	F	51	1	182	100	no	no	6
16	M	49	1	140	15	no	no	5
17	M	33	1	128	10	no	no	4
18	M	31	1	141	15	no	yes	7
19	M	33	1	137	15	no	no	7
mean		41.4		153.9	39.7			4.8
ACDF								
20	M	48	1	139	10	no	no	12
21	M	38	2	187	50	no	no	12
22	M	46	2	291	50	no	no	19
23	M	38	1	148	25	no	no	12
24	M	33	1	133	10	yes	no	28
25	M	47	1	134	30	no	no	32
26	M	34	1	130	30	yes	no	18
27	M	47	1	172	100	no	no	24
28	M	30	1	146	30	yes	no	14
29	M	45	1	150	49	yes	no	16
30	M	44	1	144	50	no	no	16
31	M	33	1	133	10	yes	no	28
32	M	24	1	135	20	yes	yes	32
33	M	52	1	130	50	no	no	26
34	M	48	1	158	20	no	no	27
35	M	45	1	128	20	no	no	12
36	M	35	1	143	30	no	no	20
37	M	30	1	149	25	no	no	13
38	M	30	1	131	10	no	no	12
mean		39.3		151.6	32.6			19.6

women, whereas all 19 patients in the ACDF group were male. The PCF group contained 4 smokers (21%), while the ACDF group had 1 smoker (5%). The mean age at the time of surgery was 41.4 years (range 27–56 years) and 39.3 years (range 24–52 years) for PCF and ACDF groups, respectively. The mean follow-up for the ACDF group was 18.1 months (range 6–34 months) and 11.2 months (range 5–24 months) for the PCF group.

Levels of surgery in the PCF group were as follows: C-7 in 11 (58%), C-6 in 3 (16%), C-8 in 2 (11%), C-5 in 1 (5%), and C-6 and C-7 in 2 (11%) patients. Surgical sites in the ACDF group were as follows: C6–7 in 11 (58%),

TABLE 2: Summary of direct costs, in dollars, of each procedure

Procedure	Instrumentation Cost	Institutional Cost	Total Direct Cost
PCF	474	3,096	3,570
ACDF	4079	5,999	10,078

C5–6 in 5 (26%), C4–5 in 1 (5%) patient, and C5–6 and C6–7 in 2 (11%) patients. (In the event that a patient was unable to be matched for age and level, an adjacent level was used.)

The average time to return to unrestricted full duty was 4.8 weeks (range 1–8 weeks) in the PCF group and 19.6 weeks (range 12–32 weeks) in the ACDF group. The difference in time was 14.8 weeks, which was statistically significant ($p < 0.001$). One patient from the PCF group was excluded from data analysis because he did not return to unrestricted full duty (Table 1).

Direct cost consisted of institutional and instrumentation costs. The institutional costs were $3096 in the PCF group and $5999 in the ACDF group, a difference of $2903. Average instrumentation costs were $474 in the PCF group and $4079 in the ACDF group, a difference of $3605. (The 12 minimally invasive PCF cases also had a rental fee of $750 per case.) The total difference in direct cost between the 2 procedures was $6508 (Table 2).

Indirect cost was calculated by multiplying the mean difference in time to return to active duty (14.8 weeks) by the salary of 4 different service ranks. The indirect cost difference for an E1, E7, O1, and O7 service member were $13,586, $17,797, $17,475, and $24,045, respectively (Table 3).

The total (indirect and direct) cost differences between procedures for an E1, E7, O1, and O7 service member were $20,094, $24,305, $23,983, and $30,553, respectively (Table 3).

Postoperative complications included 2 cases of transient recurrent laryngeal nerve palsy in the ACDF group. See Table 1 for a summary of individual data.

Clinical and Radiographic Outcomes

Eighteen of the 19 patients in the PCF group returned to full unrestricted full duty and had complete resolution of preoperative symptoms. One service member (Case 11) was unable to return to full duty because he could not tolerate the pain associated with wearing a Kevlar helmet. Another service member (Case 5), after returning to unrestricted full duty, would return 8 weeks after surgery with contralateral radicular symptoms. This patient underwent anterior decompression and then returned to unrestricted full duty 3 months afterward. Additionally, one service member (Case 16) in the PCF group had a subtotal foraminotomy, which required revision surgery. This patient returned to unrestricted full duty 5 weeks after the initial surgery. In the end, 16 individuals in this group returned to unrestricted full duty without further intervention.

In all 19 patients in the ACDF group, radiographic fusion was established by both flexion-extension cervical radiographs and CT scans between 3 and 6 months after surgery. Eighteen patients had complete resolution of their symptoms and returned to unrestricted full duty in the capacity in which they previously served. One patient (Case 22), despite a radiographic fusion, had persistent neck pain and returned to a purely administrative role.

TABLE 3: Summary of indirect costs associated with each procedure

	Cost Effectiveness ($)		
Rank	Direct	Indirect	Total
junior enlisted (E4)	6,508	13,586	20,094
senior enlisted (E7)	6,508	17,797	24,305
junior officer (O1)	6,508	17,475	23,983
senior officer (O4)	6,508	24,045	30,553

Discussion

The essence of military medicine is the identification, diagnosis, and timely treatment of the injured service member. Allowing the individual a period of convalescence to recover from an injury or surgery is a necessary step to optimize the operational readiness of the fleet and minimize the risk of further injury to the service member. During this time, the injured service member's billet may be "backfilled" by another service member to prevent overburdening the remaining members of a unit or squadron. Other times, the billet may be left open depending on available personnel. Nevertheless, the goal for the military surgeon remains to return that individual to his unit or squadron to serve in the capacity for which he or she had been trained, without restrictions or limitations and in a timely fashion. This is especially true for those individuals in the aviation, special warfare, and diving communities, which are modest in size, but have significant physical and operational demands. Therefore, minimizing the time from surgery to return to unrestricted full duty is crucial. Given this as a context, we reviewed our experience in the management of unilateral cervical radiculopathy in the military.

In our review of data obtained in these 38 active-duty patients with unilateral cervical radiculopathy, 17 (89.5%) of 19 cases in the PCF group and 18 (94.7%) of 19 cases in the ACDF group were deemed successful long-term interventions. Our sample was too small to draw meaningful conclusions between the efficacies of these procedures ($p = 1.000$) or to establish superiority of one procedure over the other. Still, at first glance the anterior approach appears to have achieved greater long-term success. Consequently, there is value in further examining those cases in which the individuals did not return to full duty.

First, we acknowledge the inherent limitation of the PCF to address unilateral disease. This is critical with regard to patient selection. In a review of Case 5, the patient presented clinically with unilateral symptoms, but from a radiographic standpoint he had bilateral neural foraminal stenosis. While bilateral foraminotomies may be readily performed via an anterior approach, the very nature of the minimally invasive posterior approach precludes this without a second incision. In hindsight, the anterior approach may have been a superior approach in this case. Accordingly, the lack of success in this patient was more a consequence of patient selection than to surgical technique. This underscores the principal of patient selection: not all patients may benefit from the PCF.[17]

Second, despite resolution in his preoperative radiculopathy, the patient in Case 11 was unable to return to full duty because of pain associated with wearing his Kevlar helmet. In the end, the patients in Cases 5 and 11 had resolution of preoperative radiculopathy but were unable to reach the outcome measure of returning to unrestricted full duty. The inability to return to full duty was limited to one individual (Case 22) in the ACDF group.

In well-selected patients, the literature has shown that decompression of the cervical neural foramen and the lateral recess for unilateral cervical radiculopathy may be accomplished by either a PCF with or without discectomy or ACDF with equal efficacy.[5,6] Nevertheless, the trend in the US over the last decade has drifted in favor of anterior approaches, whereas posterior approaches have declined dramatically.[11,15] More recently, the traditional advantages of the anterior approach appear to have been equaled by the introduction of the minimally invasive PCF. Some authors have suggested that the risks of instrumentation and increased cost of anterior surgery may be avoided by a posterior approach, without the significant postoperative pain or muscle spasms in those patients with lateral disc herniations or unilateral disc osteophyte complexes.[7] The recent publication of large series of cases involving posterior cervical foraminotomies further corroborates this and suggests a tapering to the anterior trend.[2,4,7–9,13,14] We have observed a similar trend in our own institution. Over the last 5 years, review of the neurosurgery database at our institution reveals 156 ACDFs were performed compared with 22 PCFs. One-third of the PCF procedures have been performed in the last year.

Cost Analysis

Under ideal circumstances, indirect costs should represent lost productivity due to the patient's absence from work. In the absence of detailed job analysis for each patient, indirect costs were calculated by the salaries paid to active-duty military members who were not able to perform full, unrestricted physical activity because of their surgery. While imperfect, salaries are the only available surrogate marker for lost productivity. Furthermore, the authors recognize the difficulty in calculating the cost of a service member unable to perform his duty while recovering from surgery, given the numerous ranks and corresponding salaries in the military. Therefore, the authors chose to create a 4-tier system: junior enlisted, senior enlisted, junior officer, and senior officer. This creates a range that would best illustrate the indirect costs. These estimates were intentionally underestimated to provide a low end value to the indirect cost. Service members are given financial compensation in the form of bonuses and incentives for various qualifications or specialized training. The military has a multitude of bonuses with varying amounts. Examples include flight pay, dive duty pay submarine duty pay, and hazardous duty pay. These were not included in our estimation.

The total cost difference, including both direct and indirect, between a PCF and ACDF ranged from $20,094 to $30,553 depending on the service member's rank (Table 3). As would be expected, direct costs were significantly higher in the ACDF group than in the PCF group. The average cost, institutional and instrumentation, equaled $10,078 for the ACDF group, while the PCF group totaled $3,570 per surgery, a difference of $6,508. (The second surgery performed on the 2 patients in the PCF group only increased the average cost for the entire PCF group by $718.) But the most significant contribution to the total cost was indirect costs, which ranged from $13,586 to $24,045 depending on the service member's rank. The large difference in indirect cost was reflective of those in the PCF group returning to unrestricted full duty 14.8 weeks earlier than those in the ACDF group, a statistically significant difference. On average, patients in the PCF group returned to unrestricted full duty 4.8 weeks after surgery, compared with 19.6 weeks in the ACDF group.

The difference in indirect costs between a PCF and ACDF is further accentuated when analyzing certain occupations within the military. For instance, the US Navy Manual of the Medical Department issued by the US Navy Bureau of Medicine and Surgery lists the criteria to obtain a medical waiver and return to active duty after surgical procedures. The manual states those service members in the aviation community who undergo a single-level ACDF may not return to duty any earlier than 6 months from surgery. Additional waiver criteria are as follows: single-level surgery, 6 months from the date of surgery, free of pain, complete resolution of radicular symptoms, and radiographs that demonstrate fusion with no instability in flexion and extension views. Once a waiver is granted, the service member may return to unrestricted full duty. The diving and special warfare communities have similar criteria for a waiver before returning to duty. A medical waiver for a PCF simply necessitates the service member be free of pain and have complete resolution of radicular symptoms.

Given the aforementioned criteria, the PCF has a distinct advantage. Once the foraminotomy is completed and the radicular symptoms resolved, the only thing that remains for the service member to return to active duty is to have a completely healed incision and be off all narcotic pain medications. As the authors noted above, this takes on average 4.8 weeks. For members with specialized occupations (aviation, undersea, or special warfare), the very nature of the ACDF requires a minimum of 24 weeks before the service member may be considered for return to full duty.

Conclusions

In the management of unilateral cervical radiculopathy for military active-duty personnel, PCF offers a benefit relative to ACDF in immediate short-term direct costs and long-term indirect costs. The indirect cost of time away from duty was the more significant contributor to difference in cost effectiveness.

The military spine surgeon must consider the operational demands of the service member prior to selecting the surgical approach for a unilateral cervical radiculopathy without myelopathy, as the anterior and posterior approaches result in different periods of time away from unrestricted active duty.

Disclosure

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Address correspondence to: Luis M. Tumialán, M.D., LCDR, MC, USN, Naval Medical Center San Diego, 34800 Bob Wilson Drive, San Diego, California 92134. email: luis.tumialan@med.navy.mil.

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Arthroplasty in the military: a preliminary experience with ProDisc-C and ProDisc-L

Luis M. Tumialán, M.D., LCDR, MC, USN, Ryan P. Ponton, M.D., LT, MC, USN, Angelina Garvin, B.A., CCRP, and Wayne M. Gluf, M.D., CDR, MC, USN

Department of Neurosurgery, Naval Medical Center San Diego, California

Object. The introduction of cervical and lumbar arthroplasty has allowed for management of cervical radiculopathy and lumbar degenerative disease in patients with the preservation of motion at the affected segment. While the early clinical outcomes of this technology appear promising, it remains unclear what activity limitations should be imposed after surgery in patients with these implants. This is of particular interest in military personnel, who may be required to return to a rigorous level of activity after surgery. The goals of the FDA trials evaluating various disc arthroplasty devices were to establish safety, efficacy, and equivalency to arthrodesis. Information regarding the level of physical performance attained and restrictions or limitations is lacking, as these were outside the objectives of these trials. Nevertheless, there data are essential for the military surgeon, who is tasked with guiding the postoperative management of patients treated with arthroplasty and returning them to full duty. While there is a single report of clinical results of lumbar arthroplasty in athletes, at this writing, there are no reports of either cervical or lumbar arthroplasty in active duty military personnel.

Methods. The surgical database at a single, tertiary care military treatment facility was queried for all active-duty patients who underwent placement of either a cervical or lumbar arthroplasty device over a 3-year period. The authors performed a retrospective chart review to collect patient and procedural data including blood loss, length of hospital stay, tobacco use, age, rank, complications, and ability to return to full unrestricted active duty. Arthroplasty cohorts were then compared to historical controls of arthrodesis to ascertain differences in the time required to return to full duty.

Results. Twelve patients were identified who underwent cervical arthroplasty. All patients returned to unrestricted full duty. This cohort was then compared with 12 patients who had undergone a single-level anterior cervical discectomy and fusion. The average time to return to unrestricted full duty for the arthroplasty group was 10.3 weeks (range 7–13 weeks), whereas that in the fusion group was 16.5 weeks. This difference between these 2 groups was statistically significant ($p = 0.008$). Twelve patients were identified who underwent lumbar arthroplasty. Ten (83%) of 12 patients in this group returned to unrestricted full duty. In patients who returned to full duty, it took an average of 22.6 weeks (range 12–29 weeks). This cohort was then compared with one in which patients had undergone anterior lumbar interbody fusion. Eight (67%) of 12 patients in the lumbar arthrodesis group returned to unrestricted full duty. In patients who returned to full duty, it took an average of 32.4 weeks (range 25–41 weeks). This difference was not statistically significant ($p = 0.156$).

Conclusions. The preliminary experience with cervical and lumbar arthroplasty at the authors' institution indicates that arthroplasty is comparable with arthrodesis and may actually expedite return to active duty. Patients are capable of returning to a high level of rigorous training and physical performance. There are no apparent restrictions or limitations that are required after 3 months in the cervical patient and after 6 months in the lumbar patient. Further prospective studies with long-term follow-up are indicated and will be of value when determining the role of arthroplasty compared to arthrodesis in the active-duty population. *(DOI: 10.3171/2010.1.FOCUS102)*

Key Words • **active-duty military** • **arthroplasty** • **cervical** • **lumbar** • **outcomes**

Since the FDA's approval of lumbar arthroplasty devices in 2004 and cervical devices in 2007, surgeons have rapidly incorporated this technology into clinical practice.[11,20] Over these few years, both cervical and lumbar arthroplasty have been demonstrated to be safe and at least equivalent to arthrodesis in the civilian population.[2–5,8,15–17,22] Military patients, however, represent a very different population, especially in certain military communities. The Marines and special operations communities, in particular, have rigorous physical demands that may place extraordinary physiological stresses on the cervical and lumbar spine. Parachute jumps, diving, high-impact water entries, and prolonged runs bearing heavy loads collectively represent only some of the physical demands required of these service members. While intradiscal pressures while performing tasks of daily life have been measured, the repetitive axial and rotational

Abbreviations used in this paper: ACDF = anterior cervical discectomy and fusion; ALIF = anterior lumbar interbody fusion; EBL = estimated blood loss; PLL = posterior longitudinal ligament; PRT = physical readiness test.

TABLE 1: Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
1) age between 18 & 50 yrs	1) >1 cervical or lumbar vertebral level requiring treatment
2) on full, unrestricted active duty preop	2) undergone or in the process of a Physical Evaluation Board
3) neck, arm pain, or neurological deficit confirmed by x-ray and CT or MRI to include any 1 of the following:	3) neck or arm pain of unknown etiology
i. herniated nucleus pulposus	4) active infection—local or systemic
ii. spondylosis	
iii. loss of disc height	5) spine malignancy or tumor

stress and sudden increase in external forces associated with high impact activities in the military have not been studied.[10,19,21] The magnitude of these forces remains largely unknown. This creates a difficulty in predicting the behavior of a modular implant, such as the ProDisc, under such conditions.

Because the goals of the FDA trials with various arthroplasty devices were to establish safety, efficacy, and equivalence to arthrodesis, we lack information regarding the level of physical performance attained and restrictions or limitations in arthroplasty data.[4,7,8,12,17,18,22] However, because the physical performance expectation is much higher in military patients, this data are essential for the military surgeon when guiding the postoperative management of a soldier, Marine, sailor, or airman to return to unrestricted full duty.

The authors have previously established the capacity of treated patients' return to unrestricted full duty after either lumbar or cervical fusion, indicating that single-level arthrodesis does not preclude the return to previous high-level physical performance (Pontan R, Tumialán L, Garvin A, Gluf W: "Rate of return to military active duty after single level and two level anterior cervical discectomy and fusion: a 4 year retrospective review" and Tumialán L, Ponton R, Riccio A, Gluf W: "Rate of return to military active duty after single level lumbar interbody fusion: a 5 year retrospective review." Oral Platform Presentations at the AANS/CNS Section on Disorders of the Spine and Peripheral Nerves. Orlando, Florida, 2010). With the introduction of arthroplasty, the logical questions become: What do these stresses do to an arthroplasty device and are they compatible with unrestricted full duty? Furthermore, we were not clear how quickly individuals may return to high levels of activity or what limitations, if any, should be imposed on these individuals.

With this in mind, we reviewed our preliminary experience with cervical and lumbar arthroplasty in the military over the past 3 years at a single military treatment facility. Two cohorts, one lumbar and one cervical, are retrospectively reviewed in this report. Particular attention is drawn to the time required to return to active duty and the level of function attained after surgery.

The preliminary experience with cervical and lumbar arthroplasty in our military patients indicates that it is comparable with arthrodesis and may actually expedite a return to active duty. Further prospective studies with long-term follow-up are indicated and will be of value when determining the role of arthroplasty compared with arthrodesis in military personnel.

Methods

The surgical database at a single, tertiary care military treatment facility was queried for all active-duty patients who underwent placement of either a cervical or lumbar arthroplasty device between April 2007 and October 2009. We applied the same inclusion and exclusion criteria that were used in the FDA trials (Table 1).[16,22] In addition, the governing instructions from the Bureau of Medicine and Surgery, as well as the Naval Aerospace Medical Institute, do not permit members of the aviation community to undergo arthroplasty, and so all aviators were excluded from arthroplasty.

Either the ProDisc-C or ProDisc-L (Synthes Spine) was used in all patients. A retrospective chart review was performed to collect patient and procedural data to include EBL, hospital length of stay, tobacco use, age, rank, complications, and ability to return to full unrestricted active duty. Patients underwent follow-up evaluations at 1, 3, 6, 12, and 24 months (when applicable). Flexion and extension radiographs were obtained at each evaluation to demonstrate preservation of motion and to rule out device-related complications. We questioned each service member about the level of performance attained, in particular the capacity to perform a PRT, combat fitness test (applicable only to Marines), and return to their previous level of performance (that is, parachute jumping, diving, running). Data obtained in each cohort was then compared with an age- and level-matched individuals who had undergone ACDF or ALIF. The primary focus of this comparison was to determine differences in time to return to full duty.

Surgical Technique

Cervical Spine. A Smith-Robinson technique was used to approach the affected cervical disc level. After a complete discectomy was performed, including removal of the cartilaginous endplates, patients underwent arthrodesis in which cortical or cortical cancellous allograft was used with a dynamic plate or arthroplasty. In patients who underwent arthroplasty, the technique described in previous reports was used.[3,16] The midline was marked on the vertebral bodies. The PLL was resected in all cases. With the disc space distracted, an appropriate size disc was trialed. A milling drill guide was introduced overtop of the trial and used to create keel cuts in the vertebral body. The keel cuts were then cleared of all bony debris and the cervical arthroplasty device (ProDisc-C) was inserted under direct fluoroscopic imaging.

Lumbar Spine. All patients with lumbar lesions underwent surgery via an open anterior retroperitoneal. A vascular surgeon assisted in the approach. After fluoroscopic confirmation of the level, a complete discectomy was performed, including removal of the cartilaginous endplates. In patients undergoing lumbar fusion, either lumbar tapered cages with recombinant human bone morphogenetic protein–2 or femoral ring allograft was used with a plate. In patients undergoing arthroplasty, intervertebral body distractors were used to distract the disc space and facilitate exposure of the PLL. The PLL was divided when necessary, ensuring parallel distraction of the disc space. An appropriate disc trial was then sized and placed into the disc space. An anteroposterior fluoroscopic image was obtained to ensure midline. Keel cuts were then made into the rostral and caudal vertebral bodies, and the arthroplasty device secured under fluoroscopic guidance as described in previous reports.[22]

Statistical Analysis

Analysis was based on pairings of patients for demographic variables. Descriptive statistics included mean and standard deviations for age, EBL, operative time, and time required to return to active duty. Difference between ProDisc-C and ACDF pair members, as well as ProDisc-L and ALIF pair members, were tested against zero difference by Wilcoxon signed-rank test.

Results

Cervical Spine

Twelve patients were identified who underwent cervical arthroplasty during the study period. They were all men. The average age at the time of surgery was 36.5 years. The treated levels were C5–6 (8 patients) and C6–7 (4 patients). The average operating time was 165.3 minutes and EBL was 59.5 ml. All patients returned to unrestricted full duty. No restrictions or limitations were self-identified by this group with regard to performance status after 3 months. This cohort was then age matched and level matched with 12 patients who had undergone a single-level ACDF and had returned to full duty. The average age at the time of surgery for the fusion group was 36.1 years. The mean operating time was 129 minutes and EBL was 25.5 ml. The average time to return to unrestricted full duty for the arthroplasty group was 10.3 weeks (range 7–13 weeks), whereas that for the fusion group was 16.5 weeks. This difference between these 2 groups was statistically significant ($p = 0.008$) (Table 2). Five of the 7 Navy SEALs in this group reported returning to free-fall parachute jumping and high-impact water entries. Subsequent radiographic imaging of these patients did not demonstrate implant migration or subsidence after these activities. The mean follow-up period for the arthroplasty group was 12.2 months (range 3–26 months).

TABLE 2: Comparison of cervical and lumbar ProDisc arthroplasty with fusion

Op Group & Variables	Arthroplasty	Arthrodesis	p Value
ProDisc-C vs ACDF			
no. of patients	12	12	
average age	36.5	36.1	
no. returned to full duty	12	12	
time to full duty (wks)	10.3	16.5	0.008
ProDisc-L vs ALIF			
no. of patients	12	12	
average age	37.3	40	
no. returned to full duty	10	8	
time to full duty (wks)	22.6	32.4	0.156

Lumbar Spine

Twelve patients were identified who underwent lumbar arthroplasty during the study period. There were 10 men and 2 women. The average age at the time of surgery was 37.3 years. The treated levels were L5–S1 (7 patients) and L4–5 (5 patients). The average operating time and EBL were 235.8 minutes and 209.5 ml, respectively. Ten (83%) of 12 patients in the lumbar arthroplasty group returned to unrestricted full duty. One patient was separated from the military for persistent symptoms, and one patient remains on limited-duty status at this writing. One patient experienced right S-1 radiculopathy after arthroplasty and required a foraminotomy and decompression of the nerve root after arthroplasty (see below). He eventually returned to full duty. In patients who returned to full duty, it took an average of 22.6 weeks (range 12–29 weeks). This cohort was then age matched and level matched to 12 patients who had undergone a single-level ALIF. The average age for this group was 40 years. The average operative time and blood loss were 143.1 minutes and 102.5 ml, respectively. Eight (67%) of 12 patients in the lumbar arthrodesis group returned to unrestricted full duty. In patients who returned to full duty, it took an average of 32.4 weeks (range 25–41 weeks). Although there was an apparent difference between the mean time to return to active duty, this difference was not statistically significant ($p = 0.156$), likely because of the limited number of pairs available for statistical analysis (Table 2). The mean follow-up period was 10.7 months (6–26 months).

Complications

In 1 patient in the cervical arthroplasty group we observed a progressive osteolysis from the rostral keel at 9 months. The patient required removal of the device and conversion to an anterior cervical fusion. This unusual complication was attributed to a device-related immune-mediated reaction to one of the alloys in the implant. One patient in the lumbar arthroplasty group experienced new-onset S-1 radiculopathy after surgery. Subsequent imaging demonstrated that the device was 4 mm off the midline. The patient underwent a posterior decompression of the S-1 nerve root and would return to unrestricted full duty. There was one vascular injury in the lumbar arthroplasty group, which occurred during exposure of the L4–5 level. The injury resulted in an EBL of 600 ml. The injured vessel was repaired primarily at the time of surgery and there were no long-term sequelae. This patient would return to full duty.

Discussion

The goals of the prospective randomized controlled clinical trials approved by the FDA on the ProDisc-C, ProDisc-L, Bryan, Prestige, and CHARITÉ devices were 2-fold: demonstrate the safety and efficacy of the arthroplasty device and establish that clinical outcomes were not inferior to arthrodesis.[4,7,8,12,16,18,22] In large part, the outcomes of these studies were based on health-related quality of life measures, which included an Oswestry or Neck Disability Index, patient satisfaction, absence of device failure, visual analog scale, and absence of strong narcotic or muscle relaxant. Similar to our study, these trials were performed on a relatively young patient population (average age of 42.8 and 39.2 years in the cervical and lumbar studies, respectively). Nevertheless, there is minimal information regarding restrictions or limitations imposed in the immediate postoperative period or the level of physical activity attained in the arthroplasty group. The authors of these trials did examine work, physical labor, and recreation status at 24 months, but the information is limited and for the most part not applicable to active-duty military.[12,22]

The absence of this clinical information prompted us to review our experience with cervical and lumbar arthroplasty, with a particular emphasis on return to unrestricted full duty and the level of physical performance attained. Thus, while the current literature suggests that the long-term efficacy of arthroplasty in a young active population appears to be equivalent to arthrodesis, the level of activity that can be achieved by an individual who has undergone arthroplasty has not previously been well established. Equally unclear are the restrictions and limitations for an individual in whom an arthroplasty device has been implanted. There is a concern regarding the forces generated during high-impact activities and the effect these activities may have immediately or over time on a modular implant, in particular the ultrahigh–molecular weight polyethylene inlay. Because biomechanical studies have focused on wear and failure over the course of millions of simulation cycles, the consequences of these high external forces on this modular implant are not presently known. The primary goal of this article was to explore these 2 aspects of arthroplasty in a military population to answer the question: can an individual return to his/her previously high level of performance after arthroplasty and, if so, how quickly?

Return to Full Duty and Level of Activity

Patients in both the cervical and lumbar arthroplasty cohorts returned to full duty on average 6.2 and 9.8 weeks, respectively, sooner than their arthrodesis counterparts. This difference was statistically significant in the cervical cohort but not the lumbar group. At first glance, this may suggest that the patient treated with arthroplasty has had a better outcome. In actuality, this represents more the limitations imposed by the clinician for a patient within the arthrodesis group than a superior clinical outcome for an arthroplasty patient. With the exception of the aviation community, in which individuals are restricted from undergoing disc arthroplasty by regulation and are required to undergo a minimum of 6 months of limited duty after a cervical or lumbar fusion, the return to unrestricted full duty, to a certain extent, is arbitrary and dependent on the surgeon. For instance, a surgeon may return to duty a service member who works in a more sedentary environment sooner than he would a Marine infantryman who has to bear a 60-lb pack on his return to full duty. Overall, the reluctance of a military surgeon to return an individual to unrestricted full duty after cervical or lumbar fusion is primarily born out of concern for the arthrodesis and the impact it may have on the patient's health. Returning an individual prematurely to unrestricted full duty communicates to that individual and to his/her command that there are no restrictions or limitations. To avoid long-term complications in patients with arthrodesis, we typically defer returning patients to full duty until evidence of a maturing fusion is seen on radiographs or CT scans along with the absence of motion on dynamic plain radiographs.

In patients who underwent arthroplasty, there were no radiographic criteria that would indicate when it would be safe to return to full duty. Thus, when individuals were evaluated and found to have resolution of preoperative symptoms, it was difficult to impose any restrictions or limitations upon them. We found that the patients in our series, especially in the cervical arthroplasty cohort, were returning to their previous levels of activity by their 3-month follow-up, and we therefore released them to unrestricted full duty at that time. One patient in the lumbar arthroplasty cohort successfully completed a PRT, consisting of a 1.5-mile run and maximum sit-ups and push-ups in a 2-minute period only 14 weeks after surgery. Herein lies the difference between the 2 groups: the surgeons are more apt to release an asymptomatic patient treated with arthroplasty sooner to full duty than an asymptomatic patient treated with arthrodesis.

Cervical Spine: Performance Status

Despite the earlier return to full duty in the cervical arthroplasty group, we identified no significant difference between the arthrodesis and arthroplasty at longer-term follow-up. All patients in the cervical arthrodesis and arthroplasty groups were able to return to full duty by 6 months. Review of the level of performance in the cervical arthrodesis group and cervical arthroplasty group at 6 months demonstrates equivalence in physical performance and the capacity for overseas deployment and shipboard duty. This indicated that these individuals were able to perform a PRT and a combat fitness test (applicable only to the Marines) as well as return to their level of previous training. Special operations members returned

TABLE 3: Algorithms for returning treated individuals to active duty

Treatment Group & Postop Time (Wks)	Activity
ProDisc-C	
0–3	begin nonimpact cardio exercise up to 60 mins daily: Lifecycle, StairMaster, elliptical, & walking are recommended
3–6	begin nonimpact cardio without limitations; begin light weight training at 25–50% of preop capability
7–12	begin impact cardio, including running on treadmill; progress to unlimited cardio by Week 12; advance to full weight training Wks 7–12 in a progressive fashion; cleared to return to dive/parachute duty/deployments
ProDisc-L	
0–3	Begin walking as tolerated
3–6	begin nonimpact cardio & may progress to 60 mins/day
6–10	begin unlimited cardio; light weight training may begin at maximum of 25–50% preop capability; no bent-over rows, squats, or military press
11–12	increase weights & cardio up to 75% of maximum
13–16	continue to increase weight lifting up to full tolerance & cardio (nonimpact)
17–20	begin impact cardio including running on treadmill; progress to unlimited cardio by Wk 20; may resume dive operations at 20 wks; jump operations may begin Wk 26

to parachute jumping, high-impact water entries from helicopters, diving, and long-distance runs while bearing a load. None of the patients in the cervical arthroplasty group required separation from the military for persistent symptoms. As previously stated, in 1 individual in the arthroplasty cohort a conversion to a fusion was required, after which the patient returned to full duty as a Navy SEAL. We found no need to impose restrictions or limitations on the arthroplasty group after 3 months from the date of surgery.

Lumbar Spine: Performance Status

It is no surprise that both the lumbar arthrodesis and arthroplasty groups required substantially more time to return to full duty than the cervical group. Patients in the arthroplasty group returned to full duty after an average of 22.6 weeks, whereas individuals in the arthrodesis group returned to full duty after 32.4 weeks. These 2 groups did not begin to demonstrate equivalence in performance status until 9 months after surgery. Such a trend was previously identified with the Oswestry Disability Index and visual analog scale in the CHARITÉ investigational device exemptions study.[4] On average, it took 9.8 weeks longer for the arthrodesis group to return to full duty, but this was due primarily to the previously listed reasons. Two patients who had undergone lumbar arthroplasty were unable to return to full duty as they were incapable of returning to their previous level of activity. By 6 months, 8 of the remaining 10 in the arthroplasty group had returned to full duty and, by 9 months, all 10 had returned to full duty. In particular, the special operation member and Marines returned to their previous performance status. As mentioned in the *Complications* section, 1 individual required a posterior decompression for new-onset radiculopathy. Despite this, he was able to return to full duty 22 weeks after his initial surgery. This is comparable with the experience reported by Siepe et al.[19] who reviewed data obtained after lumbar arthroplasty in athletes. In their series of 39 athletes, they identified that peak performance was reached at 5.2 months after surgery, with 37 (94.9%) of the 39 resuming their previous sporting activity.

Patient Selection

Seven patients in the cervical arthroplasty group were Navy SEALs, another 2 were highly trained operators (1 Marine and 1 landing craft air cushion engineer), and the remaining 3 were high-ranking officers. The lumbar cohort was equally selective, with 1 Navy SEAL, 1 Explosive Ordinance Disposal Technician, and 1 Marine infantryman. Hence, the marked success achieved in this series is unquestionably a result of careful patient selection by the authors. All of the patients treated with cervical arthroplasty returned to their previous high levels of performance and were subsequently deployed, and 83% of the lumbar arthroplasty cohort were capable of the same. Admittedly, the authors are highly selective in choosing which patients undergo arthroplasty. All of the patients selected for arthroplasty were of senior rank, specialized in training, and were highly motivated to return to active duty. In fact, several of the patients in the cervical cohort were selected for arthroplasty to expedite their return to full duty. This undoubtedly impacts the rate of return, time to return, and overall success of the arthroplasty cohorts. Therefore, it would be difficult to extrapolate this preliminary experience to a broader population, even within the military.

Return-to-Full-Duty Algorithm

Given the observations we have made during our preliminary experience with arthroplasty, the authors have generated a return-to-full-duty algorithm for our active-duty arthroplasty patients, which we describe below.

Cervical Spine. With the exception of the patient with the device-related complication, all patients in the cervical arthroplasty group returned to unrestricted full duty by 3 months. Based on this, we now allow individuals to begin nonimpact training as soon as they feel comfortable enough to do so after surgery. Typically, patients begin this during the 1st month after surgery once they are off all narcotic medication. During this time, patients are restricted from parachute jumps, high-impact water entries, impact training, diving, and weight training. Throughout the 2nd month, patients are allowed to engage in light impact and weight training. Provided patients remain asymptomatic, they are allowed to return to high-impact training by the 3rd month. Preservation of motion established on flexion/extension radiographs, complete resolution of preoperative symptoms, and absence of hardware complications permit the return to unrestricted full duty and the release from the limitations listed above by the 3rd month (Table 3).

Lumbar Spine. The patients who underwent lumbar arthroplasty took on average twice as long to return to full duty (22.6 weeks) as those in the cervical group, and so the postoperative algorithm above is drawn out over this time. Again patients are restricted from parachute jumps, high-impact water entries, impact training, diving, and weight training in the immediate postoperative period. They are encouraged to begin nonimpact training once off all narcotics, which is seldom before the 2nd month and typically not until the 3rd month. Light impact and weight training are begun during the 4th and 5th month and a fitness for full-duty evaluation is done by the 6th month. Confirmation of the preservation of motion, absence of hardware complications, and resolution of preoperative symptoms allow for the service member to return to unrestricted full duty by the 6th month (Table 3).

Future Studies

In addition to prospective longitudinal studies with long-term follow-up, further studies would be warranted to examine the effects of military personnel's high-impact activities on the ultrahigh–molecular weight polyethylene inlay and its interface with the chromium cobalt molybdenum alloy. At this time, implanted devices are simply evaluated by plain radiography, given the scatter caused by both CT and MR imaging. Even macroscopic defects on the polymer that may have been caused by high-energy impacts could not be captured by this current imaging. Because the consequences of the extreme forces on the polymer and the polymer-alloy interface remain outside our current radiographic capacity, techniques such as computer-assisted edge-detection techniques, as reported by McCalden and colleagues[13] (for total hip arthroplasty), may have a role to determine the wear on the polymer and examine the polymer-alloy interface.

Conclusions

The preliminary experience with cervical and lumbar arthroplasty at our institution indicates that it is comparable with arthrodesis and may actually expedite a return to active duty. As has been identified in the previous FDA trials, this study confirms that cervical and lumbar arthroplasty are associated with clinical improvements earlier in the postoperative time period than arthrodesis. Patients are capable of returning to a high level of rigorous training and physical performance, as demonstrated by the special operation patients in this series. There are no apparent restrictions or limitations that are required after 3 months in the cervical spine–treated patient and after 6 months in the lumbar spine–treated patient. Further prospective studies with long-term follow-up are indicated and will be of value when determining the role of arthroplasty compared with arthrodesis in the active-duty population, especially for the conceptual benefit of addressing adjacent-segment degeneration. To that end, we are currently enrolling active-duty military patients into a multicenter prospective outcome trial to evaluate lumbar arthroplasty. The possibility of minimizing adjacent-segment degeneration is of particular interest to the military considering the significant strains already placed on the intact spine; there may be a benefit of arthroplasty relative to arthrodesis. Although preliminary studies support this supposition, this has yet to be conclusively established.[1,6,9,14]

Disclosure

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Author contributions to the study and manuscript preparation include the following. Conception and design: LM Tumialán. Acquisition of data: LM Tumialán, RP Ponton, A Garvin. Analysis and interpretation of data: LM Tumialán, RP Ponton. Drafting the article: LM Tumialán. Critically revising the article: LM Tumialán, WM Gluf. Reviewed final version of the manuscript and approved it for submission: LM Tumialán, A Garvin, WM Gluf. Statistical analysis: LM Tumialán, RP Ponton. Administrative/technical/material support: A Garvin. Study supervision: LM Tumialán, WM Gluf.

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Address correspondence to: Lt. Commander Luis M. Tumialán, M.D., MC, USN, Naval Medical Center San Diego, 34800 Bob Wilson Drive, San Diego, California 92134. email: luis.tumialan@med.navy.mil.

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Multilevel cervical arthroplasty with artificial disc replacement

Mario J. Cardoso, M.D., D.C., and Michael K. Rosner, M.D.

Neurosurgery Service, Walter Reed Army Medical Center, Washington, DC

Object. In this study, the authors review the technique for inserting the Prestige ST in a contiguous multilevel cervical disc arthroplasty in patients with radiculopathy and myelopathy. They describe the preoperative planning, surgical technique, and their experience with 10 patients receiving a contiguous Prestige ST implant. They present contiguous multilevel cervical arthroplasty as an alternative to multilevel arthrodesis.

Methods. After institutional board review approval was obtained, the authors performed a retrospective review of all contiguous multilevel cervical disc arthroplasties with the Prestige ST artificial disc between August 2007 and November 2009 at a single institution by a single surgeon. Clinical criteria included patients who had undergone a multilevel cervical disc arthroplasty performed for radiculopathy and myelopathy without the presence of a previous cervical fusion. Between August 2007 and November 2009, 119 patients underwent cervical arthroplasty. Of the 119 patients, 31 received a Hybrid construct (total disc resection [TDR]–anterior cervical decompression and fusion [ACDF] or TDR-ACDF-TDR) and 24 received a multilevel cervical arthroplasty. The multilevel cervical arthroplasty group consisted of 14 noncontiguous and 10 contiguous implants. This paper examines patients who received contiguous Prestige ST implants.

Results. Ten men with an average age of 45 years (range 25–61 years) were treated. Five patients presented with myelopathy, 3 presented with radiculopathy, and 2 presented with myeloradiculopathy. Twenty-two 6 × 16–mm Prestige ST TDRs were implanted. Six patients received 2-level Prestige ST implants. Five patients received TDRs at C5–6 and C6–7, and 1 patient received TDRs at C3–4 and C4–5. One patient received a TDR at C3–4, C5–6, and C6–7 where C4–5 was a congenital block vertebra. Three patients (2 with 3-level disease and 1 with 4-level disease) received contiguous Prestige ST implants as well as a Prevail ACDF as part of their constructs. The mean clinical and radiographic follow-up was 12 months. There has been no case of screw backout, implant dislodgment, progressive kyphosis, formation of heterotopic bone, evidence of pseudarthrosis at the Prevail levels, or development of symptomatic adjacent level disease.

Conclusions. Multilevel cervical arthroplasty with the Prestige ST is a safe and effective alternative to fusion for the management of cervical radiculopathy and myelopathy. *(DOI: 10.3171/2010.1.FOCUS1031)*

Key Words • cervical arthroplasty • multilevel cervical arthroplasty • Prestige ST • radiculopathy • myelopathy

Anterior cervical decompression and fusion has been the procedure of choice for refractory cervical radiculopathy and myelopathy for more than 50 years.[4,18] Historically, the primary goal of surgery has been preservation and restoration of neurological function. As an adjuvant, segmental arthrodesis has been incorporated as a means to provide stability and prevent further segmental degeneration. Over the past several decades, instrumentation, interbody devices, and biologics have greatly improved segmental fixation rates. However, segmental fixation may not be the ideal adjuvant to neural decompression within the cervical spine.

In single level subaxial fixation, the cervical spine is able to compensate and maintain overall motion. However, as more levels are incorporated into the construct, cervical motion is adversely affected. Levels adjacent to a cervical fusion may experience increased stressors that contribute to degeneration.[3,6,7,12] In 1999, Hilibrand et al.[11] reported on a consecutive series of 374 patients with a total of 409 ACDFs in whom symptomatic adjacent disease was reported to occur at a rate of 2.9% per year. Although the natural progression of degenerative disc disease must be a contributing factor, the work by Goffin et al.[9] demonstrated that adjacent-segment disease is more likely related to the arthrodesis.

Brian Cummins was one of the first pioneers in cervical arthroplasty to report on the efficacy of the TDR in the cervical spine. In a small case series, Cummins et al.[5] demonstrated that cervical arthroplasty was safe, effective, and preserved segmental motion. Recently, the 5-year outcomes for the Prestige ST (Medtronic Sofamor Danek) were presented showing improved outcomes for patients receiving a TDR versus an ACDF.[10] In addition,

Abbreviations used in this paper: ACDF = anterior cervical decompression and fusion; TDR = total disc replacement; VB = vertebral body.

Cummins introduced the exciting concept of multilevel arthroplasty as an alternative to multilevel fusion.

In cadaveric spines, both hybrid (TDR and ACDF) and multilevel cervical disc arthroplasty constructs have been shown to maintain segmental motion and preserve adjacent-level range of motion.[13,16] Several case series have demonstrated that multilevel cervical arthroplasty for the treatment of radiculopathy and myelopathy can be an alternative with good outcomes.[5,15] In a prospective study, Pimenta et al.[14] demonstrated that multilevel cervical arthroplasty had improved outcomes over single-level arthroplasty. Several clear advantages to performing multilevel cervical arthroplasty are preserved motion, decreased adjacent-level biomechanical stressors, and potentially better outcomes.

In this study, we review the technique for inserting the Prestige ST in a contiguous multilevel cervical disc arthroplasty in patients with radiculopathy and myelopathy. We describe the preoperative planning, surgical technique, and our experience with 10 patients receiving a contiguous Prestige ST implant. We present contiguous multilevel cervical arthroplasty as an alternative to multilevel arthrodesis.

Methods

After institutional review board approval was obtained, a retrospective review of all contiguous multilevel cervical disc arthroplasties with the Prestige ST artificial disc between August 2007 and November 2009 at a single institution by a single surgeon (senior author M.R.) was completed. Clinical criteria included patients that had undergone a multilevel cervical disc arthroplasty performed for radiculopathy and myelopathy without the presence of a previous cervical fusion. Between August 2007 and November 2009, 119 patients underwent cervical arthroplasty. Of the 119 patients, 31 received a Hybrid construct (TDR-ACDF or TDR-ACDF-TDR) and 24 received a multilevel cervical arthroplasty. The multilevel cervical arthroplasty group consisted of 14 noncontiguous and 10 contiguous implants. This paper examines patients who received contiguous Prestige ST implants.

Clinical and Radiographic Evaluation

The clinical evaluation of any patient begins with a thorough history and physical examination. At our institution there are several disqualifiers for cervical arthroplasty; primary axial neck pain in the absence of radiculopathy or myelopathy, osteopenia or osteoporosis, autoimmune disorders, malignancy involving the spine, acute cervical trauma, subluxation of the cervical segment greater than 3.5 mm on flexion-extension radiographs, ossified posterior longitudinal ligament, severe facet arthrosis demonstrating lack of motion, and congenital stenosis. Patients with radiculopathy or myelopathy caused by disc herniation or osteophytosis are candidates for surgery.

All patients undergo preoperative radiography in flexion-extension, CT scanning, and MR imaging of the cervical spine. In addition, patients also undergo standing anteroposterior and lateral scoliosis radiographs for evaluation of overall balance and deformity. Alone, the presence of cervical kyphosis is not a disqualifier for cervical arthroplasty. The Prestige ST can be inserted between C-3 and T-1 in patients with 1-, 2-, 3-, or 4-level disease. Although not all levels may accommodate a Prestige ST, hybrid constructs utilizing stand-alone interbody spacers such as the Prevail (Medtronic Sofamor Danek) can be inserted. Given the limitations imposed by the overall anatomical shape of the C-2 VB, we have not inserted a Prestige ST at C2–3.

Computed tomography scanning can be used to approximate implant depth; however, the final Prestige ST depth tends to always be less than the preoperative measurement due to bone removal during the carpentry portion of the surgery. The VB height can be determined from the sagittal CT scan to help evaluate for potential placement of adjacent-level implants. The limitation is the inferior lip of the superior VB that will be removed, and the remaining anterior body height may no longer facilitate the placement of an adjacent-level Prestige ST. The superior and inferior Prestige ST flanges are 7.5 and 7.1 mm long. Therefore, more than 16 mm of exposed anterior VB is necessary for insertion of an adjacent level Prestige ST.

Prestige ST Implant

The Prestige ST implant is a stainless steel ball-in-trough cervical arthroplastic device. The ball-in-trough motion is relatively unconstrained and comparable to that of the cervical spine. The endplates have anterior flanges that make an angle similar to that of the VBs. The flange profiles are 3.0 and 2.5 mm with and without the set screw, respectively. The superior and inferior flange lengths are 7.5 and 7.1 mm, respectively. The flanges are secured with 4.0 × 13–mm screws or 4.5 × 13–mm salvage screws. The endplates come in 12-, 14-, 16-, and 18-mm depths that will allow an interbody height of 6, 7, 8, or 9 mm. The endplates are grit-blasted to promote osteointegration. The Prestige ST was first introduced in 2002 and was FDA approved in 2007.

Surgical Technique

Patients are positioned supine on the operating table. Patients who can tolerate slight neck extension have a shoulder roll placed to help with exposure, and pressure points are padded. For all cases we use neuromonitoring for somatosensory evoked potentials and motor evoked potentials. Preoperative antibiotics and steroids are given. Fluoroscopy and surface landmarks are used to delineate surgical levels and to determine the appropriate incision location. For most patients we use a transverse incision extending from the midline toward the sternocleidomastoid muscle. The anterior cervical spine is approached through a standard fascial dissection. After the longus colli is dissected laterally and the retractors are placed, the endotracheal cuff is deflated and reinflated to diminish recurrent laryngeal nerve compression from restraction.[1] The midline of the VBs are marked, and the overhanging lip of the superior VB is carefully drilled away to open up the disc space. The intervertebral disc and cartilaginous endplates are thoroughly removed.

TABLE 1: Characteristics of patients undergoing multilevel cervical arthroplasty with the Prestige ST

Case No.	Age (yrs), Sex	Lesion	Presentation	Procedure	Complication
1	47, M	C4–5,5–6, & 6–7 HNP	myelopathy	C4–5 TDR, C5–6 TDR, & C6–7 ACDF	none
2	48, M	C5–6 & C6–7 HNP	radiculopathy	C5–6 & C6–7 TDR	none
3	43, M	C4–5, 5–6, & 6–7 HNP	myelopathy	C4–5 TDR, C5–6 TDR, & C6–7 ACDF	none
4	25, M	C5–6 & 6–7 HNP	radiculopathy	C5–6 & 6–7 TDR	none
5	45, M	C5–6 & 6–7 HNP	radiculopathy	C5–6 & 6–7 TDR	none
6	49, M	C5–6 & 6–7 HNP	myelopathy	C5–6 & 6–7 TDR	none
7	40, M	C5–6 & 6–7 HNP	myeloradiculopathy	C5–6 & 6–7 TDR	none
8	61, M	C3–4, 4–5, & 5–6 HNP	myelopathy	C3–4 TDR, C4–5 TDR, C5–6 ACDF, & C6–7 TDR	none
9	54, M	C3–4, 5–6, & 6–7 HNP	myeloradiculopathy	C3–4, 5–6, & 6–7 TDR	none
10	39, M	C3–4 & 4–5 HNP	myelopathy	C3–4 & 4–5 TDR	none

* HNP = herniated nucleus pulposus.

After the discectomy is completed, the endplates are fashioned with a high-speed drill and made parallel. The cartilaginous endplate is removed to expose the subchondral bone. Meticulous care is taken not to violate the subchondral bone, as this may weaken the fixation of the implant. Preparing the endplates prior to decompression opens the corridor and is efficient. The posterior anulus and posterior longitudinal ligament must be removed if a TDR is considered. The posterior endplates are trumpeted, and wide foraminotomies are performed. The wide foraminal decompressions are essential since motion is retained and any foraminal encroachment may aggravate a radiculopathy. The anterior VB can only be slightly curved. Otherwise, the Prestige ST flanges will not be flush with the VB and will remain proud. The Prestige ST trials allow you to size and determine if appropriate endplate as well as anterior VB carpentry has been achieved. Prior to trial insertion, any VB distraction pins should be removed. The trials should fit snug but not under too much tension. If the implant is inserted under stiff ligaments, motion may be limited. Once the implant is inserted and secured, the head is flexed and extended under fluoroscopy to evaluate motion. It is essential that the implant be no more than 1–2 mm from midline due to the theoretical risk of uneven facet loading and potential postoperative pain as well as potential for advanced facet arthrosis.

In multilevel disease, the most cephalad level is decompressed first to ensure that the arthroplasty is at the top of the construct. The ability to insert a subsequent Prestige ST at the level below is dependent on the amount of superior anterior VB available. Once the adjacent level is ready for the implant, the profile trial, which has superior and inferior flanges the same height as the implant, is used to determine if a second Prestige ST can be inserted. If so, the implant is carefully inserted into the disc space so as not to ride up on the above implant. The top screws need to be secured almost completely but not so much as to limit securing the bottom screws. While the inferior screws are being inserted, the surgeon has to be mindful of the top flange. There is a tendency for the superior flange to ride up on the inferior flange of the superior implant while the inferior screws are inserted. Once all 4 screws are inserted, the inserter is removed and the screws are slowly tightened down, alternating in a diagonal manner. The locking screws are then inserted and tightened. The implant should be flush with that of the above level. If the implant cannot be secured, a stand-alone interbody device should be considered. The Prevail device is a possible option. The device is made of polyetheretherketone, ample amount of packing space for arthrodesis, and has a superior and inferior midline screw that will not interfere with the adjacent Prestige ST. The implant can be packed with allograft cellular bone matrix containing native mesenchymal stem cells (Osteocel, Nuvasive), autogenous bone graft, demineralized bone matrix, or combination of the above.

Results

The following data were collected and are presented in Table 1: age, sex, etiology, clinical presentation (radiculopathy, myelopathy), surgical procedure, and complications. Ten men with an average age of 45 years (range 25–61 years) were treated. Five patients presented with myelopathy, and the 3 patients presented with radiculopathy, and 2 patients presented with myeloradiculopathy. Twenty-two 6 × 16–mm Prestige ST TDRs were implanted. Six patients received 2-level Prestige ST implants. Five patients received TDRs at C5–6 and C6–7 (Fig. 1), and 1 patient received TDRs at C3–4 and C4–5. One patient received a TDR at C3–4, C5–6, and C6–7 where C4–5 was a congenital block vertebra (Fig. 2). Three patients (2 with 3-level disease and 1 with 4-level disease) received contiguous Prestige ST implants as well as a Prevail ACDF as part of their constructs.

All patients underwent operative placement of the Prestige ST and Prevail ACDF without technical difficulty. No neurological or vascular injury occurred. The mean clinical and radiographic follow-up was 12 months (range 3–27 months). There has been no case of screw backout, implant dislodgment, progressive kyphosis, formation of heterotopic bone, evidence of pseudarthrosis at the Prevail levels, or development of symptomatic adjacent-level disease.

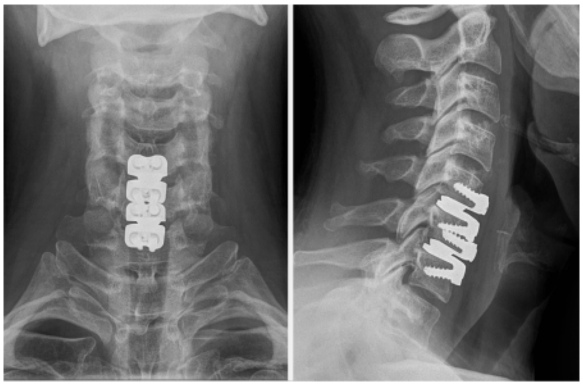

Fig. 1. Radiographs depicting a 2-level Prestige ST arthroplasty at C5–6 and C6–7.

Illustrative Case

History and Examination. This 61-year-old otherwise healthy man presented to the clinic with neck pain, progressive loss of fine motor control, clumsiness, and bilateral upper-extremity paresthesia. The patient was evaluated and treated by physical therapy with no improvement prior to the clinic visit. The patient stated that his gait had become increasingly unsteady over 1 week's time. The patient did not recall any inciting event.

On examination, the patient was hyperreflexive and had a bilateral upper-extremity paresthesia that was not limited to any one dermatome, a bilateral Hoffman sign, and an unsteady gait. Plain radiographs showed advanced degenerative disc disease at C5–6 and C-7. Analysis of the MR imaging study showed cervical stenosis at C3–4, C4–5, C5–6, and C6–7 with cord signal change at the respective levels (Fig. 3).

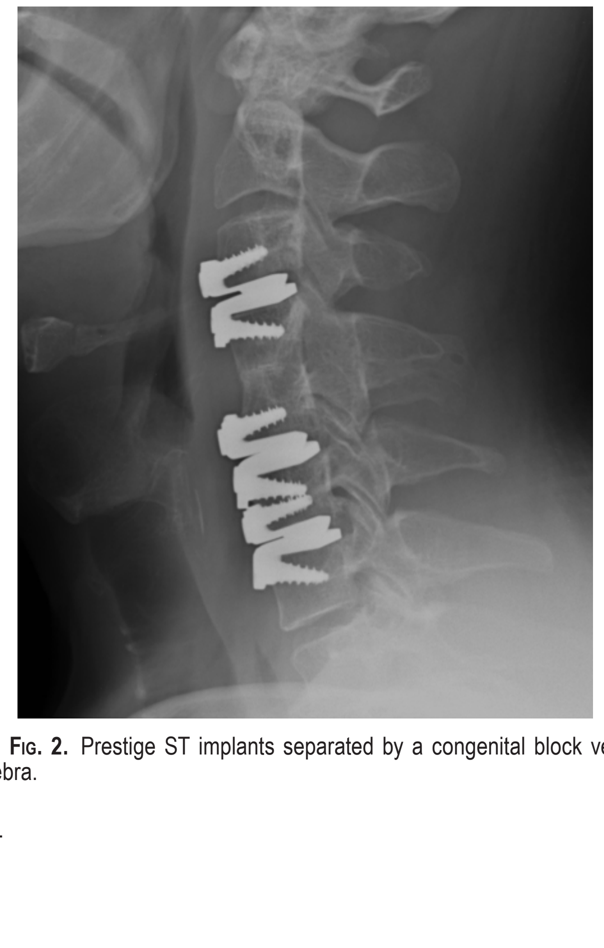

Fig. 2. Prestige ST implants separated by a congenital block vertebra.

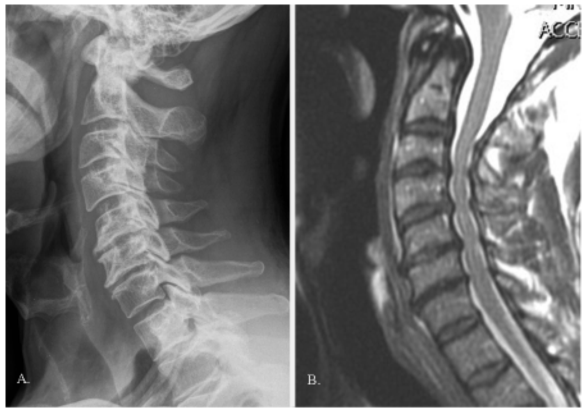

Fig. 3. A: Preoperative radiograph showing advanced degenerative changes at C5–6 and C6–7. **B:** Sagittal T2-weighted MR image demonstrating C3–4, C4–5, C5–6, and C6–7 stenosis.

Operation. The patient agreed to undergo an anterior C3–4, 4–5, 5–6, and 6–7 decompression and arthroplasty rather than fusion. A single transverse incision was made at the level of C-5. The C3–4 discectomy was performed first. Once the implant was inserted and secured at the respective level, the subsequent level was decompressed and instrumented. The C3–4 and C4–5 levels could accommodate a Prestige ST 6 × 16–mm implant; however, the C-5 VB could not accommodate a second Prestige ST. A Prevail interbody device packed with the patient's autogenous bone was inserted at the C5–6 level followed by a Prestige ST at the C6–7 level. No intraoperative complications were appreciated. The patient was extubated and was transferred to the postanesthesia care unit.

Postoperative Course. Postoperative imaging revealed excellent placement of instrumentation (Fig. 4). The patient was discharged on postoperative Day 1. On follow-up, the patient stated that paresthesia, clumsiness, and unsteady gait had all greatly improved.

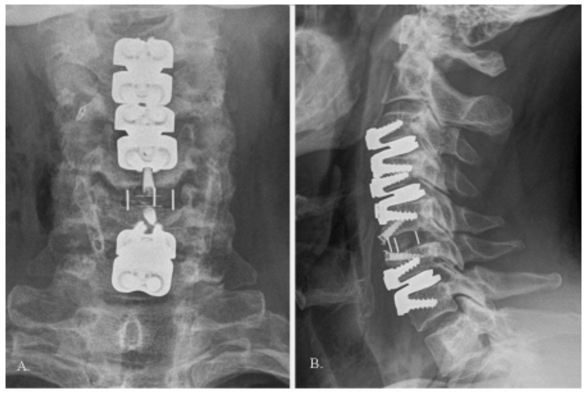

Fig. 4. A: Postoperative radiographs demonstrating a Prestige ST at C3–4, C4–5, C5–6, and C6–7. **B:** A fusion utilizing the Prevail was performed at C5–6.

Discussion

Cervical disc arthroplasty is an exciting new technique in the management of cervical radiculopathy and myelopathy. Cervical TDRs offer many distinct advantages over the traditional ACDF to include preserved segmental motion, decreased adjacent level strain, and improved outcomes.[3,6,7,10,12] Although initially intended for single-level disease, cervical TDRs are being used in contiguous and Hybrid constructs with excellent outcomes.[14,16]

Currently, only the Prestige ST and ProDisc C (Synthes Spine) have been approved by the FDA for cervical spine arthroplasty. The Prestige ST offers several advantages to include anterior fixation for initial stability, unconstrained motion similar to that of the cervical spine, and a simple insertion technique. Success is determined by proper patient selection and the surgeon's ability to obtain an appropriate decompression and fashion the endplates. As with the ACDF, if the endplates are oblique in the horizontal plane, a coronal deformity could be introduced into the cervical spine. In addition, the implant needs to be centered within several millimeters of the midline for proper loading of the facets during motion. If the implant is not centered, the unequal loading may promote posterior joint arthrosis. To date, the senior author has not had to revise any Prestige ST implants.

Inserting contiguous Prestige ST implants can be challenging. The anterior VB at a minimum must have at least 16 mm of exposed surface to accommodate a Prestige ST above and below. Interestingly, all of the contiguous Prestige ST implants inserted by the senior author have been performed in men. This is primarily due to the VB height being greater in men than in women. Of the 30 Hybrid TDR constructs performed by the senior author (unpublished data), 15 were performed in females. In all but one, attempts to insert an adjacent level Prestige ST were made using the above-described technique. In 14 of these patients, the fusion option was used at the adjacent level.

Cervical myelopathy has both a static and dynamic component. Traditionally, anterior cervical decompression has been followed by fusion.[4,18] Fusion is thought to reduce neural manipulation, arrest bone spur formation, and reduce posterior cord compression from buckled ligamentum flavum by increasing neuroforaminal height.[19] However, multilevel fusions are associated with high pseudarthrosis rates, iliac crest donor site morbidity, persistent postoperative dysphagia, and the development of adjacent-level degeneration and disease.[2,8,11,17,20] Arthroplasty may be the solution to these comorbidities. Sekhon[15] was the first to report that cervical arthroplasty in the setting of cervical myelopathy was a safe and excellent alternative to fusion. Since Sekhon's study, several other authors have shown that cervical arthroplasty in the setting of cervical myelopathy can have a good outcome.[10,14] Our results confirm that in the short term, multilevel cervical arthroplasty is a safe and effective adjuvant implant strategy to decompression in the setting of cervical myelopathy or radiculopathy.

Currently, cervical arthroplasty remains an alternative to fusion. Long-term data are still necessary to determine whether single or multiple level cervical arthroplasty is superior to the veteran ACDF.

Conclusions

Multilevel cervical arthroplasty with the Prestige ST is a safe and effective alternative to fusion for the management of cervical radiculopathy and myelopathy.

Disclosure

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the United States Army, Unites States Navy, or the Department of the Defense. The authors are employees of the Unites States government. This work was prepared as part of their official duties and as such, there is no copyright to be transferred.

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: MK Rosner. Acquisition of data: MJ Cardoso, MK Rosner. Analysis and interpretation of data: MJ Cardoso, MK Rosner. Drafting the article: MJ Cardoso. Critically revising the article: MJ Cardoso, MK Rosner. Reviewed final version of the manuscript and approved it for submission: MK Rosner. Statistical analysis: MJ Cardoso. Study supervision: MK Rosner.

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Address correspondence to: Mario J. Cardoso, M.D., Walter Reed Army Medical Center, 6900 Georgia Avenue NW, Washington, DC 20307. email: mtcardoso@comcast.net.

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Does the Wilson frame assist with optimizing surgical exposure for minimally invasive lumbar fusions?

Mario J. Cardoso, M.D., D.C., and Michael K. Rosner, M.D.

Neurosurgery Service, Walter Reed Army Medical Center, Washington, DC

Object. Minimally invasive lumbar spine surgery has dramatically evolved over the last decade. Minimally invasive techniques and transforaminal lumbar interbody fusion (TLIF) often require a steep learning curve. Surgical techniques require pre-positioning the patient in maximal kyphosis to optimize visualization of the disc space and prevent unnecessary retraction of neural structures. The authors describe their experience in validating the surgical technique recommendation of Wilson frame–induced kyphosis.

Methods. Over the past 6 months, data obtained in 20 consecutive patients (40 total levels) undergoing minimally invasive TLIF were reviewed. In each patient, preincision intraoperative radiographs were reviewed at L4–5 and L5–S1 with the patient on a Wilson frame in maximal lordosis and then in maximal kyphosis. The change in disc space angle at L4–5 and L5–S1 after changing from maximal lordosis to maximal kyphosis was reviewed. Descriptive statistics were calculated for sagittal plane angular measures at L4–5 and L5–S1 in lordosis and kyphosis, including absolute differences and percentage of change between positions. Inferential statistics were calculated using paired t-tests with $\alpha = 0.05$.

Results. Twenty patients underwent single- or multilevel minimally invasive TLIF. Inducing kyphosis with the Wilson frame aided in optimizing exposure and decreasing the need for neural structure retraction. Both L4–5 and L5–S1 showed statistically significant ($p < 0.001$) and clinically meaningful changes with increased segmental flexion in the kyphotic position. At L4–5 the mean increase in flexion was 4.5° (95% CI 2.9–6.0°), representing an average 47% change. The mean increase in flexion at L5–S1 was 3.2° (95% CI 2.3–4.2°), representing an average 20.8% change. In lordosis the mean angle at L4–5 was 10.6 ± 4.4° and at L5–S1 was 17 ± 7.0°. In kyphosis the mean angle at L4–5 was 6.1 ± 4.5° and at L5–S1 was 13.8 ± 6.5°. Additionally, there was a statistically significant difference ($p < 0.05$) in percentage of change between the 2 levels, with L4–5 showing a greater change (27% more flexion) between positions, but the absolute mean difference between the levels was small (1.3°).

Conclusions. Minimally invasive TLIF is challenging and requires a significant learning curve. The recommended surgical technique of inducing kyphosis with the Wilson frame prior to incision significantly optimizes exposure. The authors' experience demonstrates that this technique is essential when performing minimally invasive lumbar spinal fusions. *(DOI: 10.3171/2010.1.FOCUS10325)*

Key Words • **Wilson frame** • **minimally invasive technique** • **lumbar fusion**

Minimally invasive spine surgery has dramatically evolved over the last decade. New techniques and instrumentation have expanded the minimally invasive field from single nerve root decompressions to multilevel instrumented spine fusions. As patients benefit from the decreased postoperative pain, blood loss, transfusion needs, and length of hospital stay, the demand for spine surgeons to become proficient in minimally invasive spine technology will only increase.[2–4,6,15]

Transforaminal lumbar interbody fusion has become a procedure of choice in the management of various spine disorders requiring arthrodesis.[12,13,17] Compared with the traditional posterior lumbar interbody fusion, there are clear advantages that include unilateral exposure, decreased neural retraction, and a lateral approach that facilitates revision surgery. However, exposure of the posterior spinal elements still requires muscle stripping and retraction that can have an adverse effect on patient outcome.[6–11,14] With the advent of minimally invasive spine techniques, iatrogenic soft-tissue injury may be minimized.

Regardless of the exposure technique, pre-positioning of the patient in maximal segmental distraction while performing a TLIF is recommended. Theoretically, this optimizes visualization of the disc space and is thought to prevent unnecessary retraction of the neural structures. Once interbody spacer placement is completed, the patient is repositioned in lordosis and segmental instrumentation is secured. A common positioning device employed for this purpose is the Wilson frame.

Given the steep learning curve associated with mini-

Abbreviation used in this paper: TLIF = transforaminal lumbar interbody fusion.

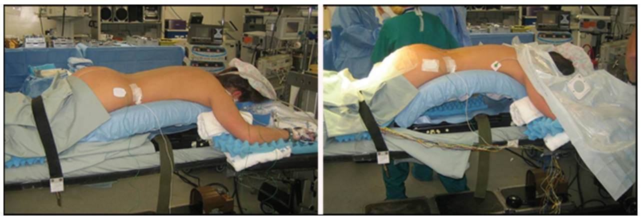

Fig. 1. Patient positioned on the Wilson frame in lordosis and kyphosis.

mally invasive spinal surgery, any technique that facilitates the surgery is valued. In contrast, any procedure not necessary to the goals of the surgery becomes an unnecessary step. To this point, the literature does not quantify the disc exposure that the Wilson frame obtains in maximal lumbar kyphosis. The purpose of this study was to present our experience in validating the surgical technique recommendation of Wilson frame–induced kyphosis for interbody fixation followed by induced lordosis for final compression.

Methods

Data obtained in 20 consecutive patients (13 men, 7 women), whose average age was 44 years (range 21–61 years) and who underwent single- or multilevel minimally invasive TLIF (40 interbody levels), were retrospectively reviewed. Preoperative diagnoses included 3 cases of Meyerding Grade I isthmic spondylolisthesis (2 patients with L-4 and 1 patient with L-5 spondylolisthesis) and 17 patients with discogenic back pain due to degenerative disc disease with and without radiculopathy. No disc spaces involved in the study were collapsed by greater than 50%.

All patients were preoperatively positioned on the Wilson frame (Mizuh OSI) mounted on the OSI Jackson table under the supervision of the attending surgeon. The Wilson frame was elevated to maximum position. Positioning was standardized for all patients regardless of body habitus with the abdomen allowed to hang. The hips were allowed to flex naturally over the inferior aspect of the Wilson frame onto the operating table. Knees were padded and a pillow was placed under the patient's legs at the ankle to allow the knees to flex. Arms were flexed toward the head of the bed and supported by arm boards (Fig. 1).

Radiographs were obtained prior to preparation and draping using C-arm fluoroscopy. During confirmation of the surgical level, a radiograph was obtained with the patient in maximal kyphosis followed by maximal lordosis. The intervertebral disc angle at L4–5 (20 sides) and L5–S1 (20 sides) was analyzed using Image Pro-Plus Version 5.1 (Media Cybernetics, Inc.) (Fig. 2). Descriptive statistics were calculated for the intervertebral body angle measured at L4–5 and L5–S1 in both kyphosis and lordosis. Absolute differences and percentage of change between positions as well as inferential statistics were calculated using paired t-tests with $\alpha = 0.05$ (SPSS Version 13.0). Mean values are presented ± the SD.

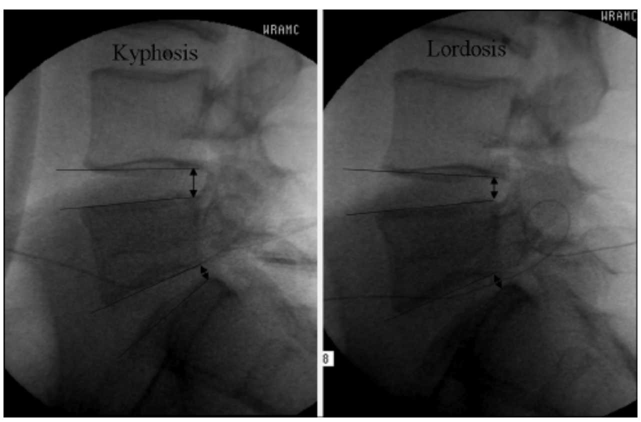

Fig. 2. Intraoperative fluoroscopic images obtained in a patient in whom kyphosis and lordosis have been induced. *Arrows* show intervertebral disc angles.

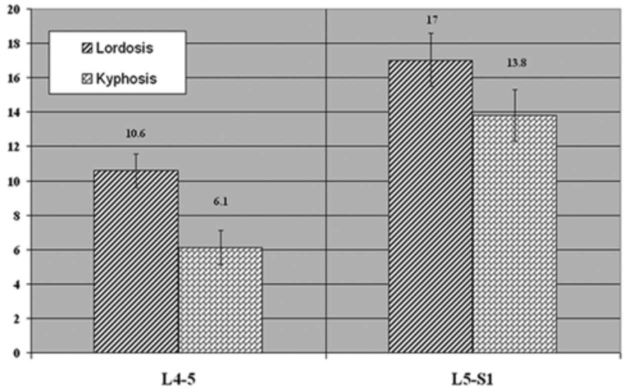

Fig. 3. Mean intervertebral angle at both L4–5 and L5–S1 in both lordosis and kyphosis in 20 patients.

Results

With the Wilson frame in the lordotic position, the mean intervertebral disc angle at L4–5 and L5–S1 was 10.6 ± 4.4 and 17.1 ± 7.0°, respectively. With the Wilson frame inducing maximal kyphosis, the L4–5 and L5–S1 disc angles decreased to 6.1 ± 4.5 and 13.8 ± 6.5°, respectively (Fig. 3). Radiographic analysis of the intervertebral disc angle at both L4–5 and L5–S1 showed a statistically significant change ($p < 0.001$) in disc angle for both levels. In addition there was a clinically meaningful change with increased segmental flexion in the kyphotic position during the procedures. The decrease in disc angle is a result of anterior disc compression and posterior disc distraction from the adjacent vertebral body going into flexion. Consequently, the lumbar intervertebral disc angle at L4–5 and L5–S1 decreased by 4.5° (95% CI 2.9–6.0°) and 3.2° (95% CI 2.3–4.2°), respectively. This represents a change of 47 and 21%, respectively, at the L4–5 and L5–S1 disc levels (Table 1). As a result, there was improved posterior

TABLE 1: Mean and percentage of intervertebral disc angle change from lordosis to kyphosis

Disc Level	Mean Intervertebral Angle Change (°)	% Intervertebral Angle Change
L4–5	4.5	47
L5–S1	3.2	21

TABLE 2: Absolute and percentage of intervertebral angle change for L4–5 and L5–S1 in 20 patients

	Absolute Change (°)		% Intervertebral Angle Change	
Case No.	L4–5: Lordosis to Kyphosis	L5–S1: Lordosis to Kyphosis	L4–5	L5–S1
1*	6.9	4.3	61.2	18.8
2	1.0	1.1	10.0	17.0
3	0.6	−0.1	7.3	−0.3
4	1.5	2.0	28.8	18.6
5	6.0	1.1	50.4	11.7
6	−0.4	4.5	−3.0	35.1
7	0.5	2.1	6.7	8.7
8	2.8	2.9	18.6	31.0
9	7.2	7.5	79.3	40.3
10†	8.6	4.4	199.1	17.0
11	9.0	6.5	53.4	29.9
12	7.5	2.6	35.4	10.3
13	1.6	1.8	11.2	8.0
14	2.2	5.0	31.0	26.5
15	5.0	1.9	74.3	10.2
16	5.5	4.2	40.6	15.7
17	0.7	5.4	14.8	23.7
18	9.1	0.5	63.2	3.5
19	7.3	2.0	75.9	38.0
20†	6.8	4.2	81.4	51.4

* Patient has Grade I L-5 spondylolisthesis.
† Patient has Grade I L-4 spondylolisthesis.

disc anulus exposure allowing for interbody instrumentation and neural element protection.

Furthermore, there was a statistically significant difference ($p < 0.05$) in percentage of change between the 2 levels with L4–5 showing 27% more flexion between positions. This is unexpected because the L5–S1 level has been reported to have a greater range of motion in flexion and extension than the L4–5 disc space.[20] The increase in L4–5 flexion may be explained by lordotic positioning on the Wilson frame placing the lumbar spine in kyphosis that is mostly appreciated at the L5–S1 disc space. The absolute mean difference between L4–5 and L5–S1 was small (1.3°) and not statistically significant ($p > 0.05$).

Discussion

Minimally invasive surgery has become the gold standard for many surgical specialties.[16,21] The benefits of lower blood loss, shorter hospital stays, and less postoperative pain are compelling and may eventually overcome concerns of a steep learning curve.[2–4,15] Techniques that simplify as well as facilitate the surgeon’s task may help to lesson any resistance associated with the technical aspects of minimally invasive spinal surgery.

Surgical techniques that involve pre-positioning of patients in maximal lumbar kyphosis optimize visualization of the disc space and minimize neural-structure retraction for intervertebral work. However, the literature supporting induced lumbar kyphosis for interbody fixation is limited. Our study is the first to report disc angle changes before and after inducing lumbar kyphosis for the purpose of lumbar interbody fusion.

Placing patients in Wilson frame–induced kyphosis decreases the intervertebral disc angle and therefore maximizes posterior disc anulus exposure. By inducing lumbar kyphosis with the Wilson frame, the L4–5 and L5–S1 disc angles decreased by 47 and 21%, respectively. As expected the L5–S1 intervertebral disc angle was greater than L4–5; however, the percentage of change from the lordotic to the kyphotic position on the Wilson frame was greater for the L4–5 level. The biomechanical literature has shown that flexion/extension is greatest at L5–S1.[20] Therefore, it would be expected that L5–S1 would experience the greatest change in intervertebral angle. We postulate that much of this motion at L5–S1 was displaced in positioning the patient on the Wilson frame, which induces baseline kyphosis. Tan and colleagues[19] noted a 50% decrease in lumbar lordosis from the standing position to being positioned on a frame that flexed the hips. Benfanti and Geissele[1] reported an 8% decrease in L4–S1 segmental lordosis from the standing position to being placed on the Wilson frame. Conversely, Guanciale et al.[5] noted that L5–S1 segmental lordosis was less dependent on frame type and has little change from the standing to frame position. However, it should be noted that the Wilson frame was not evaluated in the study. Nevertheless, a statistically and clinically significant decrease in lordosis was appreciated at both L4–5 and L5–S1.

Given the small number of patients with spondylolisthesis, a correlation with intervertebral disc angle change and isthmic spondylolisthesis could not be made. One would expect an increase in intervertebral disc angle change in both settings. In both cases of L4–5 isthmic spondylolisthesis the patient had greater flexion on kyphosis (199 and 81%) than the mean (47%); however, in the one case of L5–S1 spondylolisthesis the patient did not have greater flexion on kyphosis (19 vs 21%) (Table 2). In addition, partial and complete sacralized L-5 vertebrae, which have diminished motion from pseudo–transverse process articulations and rudimentary discs, would be expected to benefit only minimally from Wilson frame–induced kyphosis. In the current study there were no partial or complete sacralized L-5 vertebrae. Finally, there were no intervertebral disc levels with abutting vertebral endplates. Stokes et al.[18] used biplanar radiography to evaluate lumbar coupled motion and linked advanced disc degeneration with increased coupled motion in the lower lumbar spine. Based on their work, the Wilson frame technique may increase exposure between vertebrae with a collapsed disc. To evaluate this, a follow-up study is warranted.

Minimally invasive TLIF is challenging and requires a significant learning curve. The recommended surgical technique of inducing kyphosis with the Wilson frame prior to incision significantly optimizes exposure. The Wilson frame technique may also benefit surgeons performing standard open transforaminal fusions. It is our opinion that the Wilson frame technique is essential, but only time will tell whether it becomes an accepted technique among spine surgeons.

Conclusions

Wilson frame–induced kyphosis significantly increased flexion at L4–5 and L5–S1 by 47 and 21%, respectively. We found that the surgical technique of inducing kyphosis with the Wilson frame prior to incision significantly optimized exposure. Our experience demonstrates that this technique is essential when performing minimally invasive lumbar spinal fusions.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. The opinions and assertions contained herein are the private views of the authors and are not to be construed as official or reflecting the views of the US Army or the US Navy.

Author contributions to the study and manuscript preparation include the following. Conception and design: MK Rosner. Acquisition of data: MJ Cardoso. Analysis and interpretation of data: both authors. Drafting the article: MJ Cardoso. Critically revising the article: MJ Cardoso. Reviewed final version of the manuscript and approved it for submission: MK Rosner. Statistical analysis: MJ Cardoso. Administrative/technical/material support: both authors. Study supervision: MK Rosner.

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Address correspondence to: Mario J. Cardoso, M.D., Neurosurgery Service, Walter Reed Army Medical Center, 6900 Georgia Avenue NW, Washington, DC 20307. email: mtcardoso@comcast.net.

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Resident learning curve for minimal-access transforaminal lumbar interbody fusion in a military training program

Chris J. Neal, M.D.,[1] and Michael K. Rosner, M.D.[2]

[1]Division of Neurosurgery, National Naval Medical Center, Bethesda, Maryland; and [2]Division of Neurosurgery, Walter Reed Army Medical Center, Washington, DC

Object. Minimal-access transforaminal lumbar interbody fusion (TLIF) has gained popularity as a method of achieving interbody fusion via a posterior-only approach with the aim of minimizing injury to adjacent tissue. While many studies have reported successful outcomes, questions remain regarding the potential learning curve for successfully completing this procedure. The goal of this study, based on a single resident's experience at the only Accreditation Council for Graduate Medical Education–approved neurosurgical training center in the US military, was to determine if there is in fact a significant learning curve in performing a minimal-access TLIF.

Methods. The authors retrospectively reviewed all minimal-access TLIFs performed by a single neurosurgical resident between July 2006 and January 2008. Minimal-access TLIFs were performed using a tubular retractor inserted via a muscle-dilating exposure to limit approach-related morbidity. The accuracy of screw placement and operative times were assessed.

Results. A single resident/attending team performed 28 minimal-access TLIF procedures. In total, 65 screws were placed at L-2 (1 screw), L-3 (2 screws), L-4 (18 screws), L-5 (27 screws), and S-1 (17 screws) from the resident's perspective. Postoperative CTs were reviewed to determine the accuracy of screw placement. An accuracy of 95.4% (62 of 65) properly placed screws was noted on postoperative imaging. Two screws (at L-5 in the patient in Case 17 and at S-1 in the patient in Case 9) were lateral, and no revision was needed. One screw (at L-4 in Case 24) was 1 mm medial without symptoms or the need for revision. In evaluating the operative times, 2 deformity cases (Grade III spondylolisthesis) were excluded. The average operating time per level in the remaining 26 cases was 113.25 minutes. The average time per level for the first 13 cases was 121.2 minutes; the amount of time decreased to 105.3 minutes for the second group of 13 cases (p = 0.25).

Conclusions. In summary, minimal-access TLIF can be safely performed in a training environment without a significant complication rate due to the expected learning curve. *(DOI: 10.3171/2010.1.FOCUS1011)*

Key Words • minimal-access surgery • transforaminal lumbar interbody fusion • resident education • learning curve

As the first few generations of residents graduate under the work-hour restrictions imposed by the Accreditation Council for Graduate Medical Education in 2003, competency in various procedures will come under increased scrutiny in the credentialing process. Further efforts must be made during the training period to maximize resident education and proficiency. One aspect of such efforts is to understand the number of procedures that must be performed before a trainee can be considered safe and competent. Comparing the ability to perform a task more efficiently over a period of time describes the term "learning curve." Although attempts have been made to understand the learning curves associated with various procedures, the neurosurgical and spine literature is lacking any such studies compared with what is found in other surgical fields.[1,2,5,6,8]

There are certainly many variables associated with how an individual learns. In an attempt to understand this process we evaluated a single resident/attending team as the resident learned how to perform a minimal-access TLIF. This procedure has gained popularity as a method of achieving interbody fusion via a posterior-only approach with the aim of minimizing injury to adjacent tissue.[9,15,18] While the authors of many studies have reported successful outcomes, questions remain regarding the process of learning to successfully and safely perform this procedure. The goal of this study, based on a single resident's experience, was to determine if there is a significant learning curve in performing a minimal-access TLIF.

Methods

We conducted a retrospective review of all minimal-access TLIFs performed at a single center by a single resident/attending team between July 2006 and January 2008.

Abbreviation used in this paper: TLIF = transforaminal lumbar interbody fusion.

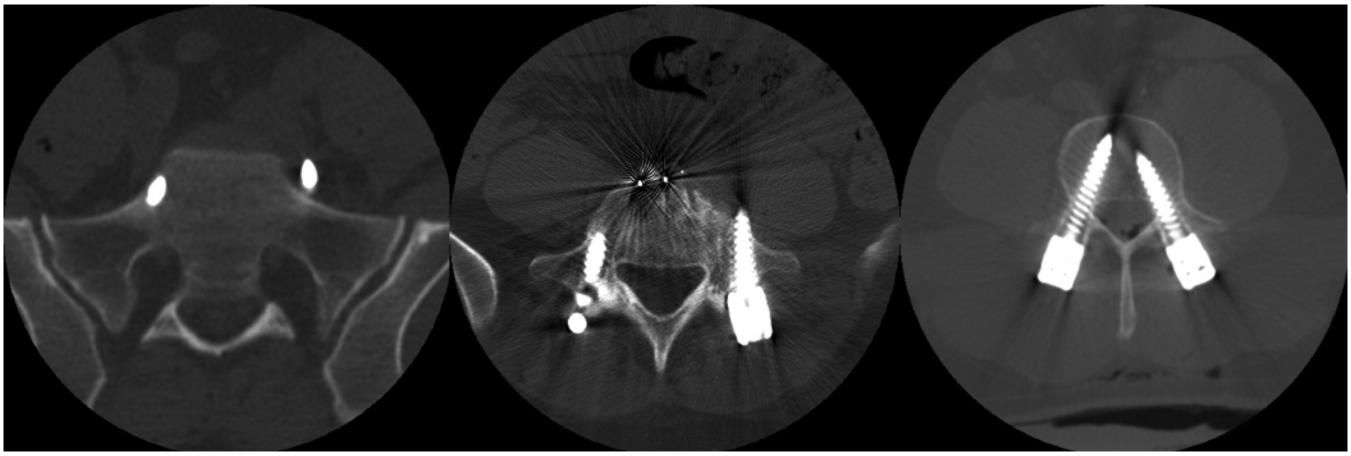

Fig. 1. Postoperative CT scans showing 2 screws (at S-1 in Case 9 and L-5 in Case 17) judged to have lateral screw placement and 1 screw (at L-4 in Case 24) with medial placement. These were clinically asymptomatic, and in none of these cases did the patient return to the operating room for screw revision.

The start date corresponded to the first minimal-access TLIF performed by the resident during his postgraduate Year 5. The resident had experience with pedicle screw placement and open TLIFs. The minimal-access TLIF was performed using a tubular retractor system (Quadrant, Medtronic) inserted via a muscle-dilating exposure to limit approach-related morbidity. Neuromonitoring was used in each case. In all cases, the resident worked on one side of the patient while the attending worked on the other side. The resident accessed the disc space and placed all screws and rods on his respective side. The disc space was identified after removing the superior aspect of the superior facet, making the superior aspect of the inferior pedicle flush with the disc space. The exiting nerve root and surrounding soft tissue were retracted superiorly from the inferior pedicle allowing for clear visualization of the disc. Pedicle screws were placed using direct visualization of the bony landmarks, specifically by identifying the junction of the pars and transverse process as well as the mammillary process when present. Placement was intraoperatively confirmed with fluoroscopy and pedicle screw stimulation. Each case was evaluated for the accuracy of screw placement and the operative time. The latter was obtained by reviewing our institution's computerized scheduling system in which the circulating nurse records the operative start and end times. The start time corresponded with skin incision, and the end time with incision closure. The accuracy of screw placement was judged according to the postoperative CT scans reviewed by the resident, attending, and a third independent observer. If the screw was not entirely contained within the pedicle, then it was considered to be out.

Results

Twenty-eight minimal-access TLIF cases that met the inclusion criteria were identified. There were 22 men and 6 women in the study with an average age of 42.7 years (range 18–80 years). The majority of the procedures were performed for degenerative disc disease. The resident placed 65 pedicle screws by using the featured approach. One screw was placed at L-2, 2 at L-3, 18 at L-4, 27 at L-5, and 17 at S-1. Procedures were performed at L2–3 (1 case), L3–4 (1 case), L4–5 (9 cases), L5–S1 (9 cases), and L4–S1 (8 cases).

In a review of the postoperative CT scans, pedicle screw placement accuracy was determined to be 95.4%, with 62 of the 65 pedicle screws placed entirely within the pedicle with an appropriate trajectory. Two screws (at L-5 in Case 17 and at S-1 in Case 9) were judged to be lateral, whereas 1 screw (at L-4 in Case 24) was medial (Fig. 1). There was no significant difference in pedicle screw accuracy between the first half of the patients compared with the second. Of the 33 pedicle screws placed in the first 14 patients, 32 (97%) were considered accurate, compared with 30 of 32 pedicle screws (93.8%) placed in the second group of 14 patients. None of the patients involved with pedicle breaches had postoperative deficits or symptoms related to screw placement, and none returned to the operating room for a revision.

In evaluating operative times, 2 cases with Grade III spondylolisthesis were excluded. The average operating time per level in the remaining 26 cases was 113.25 minutes. The average time per level for the first 13 cases was 121.2 minutes. This time decreased to 105.3 minutes for the second group of 13 cases ($p = 0.25$). The learning curve, based on operative time, was approximately 15 cases for this procedure (Fig. 2). The trend in increasing times toward the end of the study group was believed to be caused by the authors' use of this procedure for more advanced cases, as evident by the cases excluded in evaluating the operative times.

There were no intraoperative CSF leaks during the study period. Postoperatively, there was no new radiculopathy or weakness.

Discussion

Despite the fact that the current structure for neurosurgical postgraduate education has been around for decades, there is very little in the neurosurgery literature in regard to how a resident becomes competent and proficient at a particular procedure. While proficiency has

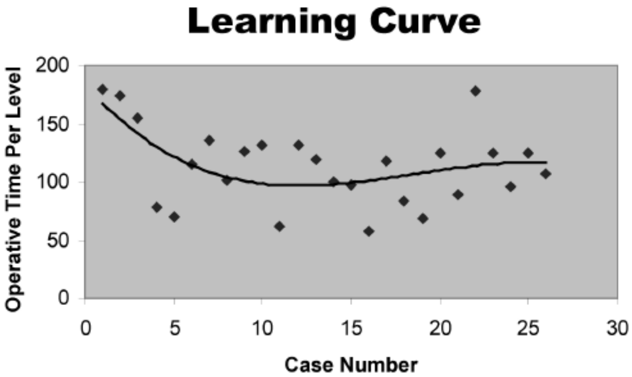

FIG. 2. Graph of the learning curve based on operative time per level. The level was approximately 15 cases. The trend in increasing times toward the end of the study group was believed to be due to more advanced cases.

always been important, it is particularly so now given that work-hour restrictions push residencies to become learning efficient. There is little doubt that an experienced surgeon tends to have shorter operating times and fewer complications. Such was the case in the study by Wiese et al.[19] in which the authors found that the operative time was significantly shorter and the complication rate was significantly lower for an experienced surgeon compared with these measures for an inexperienced group performing lumbar microdiscectomies. This finding raises the question of when a trainee becomes experienced enough with a procedure so that he or she is competent. We believe that by constructing a learning curve, better insight into an individual's educational progress can be gained.

Applying the concept of a learning curve to medical and surgical education is not new, but its formal application is infrequent. Ramsay et al.[16] conducted a study in which they searched the medical literature to ascertain how learning curves are evaluated. In searching multiple databases, they found 4571 abstracts that contained the phrase "learning curve." Among the studies represented by these abstracts, only 272 (6%) had evaluated the learning curve through statistical methods. Authors often rely on anecdotal evidence and descriptive terms such as "steep" or "long" instead of scientific evaluation.[4,10]

Several articles in the literature address the learning curve associated with spinal procedures. In 2005 Nowitzke[14] evaluated the first 35 microendoscopic discectomies performed for lumbar radiculopathy. Surgical time, conversion to an open procedure, complication rates, and surgeon comfort were taken into account. The author concluded that it takes approximately 30 cases to become proficient with the procedure. In a similar paper, McLoughlin and Fourney[13] looked at a single surgeon's experience with the first 52 consecutively performed minimally invasive microdiscectomies using a tubular retractor system. Using mainly operative time to analyze their learning curve, these authors concluded that after approximately 15 cases, a steady state was reached. These studies are similar to our work in that the authors evaluated the learning curve of adapting a minimally invasive technique to a procedure they had previously performed by an open surgical method. Our study differs in that it is focused on a resident's learning curve instead of an attending surgeon's.

Some authors believe that operative time is not a good means of evaluating a surgeon's learning curve and that other factors should be more heavily weighted. Chen et al.[3] analyzed 287 consecutive laparoscopic colorectal resections and found that operative times did not decrease over time. In fact, the surgeon with the shorter operative times had higher complication and readmission rates. Chen and colleagues concluded that learning curves for laparoscopic colorectal surgery should be based on complication and readmission rates as opposed to operative times and conversion rates. If the goal is to determine how many cases it takes a surgeon to learn how to perform a procedure proficiently as well as safely, then the authors' point is well taken in that multiple factors, not just operative times, should be considered. Evaluating complications, readmissions, patient satisfaction, and long-term outcome is crucial in obtaining a true understanding of when a surgeon has truly mastered the procedure. Speed in the operating room does not always correlate with successful patient outcomes.

The other end point in this study was pedicle screw accuracy. In comparing our results with those in the literature, we noted that a 95.4% accuracy rate is at or above the rate reported in most series.[7,12,17] In 2005 Kosmopoulos and Schizas[11] published a meta-analysis of the literature on pedicle screw placement. Subgroup analysis revealed 7 studies that evaluated in vivo placement of lumbar pedicle screws without the aid of navigation. Among the 1674 pedicle screws described in these studies, the mean placement accuracy rate was 87.3% with a range of 60–97.5%. The weakness in comparing our accuracy rate with that in this meta-analysis is the lack of consistency in how accuracy is defined.

Conclusions

Learning to perform a minimal-access TLIF can be done safely in a training environment without a significant complication rate. Pedicle screw placement accuracy was not diminished in learning the new approach. In this study, it took approximately 15 cases for the learning curve to plateau based on operative times. While we have yet to apply learning curves for all resident cases, we believe, based on these results, that this relatively straightforward measurement can be easily applied to track resident progress for core training cases. Because of the nuances of each training program, learning curves should be individualized to the institution with which they are associated. For future studies, we are currently planning to compare larger numbers of trainees at different experience levels and to assess long-term outcome and the affect the learning curve has on it.

Disclosure

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

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the US Army, US Navy, or US Department of Defense.

Author contributions to the study and manuscript preparation include the following. Conception and design: both authors. Acquisition of data: CJ Neal. Analysis and interpretation of data: both authors. Drafting the article: both authors. Critically revising the article: both authors. Reviewed final version of the manuscript and approved it for submission: MK Rosner. Statistical analysis: CJ Neal.

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Address correspondence to: Chris J. Neal, M.D., National Naval Medical Center, 8901 Rockville Pike, Bethesda, Maryland 20889. email: chrisjneal@verizon.net.

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Combat surgeons before, during, and after war: the legacy of Loyal Davis

Jeremy W. Cannon, M.D., S.M.,[1] and Richard J. Teff, M.D.[2]

[1]Department of Surgery, Wilford Hall Medical Center; and [2]Division of Neurosurgery, Brooke Army Medical Center, San Antonio, Texas

By 1942, Loyal Davis had firmly established himself as a preeminent civilian neurosurgeon. With military operations rapidly escalating, he was recruited to serve in the European Theater of Operations as a consultant to the Surgeon General. Davis brought tremendous experience, insight, and leadership to this position; however, he found the military system in which he was suddenly immersed inefficient and impassive. His requests for even basic equipment became mired in endless bureaucracy even as his communiqués to the Chief Surgeon in the European Theater and to the Surgeon General's staff in Washington seemed to fall short of their intended recipients. Then, when he attempted to vent his frustrations to his academic colleagues, he was nearly court-martialed. Notwithstanding, Davis became the first to formally recognize high-altitude frostbite and also developed protective headgear for airmen, and later in his service, he joined a contingent of senior medical leaders who visited the Soviet Union to study their system of combat casualty care. Subsequent to his service on active duty, Davis returned to his academic practice at Northwestern where he used his position as editor of *Surgery, Gynecology, and Obstetrics* to advocate for change within the military medical corps. Others like Davis have contributed greatly to the advancement of combat casualty care both during active service and long after their time in uniform. This paper examines the lessons from Davis's experiences as a military neurosurgeon and his continued advocacy for change in the medical corps along with additional recent examples of change effected by former military surgeons. For those currently serving, these lessons illustrate the value of contributing wherever a need is recognized, and for those who have served in the past, they demonstrate the importance of having a continued voice with junior combat surgeons and the military leadership.
(DOI: 10.3171/2010.2.FOCUS1024)

Key Words • **Loyal Davis** • **military neurosurgery** • **combat casualty care** • **surgical consultant** • **lessons learned**

With few exceptions, injuries to airmen, infantrymen, and sailors are similar surgically and are treated in the same way. Why should there not be a medical corps for the armed services, instead of three separate organizations with duplication of hospitals, supplies, and personnel? The only reason, it seemed to me, was the selfish desires of men to establish their own empires.

Loyal Davis

Surgeons deployed to a combat zone face numerous unique challenges. The work environment represents perhaps the greatest stressor—facing the frequent influx of new casualties often with extreme injuries in the setting of a completely new surgical practice consisting of inexperienced support staff and equipment that is likely to have been selected by a supply officer. Add to this the challenge of ordering replacement supplies through a logistics chain designed to deliver tanks and mortars to the front lines, and you can begin to appreciate the mindset of Loyal Davis in his service as a combat consultant in neurosurgery during World War II.

All biographical accounts of this great surgeon note the important contributions he made in the areas of frostbite care and protective headgear as well as his survey of the Soviet military medical system. These contributions were unfortunately colored by the extreme frustration he experienced working within the monolithic bureaucracy of the Army. This frustration notwithstanding, Davis continued his efforts to improve combat casualty care even after he hung up his uniform, by using his influence as a prominent academic surgeon. Although over 65 years have passed since Davis's service, his military experience and contributions to combat casualty care hold valuable lessons for modern combat surgeons. This article details the experiences that shaped Davis prior to and during his service as a combat consultant and then discusses his postdeployment contributions and their relevance to combat casualty care today. Recent examples of similar contributions by combat surgeons are also discussed along with applications for surgeons in today's military.

Abbreviations used in this paper: ACS = American College of Surgeons; JTTS = Joint Theater Trauma System; MEDCOM = US Army Medical Command; SOS = Services of Supply; USCENTCOM = US Central Command.

Academic Career

Many biographical works have expertly chronicled the remarkable career of Loyal Davis, including an entire issue (Volume 157, 1983) of *Surgery, Gynecology, and Obstetrics* (now *Journal of the American College of Surgeons*), which honored the long-time editor upon his death. The son of a railroad engineer from a small town in Illinois, Davis graduated from Northwestern University Medical School in 1918 even as the US involvement in the Great War was escalating. Following graduation, Davis undertook graduate studies in neuroanatomy that led to his being awarded the first doctor of philosophy degree from Northwestern University Medical School.[3] During this time, he was trained in surgery by Alan B. Kanavel who famously described the physical signs associated with flexor tenosynovitis. Kanavel had come to Northwestern in 1908 and was the chief of the Division of Surgery. He had arranged Davis's graduate work in neuroscience and encouraged his young protégé to undertake further clinical training under Harvey Cushing. So, in 1923, Davis traveled to Boston where he worked as an associate to Cushing both observing and assisting on a number of neurosurgical procedures. Cushing had served in World War I as a volunteer surgeon, as the director of Base Hospital No. 5, and as the senior consultant in neurosurgery to the American Expeditionary Force,[19] and he ran his neurosurgical service at the Peter Bent Brigham with military discipline. Cushing's pursuit of excellence in every endeavor profoundly influenced Davis who emulated "the big boy" in many respects throughout his surgical career.[12]

Upon his return to Chicago, Davis established the first neurosurgical service in the city and organized a formal department of surgery at Northwestern of which he became the chairman in 1932. During this time, Davis was appointed associate editor of *Surgery, Gynecology, and Obstetrics* by his mentor Kanavel. He then rose to editor-in-chief in 1938, a position he held until 1982.[29] During this time, he authored *Principles of Neurological Surgery* and maintained an active research laboratory in partnership with his colleague Lewis Pollock. Despite these numerous clinical and administrative responsibilities, Davis faithfully taught the Northwestern medical students and mentored numerous young surgeons, many of whom served in the 12th General Hospital based first in North Africa and then in Italy during World War II.[25]

In the European Theater of Operations

On July 5, 1942, Davis met with the chief surgical consultant to the Surgeon General, Fred W. Rankin, who recruited him to join the staff of expert consultants in the European Theater. On August 20, Davis was commissioned a lieutenant colonel in the US Army (Fig. 1), and on September 6, he joined the staff of medical consultants in Cheltenham, England, with other prominent figures in American surgery including the chief consultant in surgery, Elliott Cutler. Like the other consultants recently commissioned from civilian practice, Davis was given no clear direction but rather defined his own role.

Fig. 1. Lieutenant Colonel Loyal Davis, M.D., in his dress uniform. Courtesy of the Galter Health Sciences Library, Special Collections, Northwestern University, Chicago, Illinois.

He felt compelled to mentor junior surgeons who had been tasked with caring for neurosurgical injuries and to survey the state of combat casualty care.[7]

During the first 3 months of his service, Davis made a series of recommendations regarding hospital staffing and the need for critical equipment in the general hospitals including suction devices for the operating rooms. None of these recommendations seemed to reach the chief surgeon, Paul Hawley, who worked for the Services of Supply (SOS) and could effect such changes. Instead, Davis's recommendations "were passed back and forth or conveniently filed by a personally hostile medical officer who openly boasted that he would put the new lieutenant colonel specialist consultants in their place."[7] In a series of events reminiscent of Joseph Heller's *Catch 22*, Davis compiled his memoranda from the previous 3 months and addressed them to General Fred Rankin in Washington DC; J. Roscoe Miller, dean of Northwestern University Medical School and later president of the university; and Howard Naffziger, chairman of the Department of Neurological Surgery at the University of California, who had a close relationship with the National Research Council (R. Davis, personal communication, 2010). These packages were intercepted by censors who charged Davis with attempting to circumvent the channels of military communication and with violating the rules that allowed him to censor his own mail. He was notified of his imminent

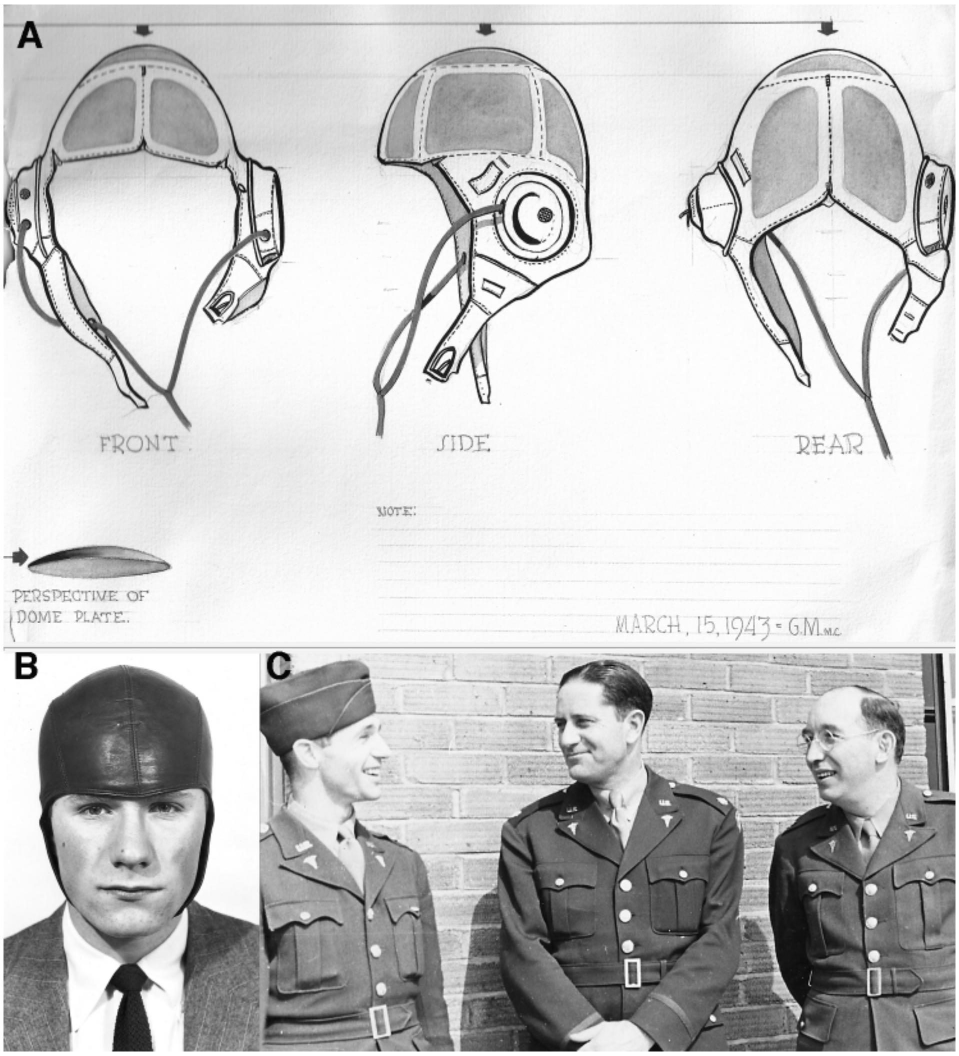

Fig. 2. **A:** Original drawings of the protective aviation helmet designed by Loyal Davis. **B:** Photograph showing that the helmet that resulted from Davis's tests was form fitting and low-profile even with the plates in place. **C:** Photograph of Davis and colleagues in front of the Oxford University ballistics laboratory where testing on the protective plates was conducted. From left to right: Lt Meredith Dickinson, M.D., Lt Col Loyal Davis, M.D., and Maj John Scarff, M.D. (staff neurosurgeon, Columbia University). Courtesy Richard A. Davis, M.D.

court-martial on Christmas Eve, 1942. Ironically, these charges resulted in a short-order face-to-face meeting with Chief Surgeon Hawley, in which Davis was assured that a court-martial would not be convened.[7] Hawley ultimately implemented changes within his staff that subsequently permitted more effective communication with his consultants, and Davis went on to make important contributions in the diagnosis and management of frostbite injuries in aircrew members and in the development of protective headgear for aviators.

Frostbite and Aircrew Helmets

At the time, frostbite was a well-known medical scourge among ground troops. However, frostbite had never been identified as an injury to which aircrews were vulnerable. Davis was one of the first to pick up on this novel mechanism of injury by taking the time to carefully interview one aircrew member whose hands initially were thought to have been blistered from a cabin fire.[7] In fact, on further questioning, this crewman related that he had not been burned when his aircraft crashed. Prior to the crash, he had actually taken off one of his electrically warmed gloves to relieve himself at altitude, and his hand was almost instantly frozen.

After describing this injury mechanism, Davis began to carefully document a number of similar cases. He also began to question the standard treatment for these injuries. At the time, frostbite was treated either by rubbing the extremity with ice or snow as originally advocated by the French surgeon Baron Lerray[21] or by other means of continued cooling including placing the affected extremity in a CO_2 "therapeutic refrigerator."[17] Davis postulated that warming the affected extremity to room temperature was a superior approach. To clarify this controversial issue, he devised a case-control study to evaluate these

Fig. 3. Mission to the Soviet Union, 1943. **Front row** (left to right): Lieutenant Colonel Loyal Davis, Mr. Ernest Rock Carling, Surgeon Rear Admiral Gordon Gordon-Taylor, Dr. Wilder Penfield. **Back row** (left to right): Mr. Reginald Watson-Jones, Maj Gen D. C. Monro, Col Elliott Cutler. This photograph was published in **Surgery, Gynecology, and Obstetrics, 157**, Davis RA, A surgeon at war, 147–159, copyright Elsevier (1983). Reprinted with permission.

disparate treatment approaches, and in fact, one of his patients even served as his own control given his bilateral, symmetric injuries. His results showed that patients treated with passive warming to room temperature had less pain and subsequent tissue loss than those treated with the widely accepted approach of continued cooling.[10]

Davis's findings ultimately shifted the therapeutic paradigm from cooling to rewarming, which ultimately gave way to rapid, active warming based on further work by Fuhrman[14] and others.[22] Interestingly, peoples of the Himalaya had been treating frostbite with active rewarming for many years despite the efforts of Westerners to discourage this practice.[18] When Davis attempted to alert the Army Air Corps to this injury mechanism and his recommended treatment, he met resistance. Malcom Grow adamantly denied the possibility of this problem when Davis presented his results, but Grow ultimately acknowledged this problem and even claimed to have discovered the entity.[10]

Davis also worked to protect aircrew members from head injury amid a maelstrom of political infighting. Davis was inspired by the story of a resourceful copilot who donned his steel Army-issue helmet over his leather flying helmet for a particular mission.[6] During the mission, a shell detonated in the cockpit. The pilot, who was wearing his lightweight leather helmet, suffered a severe penetrating head injury resulting in left hemiplegia and a homonomous hemianopsia, while the copilot with the bulky steel outer shell survived uninjured. Davis subsequently analyzed data that had been collected on aircrew injuries and found that 12% of injures were to the head and that the most frequent cause of head injury to airmen was from the type of exploding shell described above. With this motivation in hand, Davis worked with the staff of the Oxford University ballistics laboratory to identify a substance with which to make a helmet liner that would be lightweight and comfortable, allow for a full range of motion, and afford protection from exploding munitions. The results of these tests showed a 4-mm sheet of methyl methacrylate to be an optimal helmet liner when molded around a model skull and inserted within the standard issue leather aviator's helmet (Fig. 2).[6,7]

Although, his helmet design offered a sensible solution to this important problem, Davis faced dogged resistance to its implementation. Concurrent with the work of Davis, Malcom Grow had commissioned a British armorer to develop a protective suit of metal for use by the aircrews, having rejected Davis's plastic liner on the grounds that it was inadequate. When the suit was presented to the aircrews, they reportedly objected vehemently, suggesting that General Grow be required to bail out over the North Sea in the suit himself.[7] In a series of presentations made to the Surgeon General of the Army, Norman Kirk, and his staff in the fall of 1943, Davis was ultimately able to gain the support he required to care for both high-altitude frostbite injuries and to further develop protective helmets for aircrew members.

Mission to the Soviet Union

In June 1943, Davis embarked on a mission to the Soviet Union with Elliott Cutler, Wilder Penfield, and 4 British professors of surgery (Fig. 3).[11] The mission objective was to study the Soviet system of combat casualty care to glean information about important advances that could be applied in our own military hospitals. At the time, there was a general feeling of trust and camaraderie toward our Soviet allies, who were perceived as practicing highly advanced surgical care, and the mission members were eager to observe first-hand the management of the numerous casualties on the eastern front. The mission found that in contrast to popular opinion, with regard to neurosurgery, the techniques used by the Soviets were from World War I and that Soviet researchers at the Institute for Neurological Surgery had likely fabricated overly optimistic clinical results on formalin-fixed nerve grafts for peripheral nerve injuries. In his report on the activities of the consultants, Davis frankly observed that their Soviet hosts "appeared to be like 10-year-old American boys who brag about the size of their houses and chimneys and recklessly claim that their fathers can lick anyone."[7]

On a more positive note, Davis commented that "when organization alone was considered, the Soviet plans were efficient and superior."[7] In the Red Army, the Surgeon General answered directly to the People's Commissariat for Defense and the chief of staff of the Army without any intermediaries. Within this system, the Surgeon General was made aware of each planned combat operation and could theoretically prepare for the medical requirements with the authority and resources at his disposal to make such preparations.[9] Davis later admonished the American military medical corps to adopt a similar streamlined structure in a thinly veiled commentary on the bureaucratic quagmire all of his previous recommendations had encountered.[8]

For his faithful service and remarkable contributions to the care of injured soldiers, Davis was awarded the Legion of Merit.[11] In the spring of 1944, Davis returned to his position as chairman of the Department of Surgery at Northwestern, and in the ensuing years, he became widely recognized as one of the most important figures in American surgery. He held the presidency of the American Surgical Association (1957) and the American College of Surgeons (1962–63), served as Chairman of the Board of Regents of the American College of Surgeons (1960), and was a founding member of the American Board of Surgery and the American Board of Neurosurgery. In fact, in the introductory remarks of the special issue of *Surgery, Gynecology, and Obstetrics* dedicated to his life, Davis was labeled the "20th Century American Crown Prince of Surgery."[29]

Encore Recommendations in the Civilian Medical Literature

In his position as editor of *Surgery, Gynecology, and Obstetrics*, Davis was in a unique position to make ongoing contributions to the Medical Department of the Army following his active-duty service. In this capacity, Davis chose to comment on what he perceived as the root cause of the many difficulties he faced during his service: the organizational complexities and inefficiencies in the US Army Medical Corps. In a series of 2 editorials aimed at addressing this problem,[8,9] Davis marveled that "the Medical Department of the United States Army performed its tasks in an outstanding manner in this War against almost insuperable difficulties, handicaps, and obstacles which were placed in its way by a complex organization."[8]

In stark contrast to the vertical command structure of the Red Army medical organization, the US Army Medical Corps was burdened by decentralized inefficiency. Since 1918, the US Army chief surgeon was headquartered in the SOS and served essentially as an advisor to the field general, who ultimately "owned" all medical assets. Davis charged an apathetic cadre of civilian surgeons after World War I as partly responsible for the persistence of this convoluted, decentralized organization: "They universally recognized the errors in organization of the Medical Department committed in World War I, but upon their return home they were anxious to forget the tribulations of war and eager to resume their professional lives."[9] Furthermore, the national academic surgical organizations "made no attempt to learn of the problems and plans of the Medical Department in case of war. . . ."[9] Consequently, "… any criticism of … the Medical Department … should not be directed at the Surgeon General of the U.S. Army or his staff. The fault lies in the fundamental anomalous relation of his office to the General Staff and the Army as a whole, which can be corrected only by the War Department."[9]

Davis advocated a structure in which the Surgeon General has the ultimate control over all matters related to combat casualty care, with a close, direct relationship with the chief of staff of the Army. Nearly 50 years later, Army medicine underwent a series of reorganizations that nearly approximated this structure. In October 1994, the US Army Medical Command (MEDCOM) was officially established under the leadership of the Surgeon General of the Army.[2] This unprecedented unification gave ultimate command authority over all nondeployed Army medical assets to the Surgeon General, who is supervised by the chief of staff of the Army and is responsible to the Secretary of the Army.[1] Lieutenant General Eric B. Schoomaker, M.D., Ph.D., became the fifth MEDCOM commander on December 13, 2007.

Although this structure is significantly streamlined relative to the command structure against which Davis railed, the MEDCOM commander does not control deployed medical assets. This authority still rests with the line of the Army. In the case of Operation Iraqi Freedom and Operation Enduring Freedom, the US Central Command (USCENTCOM) commander, General David Petraeus, controls all medical personnel, facilities, equipment, and supplies. Among medical officers, the highest ranking are the colonels serving as hospital commanders who in every instance report to their respective nonmedical base commander.

Although the line still officially controls deployed medical personnel, equipment, and supplies, medical care and practice policy is established by a new program, the Joint Theater Trauma System (JTTS). The JTTS was created with the support of the Surgeons General of the Armed Forces, USCENTCOM, the Army Institute of Surgical Research, and the ACS Committee on Trauma with the stated mission of getting "the right patient to the right place at the right time."[13] This system is led by an in-theater senior trauma surgeon similar to the consultants of Davis's era. This individual and a small support staff visit the various medical facilities in theater with the goal of disseminating the best current practices of combat casualty care. Simultaneously, the stateside JTTS director develops clinical practice guidelines, which attempt to standardize in-theater medical care using the current best practice. Within this system, one author (R.J.T.) was able to directly impact the training of forward surgeons by teaching them to perform emergency, life-saving neurosurgical procedures under austere conditions. However, even with the JTTS, implementing lasting policy changes, obtaining essential equipment, and changing staffing levels as the tactical situation changes still present challenges and frustrations reminiscent of Davis's experiences.

The Importance of a Continued Voice

Like Davis in the editorials he authored following his active-duty service, others have made important encore contributions that have changed our combat casualty care for the better by shining a spotlight on the underbelly of the military system. Although in Loyal Davis's day an undertone of antipathy existed between the so-called regular Army Medical Corps and the newly minted lieutenant colonel and colonel consultants,[7,11] there is little room for such pretension in today's military. The vast majority of active-duty surgeons begin their military service directly upon completing residency training and have relatively short commitments, resulting in a significant number of junior surgeons[4] who turn over frequently (Ragel BT, Sholes AH, Taggard DA, Liu JM, Klimo P Jr: Effect of surgeon turnover and deployments on neurosurgical case volume at a military hospital. Paper presented at the 58th Annual Congress of Neurological Surgeons. Orlando, Florida, September 20–25, 2009). In addition, with the current operations tempo, many of these surgeons deploy for the first time shortly after entering their first staff position. As a result, the active-duty surgeons in today's military are generally receptive to the potential contributions and invaluable mentorship that more senior surgeons with combat and civilian trauma experience can provide.[4] Several recent examples of such contributions bear discussion.

The first example of an essential contribution by a former active-duty surgeon is the scathing article by Dr. Donald Trunkey after the Gulf War titled "Lessons Learned."[26] In many ways, the medical response during Desert Storm was a shambles. The myriad problems with patient movement, hospital facilities, and predeployment training were detailed in a series of retrospective reports by the General Accounting Office.[5,15,16] Trunkey was activated from the reserves while he was chairman of the Department of Surgery at the Oregon Health & Science University to serve on the staff of the 50th General Hospital during Desert Storm. In his critique of this combat experience, he corroborated the General Accounting Office findings that physician rosters were unfilled, supplies inadequate, patient transport challenges unanticipated, and the medical command and control suboptimal. Furthermore, he confirmed that medical research had not been allowed to be conducted in theater by the command.[26] Trunkey implicated a lack of high-ranking medical officials within the command structure and advocated for a general officer with bona-fide medical experience in theater as capable of addressing both the patient evacuation issues and the absence of research teams. To keep active-duty surgeons and other medical staff current in our military hospitals, he advocated for the establishment of active-duty trauma centers that would accept and care for civilian trauma victims. He also suggested that by forming reserve medical units with a mix of academic and community staff affiliated with academic trauma centers, deployment taskings could be filled with qualified personnel without severely compromising the entire hospital staff during a deployment. In closing, like Davis, Trunkey admonished "representatives from military medicine and the American College of Surgeons" to "jointly devise trauma training programs that would benefit both the civilian and military community."[26]

Subsequent to the publication of Trunkey's article, a number of changes were implemented largely from a grass-roots effort to address these shortcomings, and these changes are largely responsible for the great successes of our current system of combat casualty care.[13,23,27] Predeployment training for surgeons, nurses, and medics is now conducted in collaboration with civilian trauma centers; in-theater transport routes have been dramatically simplified; subspecialty surgical requirements are clearly defined and filled by experienced surgeons; patient care guidelines are established by a consensus of experts and broadly disseminated; civilian consultant surgeons have been called upon to review our process of care; and surgical research teams are now actively engaged in collecting data in the field. To further validate these improvements, the ACS Committee on Trauma recently conducted a site visit to the Landstuhl Regional Medical Center. Led by Trunkey and other senior civilian surgeons, this verification review resulted in Landstuhl Regional Medical Center being granted status as the first ACS Level 2 trauma center outside the US.[20]

Many additional examples of such contributions exist. Norman Rich's establishment of the combat vascular registry in Vietnam,[24] and his continued service to the Surgical Department of the Uniformed Services University of the Health Sciences has directly saved innumerable lives and inspired a generation of military vascular surgeons. Gerald Grant's work in traumatic brain injury that began in the Air Force Theater Hospital in Balad, Iraq,[28] now continues in the Department of Neurosurgery at Duke University and promises to better the lives of numerous combat casualty victims. One author (R.J.T.) served for an entire year in Iraq and has since joined the faculty as a civilian surgeon at Brooke Army Medical Center, which will soon be renamed the San Antonio Military Medical Center as it merges with Wilford Hall Medical Center to become the largest military treatment facility and the only Level 1 trauma center in the Department of Defense.

Conclusions

Loyal Davis left his academic post for nearly 2 years to serve in the US Army, during which time he made landmark contributions in the recognition and prevention of frostbite and head injuries among airmen. He struggled mightily with the inefficiencies he faced in attempting to implement change; however, his contributions were ultimately recognized and acted upon. Furthermore, he used his significant influence as a prominent academic surgeon to suggest changes in the military medical structure that have been recently implemented.

Surgeons from modern conflicts have also contributed significantly to the current practice of combat casualty care both in uniform and after their entry or reentry into civilian practice. The insights of these surgeons have proven invaluable in elevating the quality of our combat casualty care and in creating a safe and efficient system of care. Nonetheless, our military system of care remains extraordinarily complex. Within this system, frustrations still arise, and lessons learned have been and will again be forgotten to the detriment of our fellow men and women in uniform. For this reason, there will always be room for those in the mold of Davis who observe and act on opportunities to improve our system of care and who remember long after their active service that, as the French diplomat Clemenceau once said, "War is too serious a matter to entrust to military men."

Disclosure

The opinions contained in this article are solely the authors' private ones and are not to be construed as official or reflecting the views of the United States Air Force, the United States Army, or the Department of Defense.

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Address correspondence to: Jeremy W. Cannon, 202 Furr Drive, San Antonio, Texas 78201. email: jcannon@massmed.org.

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

Pankaj K. Agarwalla, M.St.,[1] Gavin P. Dunn, M.D., Ph.D.,[1] and Edward R. Laws, M.D.[2]

[1]Department of Neurosurgery, Massachusetts General Hospital; and [2]Department of Neurosurgery, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts

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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Key Words • **military** • **traumatic brain injury** • **neurosurgical history** • **projectile injury**

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[22] 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[22] 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 deeply 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.[74] 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.[21] In the 1890s, he performed original experiments using clay and animal models to explore the forces from bullets.[47] In his clay model of the brain, he fired bullets of different caliber at a range of velocities into clay of various states of hydration. He demonstrated that velocity and cavity formation were an important factor in tissue damage from projectiles.[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.[50] In his article in the journal *Nature*, Horsley stated, "The medulla oblongata is thus subjected to pressure from two sources: (I) the hydrodyamic displacement of the brain *en masse*; (2) the direct crushing effect due to the movement of the cerebrospinal fluid in the ventricles."[47] 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.[47,50] Almost instantly after the respiratory failure, however, fatal hemorrhage was of serious concern.[47] 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.[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.[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.[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.[39] 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%).[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."[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%.[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.[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.[31] 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.[38] 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.[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.[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."[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.[40] 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.[26] 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 condolence 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;"[4] 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."[4]

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.[3] 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.[3] 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.[3]

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,[70] 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[10] 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.[10,11] Haynes'[42] 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.[42] Slemon[71] 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[14] 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.[14] 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."[14] 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[62] 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[32] 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.[68] The first mobile unit was commanded by Peter Ascroft in North Africa.[68] Ascroft,[4] 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.[4] 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.[4] 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.[25,68] Eden[25] 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.[25] Once again, however, Eden echoed previous experience that "the initial operation should be the final and complete one."[25] 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.[25] Nevertheless, his infection rates were reduced from the previous benchmark of about 25% to 5%, with approximately 90% of wounds healing by primary intention.[25] 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[69] 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[29] and Gaynor and Gurwitz[32] in forward hospitals highlighted the importance of timing in addition to adequacy of wound debridement. Grunnagle[35] 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[55] wrote about an early series of 11 patients treated for penetrating head wounds who suffered from hematomas 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[12] 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.[12] Finally, at this time, additional therapy with sulfadiazine was common to cover additional organisms. Abbott,[1] 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[65] 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.[77] 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.[27] confirmed the harmful effects of intrathecal penicillin. In terms of the actual bacteriological makeup of wounds, Campbell[14] noted that *Staphylococcus* was the causative organism for most infections, although Ecker's[23] 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,[4] 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[14] 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,[24] Finlayson,[29] Grunnagle,[35] and Gaynor and Gurwitz[32] all recommended primary dural closure, with a fascial graft if necessary. Shearburn and Mulford[70] 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[34] noted in his series from Burma. Of note, Small and Turner[72] 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. Shearburn and Mulford[70] documented drain placement with 79 patients receiving a drain and 43 without, although it is not clear whether they systematically chose some patients for drain placement, for example patients with signs/symptoms suggesting higher likelihood of infection. In their series, Schwartz and Roulhac[69] did not prefer to leave a drain because this could serve as a source of infection. Interestingly, Grunnagle[35] 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[43] 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 Cushing's series, Haynes[41] 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.[54] Cairns[13] 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 Russell's[67] 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[66] 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.[66] 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[66] 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 as to 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% had their first seizure between 2 and 5 years after injury.[66] 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,[1] 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.[1] Finlayson,[29] 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 Maltby[53] 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."[76] 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.[75] Whereas World War II saw the creation of mobile neurosurgical units, this system really came into its own in the Korean War.[58] The first mobile neurosurgical unit was established at Kumsong, 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.[75] 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%.[75] The incidence of meningocerebritis dropped to approximately 1%.[59] 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.[59] Meirowsky and Harsh[59] 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.[59] In terms of studying infections, Wannamaker and Pulaski[80] 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[78] 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 corticomeningeal scar formation."

Surgical advances also occurred in the management of hematomas following injury, as Barnett and Meirowsky[5] 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.[5] 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.[5]

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.[57] 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.[75] Additionally, Wannamaker[79] 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.[75]

Postoperative Sequelae

In Lewin and Gibson's series[51] 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,[75,76] 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.

Legacy of the Korean War

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 transfusions 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 indriven 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 forceful 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."[75] 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. Hammon[36] 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 debridement, 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. Furthermore, 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 intracerebral 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. Hammon[37] studied 42 patients with retained intracranial bone fragments who were brought to Walter Reed Army Medical Center; of these, 40 patients required further debridement, with 8 in-hospital deaths. The surviving patients underwent courses of debridement and antibiotics. With regard to the safety of secondary operations, both the series by Hammon[37] and further work by Meirowsky[56] 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 War[63] demonstrated a high mortality (54%) and morbidity (82%) rate, although the overall incidence of this serious complication was only 3% from a study population of 1221. These findings supported previous treatment strategies of removing all indriven bone fragments to prevent recurrent infection or cerebral abscess.

Further advances from the Vietnam War included primary 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 fragments from blasts.[16] Even in operative technique, others had argued for a craniotomy technique over a craniectomy technique in certain selected cases for debridement.[64]

TABLE 1: Central issues in the management of intracranial projectile injuries*

Clinical Issue	Modern Management Principles
resuscitation	standard trauma resuscitative measures ideally at a designated trauma center;[54] fluid resuscitation with crystalloid-based fluid preferred;[65] GCS score after resuscitation highly predictive of outcome[51,77]
ICP monitoring	ICP monitoring is often used and can accurately predict negative outcomes[2,16]
craniotomy	aggressive, decompressive hemicraniectomy can improve intracranial hypertension
debridement	despite previous extensive debridements, modern studies demonstrate effectiveness of modern neuroimaging to identify symptomatic bone/missile fragments, and the effectiveness of a less extensive debridement than previously advocated, especially in civilian gunshot wounds;[3,9,67] removal of indriven fragments when accessible is recommended; standard antibiotic protocols are used until debridement is complete
closure	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
seizure	although not studied extensively in penetrating missile injury, phenytoin for 1 week after injury can reduce incidence of seizures[24,79]

* GCS = Glasgow Coma Scale.

Finally, Vietnam saw the culmination of the evacuation strategy advocated by Meirowsky, Campbell, and others.[49]

Summary

Following the previous survey of the historical development of neurosurgical contributions to the management of missile injuries, this section will focus on the current management of penetrating projectile injuries of the cerebrum. With the ongoing conflicts in Iraq and Afghanistan, this story is still being written. This discussion will emphasize newer work on the pathophysiology of these injuries as well as modern updates to their surgical treatment. Rather than be a stand-alone and in-depth discussion of our current practice, we hope that a review of a contemporary perspective on missile injury management shows this area to be one of neurosurgery's palimpsests, layered by the extensive experiences of neurosurgeons and their patients in the crucible of war.

Pathophysiology and Mechanism of Injury

Significant work has been conducted to examine the patholphysiology 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.[28,44] 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.[28,44] 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.[44] 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.[28] 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.[28] 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.[17] In fact, a clinical study[73] 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 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.[48] According to a review by Carey,[15] 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 colleagues[9] 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 Hammon[36,37] 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 Macleod[52] 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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Address correspondence to: Edward R. Laws, M.D., Department of Neurosurgery, Brigham and Women's Hospital, Harvard Medical School, 75 Francis Street, Boston, Massachusetts 02115. email: elaws@partners.org.

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The development of military medical care for peripheral nerve injuries during World War I

William Hanigan, M.D., Ph.D.

Department of Neurosurgery, University of Mississippi Medical Center, Jackson, Mississippi

Although the clinical and electrical diagnoses and treatments of peripheral nerve injuries (PNIs) had been described prior to World War I, many reports were fragmented and incomplete. Individual physicians' experiences were not extensive, and in 1914 the patient with a PNI remained a subject of medical curiosity, and was hardly a focus of comprehensive care.

World War I altered these conditions; casualties with septic wounds and PNIs swamped the general hospitals. By 1915, specialized hospitals or wards were developed to care for neurological injuries. In the United Kingdom, Sir Robert Jones developed the concept of Military Orthopedic Centres, with coordinated specialized care and rehabilitation. Military appointments of neurologists and electrotherapists sharpened clinical diagnoses and examinations. Surgical techniques were introduced, then discarded or accepted as surgeons developed skills to meet the new conditions. The US Surgeon General, William Gorgas, and his consultant in neurosurgery, Charles Frazier, went a step further, with the organization of a research laboratory as well as the establishment of a Peripheral Nerve Commission and Registry.

Despite these developments and good intentions, postwar follow-up for PNIs remained incomplete at best. Records were lost, personnel transferred, and patients discharged from the system. The lack of a standardized grading system seriously impaired the ability to record clinical changes and compare outcomes. Nevertheless, specialized treatment of a large number of PNIs during World War I established a foundation for comprehensive care that influenced military medical services in the next world war. *(DOI: 10.3171/2010.3.FOCUS103)*

Key Words • **peripheral nerve injury** • **World War I** • **military medical care**

The re-growth of a severed nerve is a romance. It is, perhaps the most beautiful example of Nature's power of repair, but it cannot be hastened by artificial means. It is a very delicate process, easily arrested or retarded: it follows certain natural laws, which take a long time to work out. After the surgeon has removed the obstacles, which forbid Nature to begin her beneficent work, all that he can do is stand on guard to see that nothing shall be allowed to interfere with Nature.

Sir Robert Jones[33]

Sir Robert Jones, a respected British orthopedic surgeon and beloved teacher, waxed eloquent about the peripheral nerve in 1918. By this time, the central role of PNIs to his concept of comprehensive management of war injuries was apparent to the casualty, medical officer, War Office, and government; in fact, all the stakeholders in military medicine. Complex historical issues of specialization, which were not readily apparent in earlier wartime medical organizations, were important elements of this expansion.[4,66,68,78] In this report I will outline the buildup of the sophisticated treatment of PNIs during World War I, even though these injuries seemed unlikely candidates for attention during a global war.[69]

The Unassuming Peripheral Nerve

Associated with the emerging specialty of neurology, a surprising number of elaborate investigations described the anatomy and clinical examinations of the peripheral nervous system during the 19th and early 20th centuries. Descriptions of the loss of motor power in muscles innervated by specific peripheral nerves were followed by various clinical reports of "trick" movements mimicking functional regeneration.[9,17,62,63] Detailed studies of sensory loss and recovery were explained by sophisticated theories of collateral innervation, nerve anastomosis, or nerve growth from healthy, adjacent areas.[9,25,26,56] Findings in studies of the fascicular structure of the peripheral nerve and of histological degeneration after PNI were confirmed by the introduction of the silver precipitation stain of Golgi and the methylene blue method of Ehrlich.[18,64] The monogenetic or downgrowth of nerve regeneration had been established by investigators such as G. Carl Huber,[29] who described the principle in simple terms:

Abbreviations used in this paper: AAMD = American Army Medical Department; PNI = peripheral nerve injury; UK = United Kingdom.

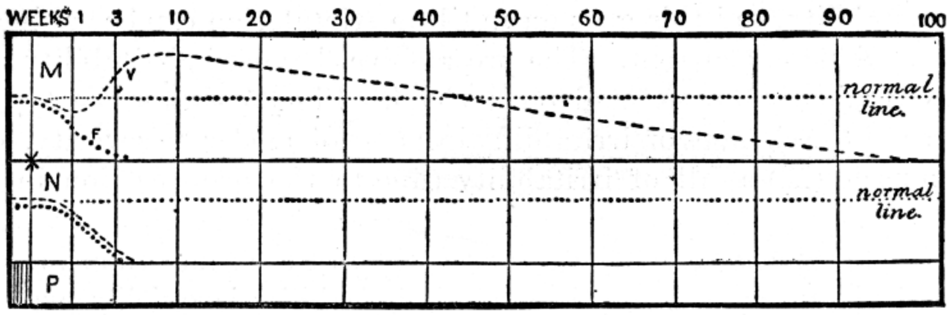

Fig. 1. Chart based on Wilhelm Erb's reaction of degeneration in a complete and permanent nerve lesion. The voluntary power (P) of the muscle is lost immediately. The nerve's (N) response to faradism (F) or galvanism is normal for approximately the 1st week, and then declines until absent by the 3rd week. The muscle (M) response to faradism is similar to the nerve, whereas its response to galvanic current (V) falls in the 1st week, rises to above normal for the next 37 weeks, and then slowly declines until absent by approximately 2 years after the lesion. (Reprinted from Gowers WR: **A Manual of Diseases of the Nervous System, ed 2.** Philadelphia: P. Blakiston's Son & Co, 1898, Vol 1, p 56 [Figure 36].)

> The regeneration of the peripheral end (which always degenerates so that only the old sheaths of Schwann containing a band of nucleated protoplasm, developed from the hyperthropied [*sic*] protoplasm and proliferated nuclei of its fibers, are met with) is the result of an outgrowth of new axis cylinders from undegenerated axes of the central stump, the budding axes following paths of least resistance.

The diagnostic use of electricity for PNIs and disease began with the development of the faradic induction coil (alternating intermittent, nonsymmetrical current) and the galvanic battery (continuous current in the same direction over a sustained period), and culminated with Wilhelm Erb's[10] textbook published in 1883.[18,74] Erb's points and charts for the reactions of degeneration were diagnostic standards in the early 20th century (Fig. 1). Electrotherapists, such as Herbert Tibbitts, who organized the West End Hospital for Diseases of the Nervous System on Welbeck Street in London, were associated with a new School of Massage and Electricity, and gained medical credibility.[72] The "nerve force" perhaps associated with electricity was still unsolved, but it was enough that the peripheral nerve and its connections could be accurately examined in health and disease, with a hint at rational therapy.

The development of surgical therapy for PNIs depended on the clinical advances during this time. According to Artico et al.,[1] attempts at repair probably began as early as 1596, and included Paget's description in 1847 of a successful primary suture of the median nerve, but remained stalled by concerns about sepsis, stricture, "neuritis," or convulsions. Primary suture was rare, and secondary exploration and suture were discouraged. Most closed injuries recovered on their own, and given the early description of nerve degeneration after injury, it did not make sense to attempt a suture that was doomed to failure.

The surgical revolution in the last half of the 19th century changed the indications for repair. Anesthesia, asepsis, better instruments, and the basic notion that the 2 ends of a cut nerve could be sutured allowed surgeons more creative leeway. Techniques proliferated as nerve ends were cut tangentially before suture, bound together, sutured to the skin or "á distance," and transplanted into noninjured nerves, either through slits in the epineurium or by partially dividing normal nerves and suturing one end to the distal stump. As described by Snyder,[75] Edward Létiévant in 1873 described an ingenious "double nerve flap" that looked much like a modern exit ramp for an expressway (Fig. 2). Other methods for bridging nerve gaps included various conduits or tubes fashioned using bones, arteries, veins, plasma, blood clots, or fascia, with the stumps sutured at each end of the tube. According to Dellon,[7] Dr. Charles H. Cargile, in Arkansas, began selling his preparations of ox peritoneum for either tubulization or as a wrap to protect the suture line.

Several surgeons attempted transplants with the patient's own nerves, stored human homografts, or "heterografts" from other species. In 1896, Mr. Mayo-Robson, the Hunterian Professor at Leeds, England, reported a graft in a 29-year-old gardener who had severed both ulnar and median nerves in the arm. Robson examined the patient 7 months later and described atrophy of all muscles, but preservation of sensation over the thenar eminence. There was no muscle reaction to faradic current, and a minimal reaction to galvanic current. Mr. Robson dissected the scar and all 4 nerve stumps. He used a stored rabbit's sciatic nerve to bridge a three-quarter-inch gap of

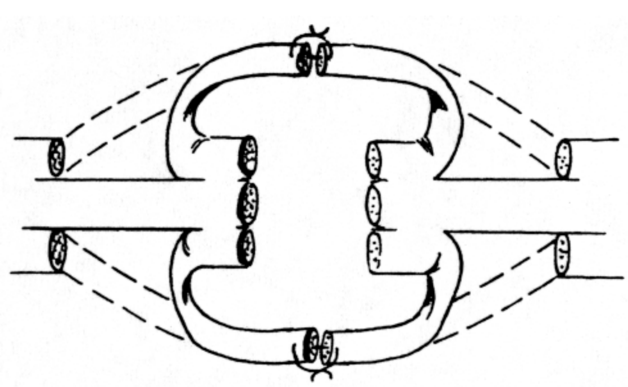

Fig. 2. Drawing of Létiévant's "double nerve flap." (Adapted with permission from Elsevier from Snyder CC: The history of nerve repair, in Omer GE, Spinner M (eds): **Management of Peripheral Nerve Problems.** Philadelphia: WB Saunders, 1980, p 355 [Figure 20–2].)

the ulnar nerve, but ran out of nerve for the 3-inch gap in the median nerve. An assistant came in, killed a rabbit, and dissected out the spinal cord, which was sutured to both ends of the patient's median nerve. Within 10 days, sensation returned in the palm, and within 3 months there was movement in the flexors of the forearm. The patient was lost to follow-up until 6 years later. Examination at that time revealed good muscle tone and intact function of the hand and forearm. The reaction to faradic current was normal. Although the report met with skepticism, the influence of the prestigious *British Medical Journal* carried the day.[67]

All these articles suggested a certain enthusiasm for the repair of PNIs, but they lacked surgical credibility. Civilian injuries were few in number, and the reports were scattered, occasionally unclear or ill thought out, and with insufficient follow-up. Consequently, military surgery might have a great deal to offer during this period. However, with one exception, this was not the case. The celebrated investigations of PNIs recorded by Silas W. Mitchell, George R. Morehouse, and William W. Keen at the Christian Street and Turner's Lane Hospitals in Philadelphia were the first to systematically describe, examine, and offer therapy for wartime PNIs. The American official medical history, *The Medical and Surgical History of the War of the Rebellion*, described multiple PNIs, but the descriptions were not specific, and follow-up continued only until the soldier was pensioned. The author, Assistant Surgeon George A. Otis,[57] gave full credit to the work by Mitchell and his collaborators.[45–47]

Despite the popularity of Mitchell's work, there was no large-scale effort to include PNIs in the medical literature during the wars in the late 19th and early 20th centuries. Head and coworkers[25,26] recruited casualties from the Second South African (Boer) War for their studies on sensory loss. American[38] and British[40] medical observers during the Russo-Japanese War focused on military sanitation, whereas Hashimoto and Tokuoka[24] described a technique in which arteries were used for tubulization. In the Balkan wars, Gerulanos[15] stated that approximately 40% of PNIs recovered without surgery. In another report, Denk[8] used fascia for tubulization in a few PNIs.

By the start of World War I, neurologists had established control over the clinical evaluation and diagnoses of PNIs. Electrodiagnosis had made inroads into the quantifiable evaluation of degeneration and regeneration of PNIs. Electrotherapy had emerged as an acceptable clinical tool, and surgeons had developed elegant, although not entirely valid techniques.[73] The unassuming peripheral nerve had become a centerpiece for intricate medical care.

The Medical Services' Dilemma

Every account of World War I stuns the reader with the number of casualties. By 1915, more than 1500 casualties with PNIs swamped the Val-de-Grâce Military Hospital in Paris alone.[85] Although military diagnostic codes did not specifically list PNIs, some idea of the extent of the problem can be calculated. Perhaps the most accurate data were reported in 1920 by Lieutenant Colonel Charles Frazier, head of the American Peripheral Nerve Commission. By that time, there were 3000 patients with PNIs in American hospitals. He assumed that 15% of the casualties had been discharged, so that with a total 208,000 casualties, there was a 1.6% incidence of PNIs.[13] This was in line with other estimates of 1.5–2%, and suggested that the French Service de Santé may have treated approximately 30,000 PNIs, although this was probably an underestimate.[16] Athanassio-Benisty[2] thought that 20% of all wounds involved PNIs. Sir William Thorburn,[86] in a chapter on PNIs in the British *Official Medical History of the Great War*, estimated that 20% of "severe" casualties sustained PNIs, but he did not define "severe." Using Frazier's 1.6% estimate in the 2,497,400 British battle casualties during the war who did not die of wounds, approximately 32,079 sustained PNIs.[48] By 1918, many military surgeons had published articles on PNIs, with series of more than 100 cases and a few with more than 500 patients.

Whatever the numbers, the wounds were a mess. Artillery accounted for 60%; bayonets for less than 1%. Primary suture was very rare. Gas gangrene (and other bacteria) caused septic wounds, and by 1915, these wounds were left open and irrigated continuously with a variety of antiseptic solutions. While this technique reduced mortality rates and risk of amputation, it resulted in months in bed and healing by secondary closure or slow granulation. Secondary suture was associated with massive scarring. Nerves were contused, twisted, shattered, partially sliced, trapped in broken bone or scar; sometimes they appeared normal and yet didn't work. Even after the initial wound closure and healing, the surgeon had to deal with "flare." This was a recurrent infection when opening the old wound. Consequently, patients received antitetanus serum and underwent wound manipulation or massage prior to exploration. This was an apparent effort to aggravate the bacteria, which were lying in wait for the surgeon and his scalpel. Occasionally, it was effective, but then the patient had to wait for another chance. Thus, the surgery of PNIs during the war meant dealing with the most difficult of injuries, far more disastrous than those in civilian life, while developing indications, timing, and surgical techniques for complex surgical wounds. And there were thousands of patients!

First Impressions

This early period was confused; casualties were transferred to field or base hospitals without histories, records, or even identification. To make matters worse, wounds were complicated, usually infected, and required experienced medical officers. A few articles in the medical journals published prewar reviews, but it wasn't until 1915 that early reports attempted to sort out the injuries and treatment. Blunt injuries were left alone and seemed to recover on their own. Penetrating injuries were septic and allowed to heal. If surgery was required, it would have to be performed after the infection had cleared.[54,85]

When surgery was performed, military surgeons faced injuries that they were unprepared to handle in any standard fashion.

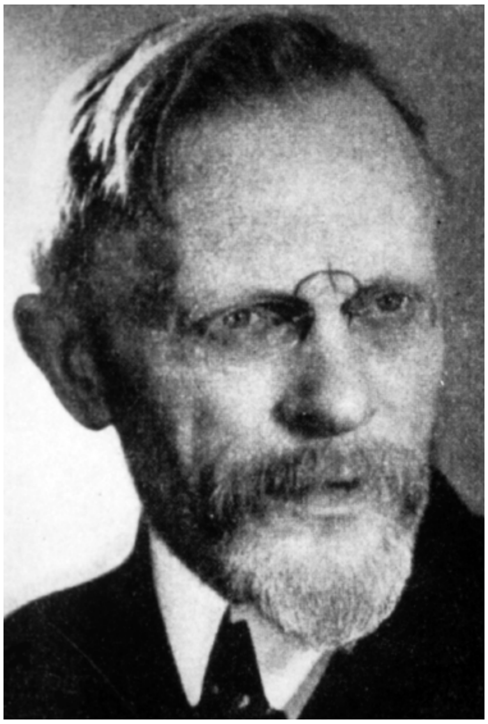

Fig. 3. Photograph of Jules Tinel (1879–1952).

Several patterns emerged throughout 1915. First, all the military services began to concentrate casualties with neurological injuries, including PNIs, in specialized wards or hospitals. The French Service de Santé established 12 "Services Neurologique" around the Paris region, with more than 200 beds in each. Dozens were organized throughout the country.[49] Second, the timing of surgery became a critical issue. The neurologist and his electrodiagnoses were the gatekeepers for surgical intervention. Clinical examination and the Erb reaction of degeneration indicated when it was time to explore the injured nerves. Various coils, condensers, and so on were cumbersome and sometimes unreliable, so efforts were made to standardize equipment.[27] Casualties with "hysterical paralysis" began to stumble into the centers. Their behaviors could mimic PNIs to an uncanny extent. Faradization of the affected muscles several weeks after the onset of the injury solved the problem, but as the war dragged on, electrodiagnosis transformed into electrotherapy for war neuroses. Inexperience with the complex equipment led to painful or dangerous techniques, although historians have been quick to point out that the draconian "torpillage" or "traitement brusque" were associated with arcane behavioral theories and cultural bias.[90]

The results of surgery and nonoperative intervention were areas of contention. Theodore Tuffier reported on 250 cases in 1915. Tuffier, who would become the Inspector General of the Surgical Services of the French Army and President of the Interallied Surgical Conference, was an influential, internationally known surgeon. His report was simple: in 250 cases of PNI, nerve suture was performed in 19. None of these operations restored useful function. On the other hand, Otto Hoffman in Germany reported 70–80% "positive" results for nerve sutures, 75% in his own series of less than 50 cases. British surgeons emphasized delayed surgery on clean wounds, with various techniques of nerve suture. Hoffman and the British sutured nerve endings, but suggested that follow-up required several years, which is an eternity in wartime.[11,23,54]

Two critical reports were published in 1915, the first by Paul Hoffman, a physician and physiologist, and the second several months later by Jules Tinel, a neurologist with the French Third Army at Le Mans (Fig. 3). Both reports described the "signe du fourmillement" in PNIs. Although misinterpreted during the war (and later), a "tingling" when pressing on the area of nerve injury or above the injury that gradually extended down the nerve indicated regeneration at least for sensory fibers. Pain was not an accurate sign, and the tingling did not predict the return of voluntary movement.[92] The eponym "Tinel's sign" took priority, not so much because of France's victory, but due to Tinel's later publication of a text that would have significant influence during the war.[89] His experience with PNIs was extensive; he was the first to describe ischemic paralysis associated with arterial injuries, as well as his rapid, reproducible clinical sign to judge the success of conservative or operative therapy. The accurate prediction of sensory fiber regrowth, presumably earlier than motor regeneration, was a valuable clinical tool in lieu of the time-consuming, but perhaps more accurate electrical examination. Both Tinel and Hoffman would go on to distinguished careers—Hoffman with his H-reflex and Tinel with his extensive publications and collaboration with the resistance during World War II.[69]

A Rough Consensus: Sir Robert Jones and William Mackenzie

The war became a stalemate, with a static trench line along the western front. Immobility combined with tactical futility produced large numbers of casualties in small areas, described today as a massive force/space ratio. The Allied Medical Services responded to these operational conditions with rapid triage and comprehensive frontline surgery, followed by appropriate transport to base hospitals in France or general hospitals in the UK. (A similar system developed for the Central Powers.) Medical officers were faced with broken but salvaged limbs, and PNIs that required sophisticated operative decisions.

Tinel spoke for the French neurologists—left alone, approximately 60% of PNIs would recover. Other authors agreed with the conservative approach, writing that spontaneous recovery could sometimes occur 7 or 8 months after injury. Many medical officers were not patient enough to wait, although it did not appear that the results of delayed surgery were a great deal different from early operations. There were, however, several reasons for rapid intervention. First, there was less scarring, and technically that made for easier surgery. Second, if the nerve was injured, there would be less time for nerves and muscles to degenerate, and finally, hospitals were overburdened with casualties waiting for surgery. An arbitrary time frame of a 2- to 3-month delay in surgery developed. If there was

TABLE 1: Anatomic Location of 2,390 PNIs in United States Peripheral Nerve Centers during World War I*

Nerve	Total	Operated Number	Operated Per cent
Brachial plexus	132	20	15.1
Musculospiral	516	228	44.1
Median	269	111	41.2
Ulnar	492	252	51.2
Sciatic	551	307	55.7
External popliteal	395	157	39.7
Internal popliteal	35	10	28.5
	2,390	1,088	

* Reprinted from Frazier C: Results of peripheral nerve surgery, in Weed FW (ed): **The Medical Department of the United States Army in the World War, Vol 11, Part 1.** Washington, DC: Government Printing Office, 1927, p 1085.

evidence of a complete nerve injury and if there were no signs of clinical or electrical recovery, surgery would proceed. This management required frequent examinations made by skilled neurologists familiar with electrodiagnosis. The Tinel sign could serve as an alternative clinical maneuver to demonstrate nerve recovery.[13,52,55,58,76,86]

Along with the indications for surgical intervention, surgeons had to determine how to repair the various lesions that they encountered at operation. Some techniques were generally agreed on, although opinions differed occasionally. A sterile operative field, large incisions, thorough dissection, complete visualization of all the injured nerves, direct palpation, and the use of fine curved needles became standard. General or local anesthesia, the use of tourniquets, and the type of sutures were always debated.[81] Intraoperative judgment, however, was critical; skill and experience were necessary to repair complex PNIs adequately. Consequently, surgery was increasingly limited to individuals trained in these techniques.

Table 1 shows the location of PNIs treated in the US during World War I. The table, developed by Captain Charles Frazier for the AAMD, indicated that 53.1% of PNIs were in the upper extremities. Sciatic and radial nerve injuries were the most common. One other series in the British Official Medical History indicated that 5.5% of PNIs involved the brachial plexus, and approximately 8.1% were "combined" injuries.[86] Table 2 gives some idea of the problems the surgeons faced in the operating room. Approximately one-third of the nerves were severed, with bulb neuromas and encasement in scar. Another third had neuromas in continuity; the remainder were partially severed, contused, or compressed by an adjacent aneurysm or bone. Approximately 1% appeared normal but were physiologically inert. The French also described "sclerosis," or a lengthy, diffuse intraneural scar.[37]

First the French learned what not to do. Létiévant's "suture á lambeaux" (see Fig. 2) only created more scarring and was useless. Suture "á distance" was without effect, as was "nerve implantation." Although some surgeons disagreed, most gave up pedicle flaps or "bypass" operations.[71,79,80]

What to do was more complicated. For example, fine chromic or waxed silk epineural sutures, with identification sutures to match fascicular structure, were used for end-to-end anastomoses. The suture line was protected with fat, fascia, or was transposed to acceptable sites. Bulb neuromas had to be resected until "normal" fascicles were seen. External neurolysis or "liberation" was used to free up nerves that had been encased in scar or bone, although Tinel advised surgeons that "a good resection is better than a bad liberation."[87] Internal neurolysis or "capsulectomy" was performed reluctantly, and only if the fascicular structure was visualized clearly (Fig. 4). Lateral neuromas or notching were resected and sutured, leaving a normal portion of the nerve intact (Fig. 5).

Gaps in nerve endings required considerable ingenuity. Acceptable techniques used transposition, flexion-relaxation of the limb, or external neurolysis to remove tension at the suture site. Limb shortening was discouraged. Some advocated 2-stage stretching. Dr. Robert Kennedy, in Glasgow, used his homemade nerve "stretcher" to torture the nerve into position (Fig. 6). Nerve grafting was common. Autografts, homografts, or heterografts were used, but by the end of the war, rabbit spinal cords were

TABLE 2: Lesions of peripheral nerves found during surgery in 90 patients with war injuries*

Complete Section	34
Neuroma	9
" with lateral or central cicatrix	22
" " lateral notch	4
" " involvement in callus	4
Lateral notch with neuroma	3
" " " involvement in callus	2
" " " scar	3
" " " deformity of bone	2
Foreign body in the nerve	1
Pressure of aneurysm	4
Contusion	1
Nothing abnormal	1

* Reprinted from Thorburn SW: Injuries to the peripheral nerves, in Macpherson WG, Bolwby AA, Wallace C, et al. (eds): **History of the Great War: Medical Services, Surgery of the War, Vol 2.** London: His Majesty's Stationery Office, 1922, p 148.

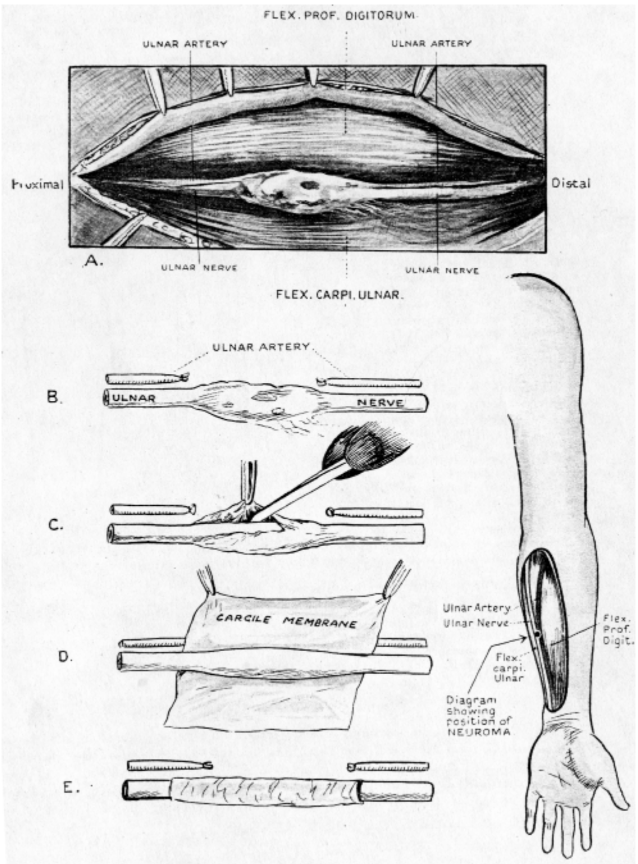

Fig. 4. Intraoperative drawing of a "neurolysis capsulectomy" and wrapping of the exposed ulnar nerve with Cargile membrane. Flex. = flexor; Prof. Digit. = profundus digitorum. (Reprinted from Joyce JL: A study of a series of peripheral nerve injuries from a surgical aspect. **Br J Surg 6:**441, 1918–1919 [Figure 382].)

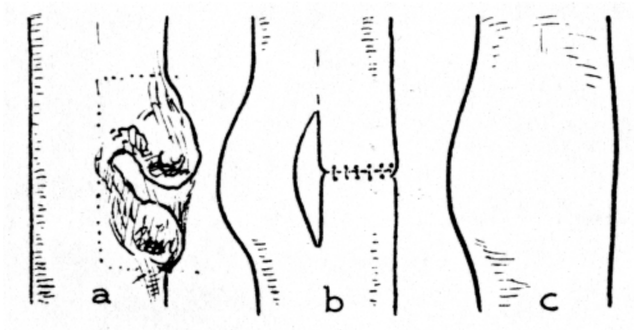

Fig. 5. Drawings showing early nerve repair procedures. **a:** Lateral notch in external sciatica. **b:** After resection and suture. **c:** Nineteen months later, no recovery. (Reprinted from Joyce JL: A study of a series of peripheral nerve injuries from a surgical aspect. **Br J Surg 6:**438, 1918–1919 [Figure 377].)

abandoned, despite another case reported by the indefatigable Mr. Mayo-Robson.[41] In 1917, Langley[35] and Langley and Hashimoto[36] demonstrated the potential of suturing specific "bundles" of fascicles through a cable graft, thereby increasing the potential of accurate axonal regeneration. Intraoperative bipolar stimulation was used to delineate sensory fascicles in the proximal stump (Fig. 7) or motor fascicles in the distal stump to increase the accuracy of reconstruction.[51] Tubulization remained a common practice and was performed using tubes made from all available materials.

"Irritative" nerve lesions, such as stump pain or causalgia, were treated surgically. The former condition was treated successfully with the resection of the neuroma, suture of the nerve ending, and injection of absolute alcohol into the nerve proximal to the suture. Although the role of the sympathetic nerves and the pathophysiological mechanisms of causalgia had been investigated, treatment was limited to repair of the nerve and stripping the epineurium to destroy the sympathetic nerve endings, or the injection of 60% alcohol above the injury, presumably to destroy only the sensory fibers. These maneuvers, however, were usually ineffective, although an occasional patient would experience partial relief.[82,88]

An increasingly lengthy war of attrition pulled in government policy and public concern. Conscription, large numbers of crippled citizen-soldiers, and novel pension schemes demanded a sea change in medical care. The idea of an all-inclusive center for hospital care and workshop training was a rational extension of the prewar recognition of the need for some type of physical therapy in patients with PNIs. The German Lazarettschule and French efforts toward comprehensive care for disabled soldiers had been in place since 1914.[42] Now the focus of efforts became reconstruction, and its champion was Robert Jones, who trained (and lived) with his uncle, Hugh Owen Thomas. He developed his interest in orthopedic surgery treating crippled children in Liverpool, followed by an appointment as surgeon to the Manchester Ship Canal Project. In 1916, while pushing for his military orthopedic centers, he became the Inspector General for Military Orthopedics in the Army Medical Service. Later that year, he established his first hospital at Shepherd's Bush in London.[5,91] He was joined there by King Manuel, recently deposed from the throne of Portugal, who was an energetic advocate for curative workshops, and later by an Australian, William Mackenzie, who helped to develop the muscle reeducation program. Mackenzie was awarded his fellowship from the Royal College of Surgeons of Edinburgh, and worked

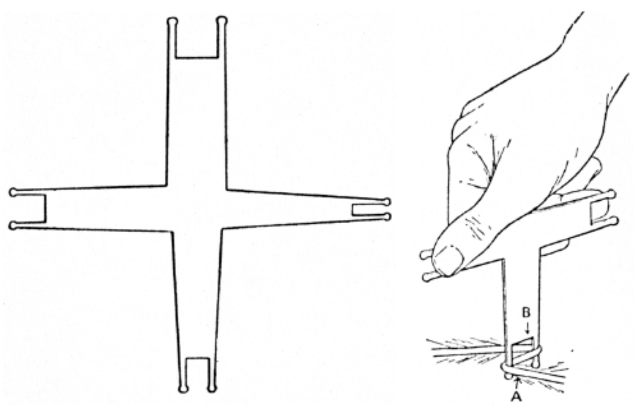

Fig. 6. A drawing of the "nerve stretcher" and a technique to twist the nerve into submission and bridge the gap. (Reprinted from Kennedy R: Some notes on operative procedure and nerve injuries. **Br J Surg 6:**320, 1918–1919 [Figures 288 and 289].)

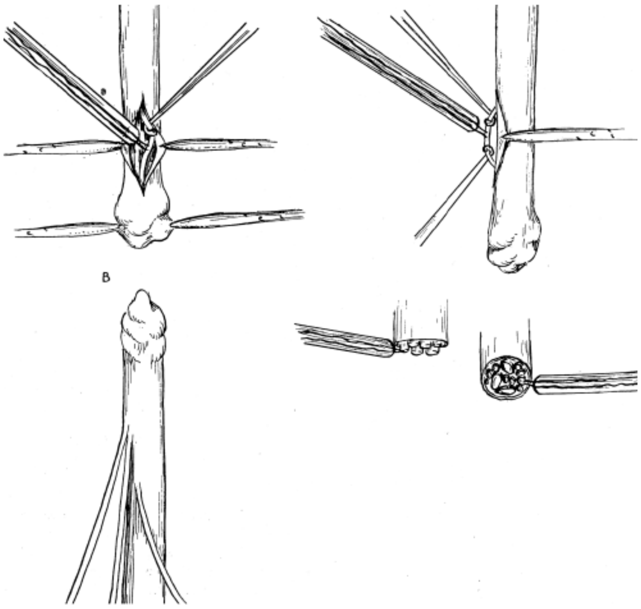

Fig. 7. In the drawing labeled "B", a stimulator is placed on a fascicle after dissection of the epineurium of the proximal stump. Motor branches arise from the distal stump. Stimulation of the distal stump was usually ineffective. (Reprinted from Ney KW: Technique of nerve surgery, in Weed FW [ed]: **The Medical Department of the United States Army in the World War, Vol 11, Part 1.** Washington, DC: Government Printing Office, 1927, p 962 [Figure 152].)

with crippled children at the Children's Hospital in Melbourne. His theories and experiences were outlined in his book, *The Actions of Muscles: Including Muscle Rest and Re-Education*.[39]

Here was Jones' vision of a comprehensive center to provide continuous skilled care. Together with the Almeric Paget Massage Corporation, Shepherd's Bush included departments of electrotherapeutics, balneological therapy, heat therapy, a gymnasium, equipment for muscle reeducation (Fig. 8), and a creative workshop for vocational rehabilitation. There was a section for the radium treatment of scars. Specially trained personnel administered physical therapy, hydrotherapy, or electrotherapy to prevent muscle contractions or scarring; postoperative care meant massage, followed by passive and then active muscle reeducation. Galvanic current was used to administer "ionic" medications, such as salicylates of soda, while static electricity or radiant light and heat were used to relieve muscle pain. Hydrotherapy prepared the stiff limbs for massage. (All these techniques could be used in patients suffering from shell shock as well.) The entire system would be under the control of orthopedists, as Jones described in his edited textbook, *Orthopedic Surgery of Injuries*. The second volume included 6 extensive chapters on the diagnosis and treatment of PNIs, as well as 2 chapters on injuries of the head and spine. His intention was to call in other specialists on an as-needed basis.[34,84] The affable Jones also trained a cadre of young orthopedists from the UK, Dominions, and a team from the US, to spread the word.

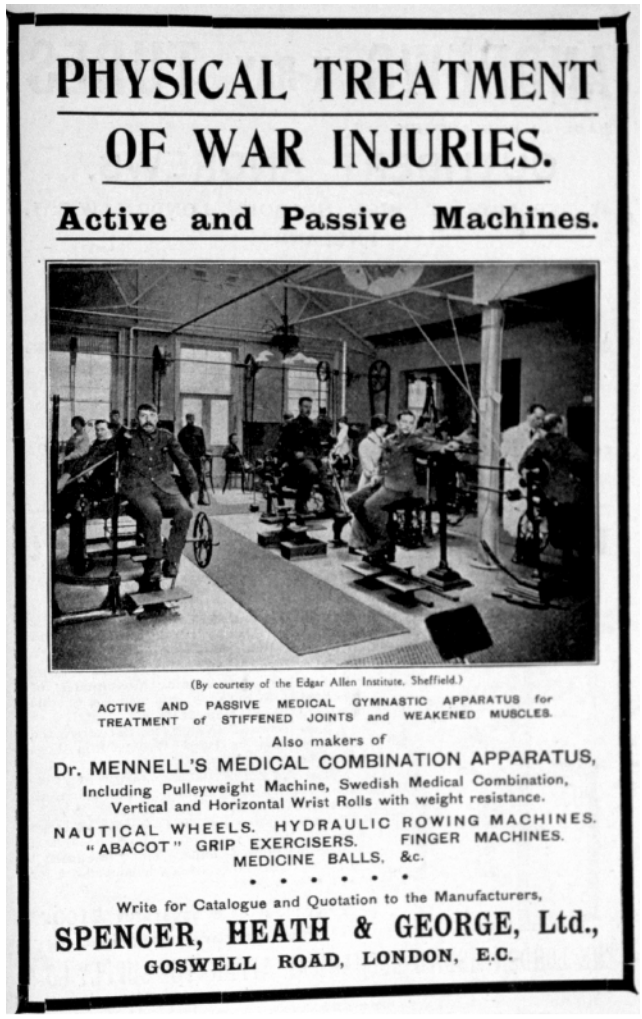

Fig. 8. Advertisement for "Active and Passive Machines" for the physical treatment of war injuries. (Reprinted from the journal **Recalled to Life,** April 1918.)

The Americans: Charles Frazier and Robert McKenzie

By the time Congress declared war on Germany in April 1917, the AAMD knew a great deal about the war. Military observers had traveled throughout Europe and had reported on the medical developments.[22,42] By June, a new division in the Surgeon General's Office, called Surgery of the Head, started collecting abstracts for the manual *War Surgery of the Nervous System*, one-third of which dealt with PNIs.[54,58] The rapid buildup of the American Expeditionary Force and the equally rapid Armistice meant that most casualties with PNIs were transported back to the US. Surgical indications, techniques, treatment, and aftercare mirrored the allies' management, so that various specialists had to be recruited and trained. Hospitals had to be constructed, and ancillary personnel were necessary for effective management. It was the Surgeon General of the Army, William Gorgas, to whom the responsibility fell in the creation of a system for the treatment of crippled men. Gorgas, the son of Joshua Gorgas, Chief of Ordnance for the Confederate Army, was

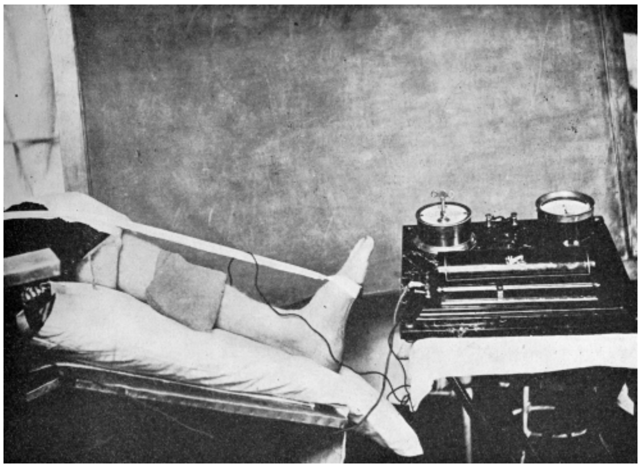

Fig. 9. Photograph of setup for a machine delivering interrupted galvanic current to muscles in case of injury to the external popliteal nerve, with footdrop. (Reprinted from Crane AG: Physical reconstruction and vocational education, in Weed FW [ed]: **The Medical Department of the United States Army in the World War, Vol 11, Part 1.** Washington, DC: Government Printing Office, 1927, p 151 [Figure 67].)

an internationally respected sanitarian, who had made his reputation in Havana and the Panama Canal. He was a scientist and field worker, hardly an administrator, and he depended on a cadre of mostly East Coast consultants for much of the buildup.

Numerous organizations crowded into Gorgas' office in 1917. Members of the American Orthopedic Association (founded in 1887), American College of Surgeons (founded in 1913), American Association of Electro-therapeutics and Radiology (founded in 1890 as the American Electro-therapeutic Association), committees of physical therapists, the newly minted National Society for the Promotion of Occupational Therapy, the huge American Red Cross, and of course representatives selected for their expertise in brain surgery enthusiastically offered their services.[19,20,59] Robert T. McKenzie, a Canadian who had trained with Dr. James Naismith at McGill University, joined the Division of Physical Reconstruction. McKenzie was the head of the Department of Physical Education at the University of Pennsylvania, and worked on staff for Sir Alfred Keogh, Director General of Medical Services for the British Army, as inspector for remedial physical education. In 1918, he published *Reclaiming the Maimed*, a book that became a manual for the AAMD and outlined the equipment, personnel, and function of a rehabilitation program.[43]

Gorgas could never "bell" all these specialized cats. It took more than a year to organize the Divisions of General Surgery, Orthopedic Surgery, and Physical Reconstruction, and a section of brain surgery under the Division of Surgery of the Head. The orthopedic surgeons, many whom trained under Jones, lost their bid for specialized hospitals under their control. The returning troops with PNIs would be treated in 12 peripheral nerve centers, with each center commanded by a medical officer experienced in neurological surgery, associated with a consulting neurologist. The centers were usually located in general hospitals, with reconstructive facilities shared by orthopedics and staffed by electrotherapists and physiotherapists.[3,6] The neurosurgical victory, of sorts, was due to Charles Frazier's political clout in Philadelphia and along the East Coast. Frazier was Professor of Clinical Surgery and former Dean of the University of Pennsylvania's Medical School. He was well known for his work in neurosurgery and PNIs, having studied under S. Weir Mitchell. Gorgas made him consultant in neurosurgery to the Surgeon General, an appointment that carried considerable authority in the development of rehabilitation work in the US.[21] As senior consultant, Frazier was also appointed head of the Peripheral Nerve Commission, which was to report on the treatment and outcomes of PNIs after the war. Finally, both Gorgas and Frazier recruited G. Carl Huber at the University of Michigan to organize the second neurosurgical laboratory to investigate problems associated with PNIs. Although the research fit Huber's prior histological studies in nerve regeneration, the contract surgeon Huber, the son of Swiss missionaries, reluctantly accepted the appointment. Over the next year, Lieutenant Colonel Dean Lewis, Major J. Corbitt, Major B. Stookey, and Major T. Roberg worked with Huber or Walter Ransom at Northwestern University.[32,95] Both the first and second army laboratories were examples of the funding of medical research by the military services during World War I. Details of Huber's 278 animal experiments, along with an extensive review of the literature, were published in 192 pages of the official American medical history. Huber used pyridine silver stains to study various techniques to bridge nerve gaps and the formation of stump neuromas. His research justified the use of autografts or homografts; heterografts were unacceptable. Dr. Cargile received a boost. His "alcoholized" membranes were successful for protecting the suture line. Tubular grafts uniformly failed and were not recommended. Nerves sutured under tension failed to regenerate, whereas alcohol injections limited the formation of amputation neuromas.[30,32]

Eventually, the American system developed according to Jones' concept. Large military centers with trained, experienced personnel and elaborate equipment for electrodiagnosis and therapy (Fig. 9), gymnastic training, and vocational reeducation created win/win situations for the casualties, pension systems, and civilian population. Specialization was an essential element, although the issue of professional control created difficulties, particularly in the US. Both Frazier and Huber had lobbied for the neurosurgeons. Huber defended his bias, writing:

> The nervous system consists of independent anatomic units. The neurons related to each other by contiguity and not by continuity. The peripheral nervous system is therefore on anatomical and functional considerations a part of the central nervous system and *its surgical treatment should be recognized as such*.[31] (Emphasis mine. –W.H.)

In Britain, Jones organized freestanding orthopedic centers, whereas in France, the prewar influence of the neurologists resulted in medical control over surgical therapy. Despite the administrative differences and historical judgments on pension concerns and government intrusion, these were reasonable, progressive responses to overwhelming problems.

After the Armistice

The [surgical] rule should be radical nerve exploration, but conservative nerve operation.

Brian Stookey[83]

Following the war, there was a flurry of articles concerning PNIs and surgical therapy. Frazier was the Surgeon General's representative at the Interallied Surgical Conference in 1920, and he chose to speak on PNIs.[14] K. Winfield Ney, a 70-day brain surgeon, who trained during the war under the AAMD, started his career with his experiences in PNIs and later became Professor of Neurosurgery at New York Polyclinic Medical School.[21,50,51] Lewis Pollock, who would become chairman of the Department of Nervous System and Mental Diseases at Northwestern University, wrote *Clinical Signs of Nerve Injury and Regeneration* and several chapters in the American official medical history of World War I based on his wartime experiences.[61–63] In 1933, he and Loyal Davis published a well-known textbook on PNIs.[65] Brian Stookey, who worked as Huber's subordinate, wrote his first report condemning nerve flaps for bridging nerve defects and later authored one of the first definitive texts on PNIs while an assistant professor of neurosurgery at the New York Postgraduate Medical School.[81] The influence of these decidedly neurological surgeons did not parallel the postwar experience in the UK. Although the *British Journal of Surgery* was crammed with articles on PNIs in its last postwar editions, many of these were written by general surgeons, such as Henry Souttar.[77] Percy Sargent, known for his work on head injuries with Gordon Holmes during the war, investigated suture materials for PNIs and was appointed a member of the "Committee Upon Injuries of the Nervous System" for the Medical Research Council that published its first report in 1920.[44,70] Sargent coauthored the chapter on head injuries for Jones' textbook, but chapters on PNIs were written by various orthopedic surgeons who had worked with Jones in his military hospitals. Sir William Thorburn, a Manchester general surgeon, who achieved considerable prewar recognition for his work on spinal cord injuries and PNIs, wrote the chapter for the British *Official Medical History of The Great War*.[53,86] Thorburn's colleague, Harry Platt, an orthopedic surgeon at Manchester and President of the Royal College of Surgery in 1954, developed a reputation for treatment of PNIs.[60]

While the surgeons trumpeted their technical success, Jones' idea for centralized orthopedic centers throughout the UK died a financial death during the 1920s. Moreover, the Royal College of Surgeons was not too thrilled with the idea of an orthopedic takeover of surgical care, particularly for injuries that had been treated by general surgeons during the war. Jones eventually transformed his vision into a smaller group of orthopedic hospitals for civilian injuries and crippled children, but the comprehensive model at Shepherd's Bush never got off the postwar ground. In 1926, the center was taken over by the Ministry of Pensions. Long-term follow-up of veterans with PNIs failed through loss of interest or records, discharge, and the lack of a centralized system. The Medical Research Council's report never analyzed surgical outcomes.

Similar failures plagued the AAMD, despite Frazier's attempt to concentrate PNIs in the appropriate hospitals. A report by one military surgeon described the problem with characteristic understatement:

> Careful preliminary study, operations and appropriate cases and prolonged and systematic follow-up, with massage, bathing, electro-therapy, proper splinting, and frequent examinations for evidence of returning function, constituted the treatment at this hospital. No conclusions can be reached, because of the transfer of this group of cases to another hospital.[28]

By 1921, the Veteran's Bureau had taken over treatment of patients who were under active care or who were compensable. Records and patients disappeared. In a short chapter in the American official medical history, Frazier summarized the results in 470 of approximately 1414 operations as 34% "good," 36% "mediocre," and the rest "failures." He admitted that the definitions were "loose" and subject to the skill of the examiner. There were records on 60 transplants; none was successful. Showing his frustration, he wrote: "Considering the total number of cases and the results as recorded, the employment of the transplant, either 'auto' or 'homo' as a practical method of bridging defects in peripheral nerves has proven to be a dismal failure in the hands of the surgeons of our country."[12] There the matter rested.

Lessons Learned

It could be argued that prewar developments would have resulted in similar changes in medical care for PNIs without the influence of World War I. That is possible, but doubtful. War has a tendency to focus one's attention, and the changes over a very short period of time were not specific to one technique or specialist, because they were part of a system of coordinating medical expertise to accomplish specific goals. However flawed in achievement, the practical value of the process seemed to take effect.

Twenty-one years after World War I, a second global war resulted in another large population of casualties with PNIs. The lessons learned from their medical management in World War I were underplayed but critical. The American official medical history in 1959 clearly stated the impact:

> It is extremely unfortunate that the Official History of the U.S. Army Medical Department in World War I was not made readily available to military surgeons in World War II. It should have been required reading for them and for other military surgeons. It contains fundamental information on peripheral nerve anatomy and on technical methods of nerve exposure, mobilization, transplantation, and suture…
>
> Generally speaking, no important technical advances were made in the surgery of peripheral nerve injuries in World War II, with the possible exception of the introduction of tantalum wire sutures and tantalum cuffs. The striking improvement in results rested more upon a fuller appreciation of the principles of nerve repair than upon mechanical or surgical advances in technique.[93]

The AAMD established 12 peripheral nerve centers during the war, along with a new Peripheral Nerve Commission and Registry. R. Glen Spurling and Barnes Woodhall, both neurosurgeons, headed up the American effort. The British organized 5 nerve injury centers as part of their Emergency Medical Services. Not unexpectedly, orthopedic surgeons, such as H. J. Seddon and Harry Platt, supervised medical care.

Although the lines of authority were clear on both sides of the Atlantic, by this time it was obvious that the treatment of PNIs required the coordinated efforts of multiple specialties that now included plastic surgery and hand surgery. Lengthy rehabilitation was designed into the system, and after the war, as the veterans' facilities expanded, long-term follow-up data were available that had been absent after World War I. In 1954, the British Medical Research Council published Special Report No. 282 on PNIs.[71] This monograph detailed 3-year follow-up examinations on almost 1500 PNIs. Risk factors, such as location of sutures or time to surgery, were independently presented, along with the results of 67 autologous nerve grafts. Twenty-eight of these showed outcomes that were equivalent to primary suture at the same level. Surgical treatment of brachial plexus injuries was discouraged. Two years later, Woodhall and Gilbert Beebe, a statistician, published a report sponsored by the Veteran's Administration and the National Research Council on a 3- to 5-year follow-up in 3656 PNIs in casualties from World War II.[94]

The authors of both studies took care to acknowledge the work of their predecessors during World War I. As the first to "stand on guard" over nerve regeneration, they deserved this respect.

Disclosure

The author reports no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Acknowledgment

The secretarial assistance of Laura Day is gratefully acknowledged by the author.

Dedication

This report is dedicated to the memory of Dr. Robert Tiel, a student of PNIs and a good friend.

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Address correspondence to: William C. Hanigan, M.D., Ph.D., Department of Neurosurgery, University of Mississippi Medical Center, 2500 North State Street, Jackson, Mississippi 39216. email: WHanigan@umsmed.edu.

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Brain-computer interfaces: military, neurosurgical, and ethical perspective

***Ivan S. Kotchetkov, B.A., Brian Y. Hwang, B.A., Geoffrey Appelboom, M.D., Christopher P. Kellner, M.D., and E. Sander Connolly Jr., M.D.**

Department of Neurological Surgery, Columbia University College of Physicians and Surgeons, New York, New York

Brain-computer interfaces (BCIs) are devices that acquire and transform neural signals into actions intended by the user. These devices have been a rapidly developing area of research over the past 2 decades, and the military has made significant contributions to these efforts. Presently, BCIs can provide humans with rudimentary control over computer systems and robotic devices. Continued advances in BCI technology are especially pertinent in the military setting, given the potential for therapeutic applications to restore function after combat injury, and for the evolving use of BCI devices in military operations and performance enhancement. Neurosurgeons will play a central role in the further development and implementation of BCIs, but they will also have to navigate important ethical questions in the translation of this highly promising technology. In the following commentary the authors discuss realistic expectations for BCI use in the military and underscore the intersection of the neurosurgeon's civic and clinical duty to care for those who serve their country. *(DOI: 10.3171/2010.2.FOCUS1027)*

Key Words • **brain-computer interface** • **military neurosurgeon** • **ethics** • **brain-machine interface**

Brain-computer interfaces, also called brain-machine interfaces or neural interface systems, represent a direct communication pathway between the brain and an external device.[18,32,59] The devices used for the BCI acquire brain signals such as an EEG rhythm or electrophysiological recordings of neuronal firing and translate them into commands intended by the user. Brain-computer interfaces accomplish this through novel output pathways that do not use the normal conduits of the nervous system.[32]

During the past 40 years, BCIs have rapidly progressed from mere neuroscientific theory into a rudimentary yet highly promising technology. Increasing levels of brain-derived control have been attained in nonhuman primates and in humans.[13,21,32,48,50,51,54,55] Moreover, rapid progress of supporting technologies from the fields of computational neuroscience, biomaterial engineering, and computer processing have significantly contributed to the ongoing development of BCIs. Importantly, an ever-increasing understanding of motor, cognitive, and sensory functions through cortical mapping has led to improvements in device designs as well as a wider gamut of possible BCI applications.[32,42,43]

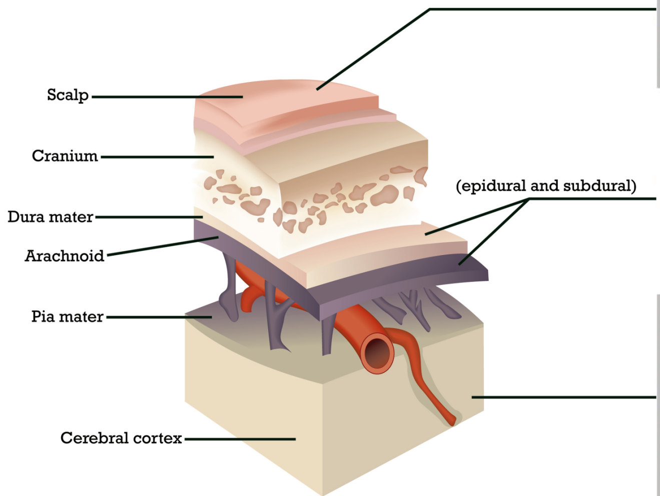
Media hype and popular imagination regarding potential applications of BCIs have greatly exceeded the current state of the technology. Nevertheless, practical and clinically useful BCIs are increasingly becoming a reality, and this has important implications for neurosurgeons practicing and conducting research in military settings. Our aim in this commentary is to use an understanding of current achievements in the field of BCIs to discuss realistic expectations for future adaptation of BCI systems in military settings and to highlight the complex role of military neurosurgeons in the further expansion of this technology. The implications of neurosurgical BCI implantation for restoring function to injured soldiers as well as the potential to enhance military training and operations are considered from an ethical perspective. In the context of our national duty to support those who serve our country, we reinforce the importance of physician beneficence and nonmaleficence in any BCI application, alongside responsible and just distribution of the technology.

State of BCI Technology at Present

For BCIs to translate the user's intentions accurately into actions, "learning" must take place on both ends of the interface: the user must modulate his or her brain signals to improve performance of the BCI, while the device must identify, interpret, and adapt to the neural signals that are most predictive of the desired output. This is achieved through feedback and fine-tuning mechanisms that are similar to those used when learning a new mo-

Abbreviations used in this paper: BCI = brain-computer interface; DARPA = Defense Advanced Research Projects Agency; ECoG = electrocorticography; EEG = electroencephalography.

* Mr. Kotchetkov and Mr. Hwang contributed equally to this work.



BCI Class	Predominant Platform	Advantages	Limitations
Non-Invasive	EEG[1]	• Inexpensive • No surgical implantation	• No information on components of movement • Interference from non-cortical stimuli
Partially-Invasive	ECoG[2]	• Provides information on components of movement • No cortical damage	• Neurosurgical implantation required • Not studied in motor-impaired patients
Invasive	Cortical Multi-electrode Array	• Higher performance and rate of data output • Direct recording of cortical neuron potentials	• Vascular and neuronal damage • Lack of signal stability over time • Neurosurgical implantation required

[1]Electroencephalography, [2] Electrocorticography

Fig. 1. Three classes of BCIs: their anatomical locations, advantages, and limitations.

tor task.[32] Some BCI designs rely on a training phase in which the subject performs a designated task and a computational algorithm is employed to select the neuronal signals that best correlate with execution of that task. A code is generated for each command that can subsequently be used for control of an external device.[31,39,40] Alternatively, a real-time adaptive algorithm can be employed during the learning phase to concurrently select for the signals that are most predictive of the user's intentions by continuously refining them based on comparisons of past and intended trajectories.[40,54,60] Recordings from larger populations of neurons, or neuronal ensembles, are generally the preferred source for extracting useful and relevant information to guide appropriate activity.[2,6,40] Although input from a single neuron can result in successful BCI control,[7,22] averaging neuronal signals over many trial sessions is often necessary for predicting behavior,[46] and therefore synthesizing the electrical firing of neuronal ensembles can remove the variability associated with using the input of a single neuron.[2,40] As the user learns to operate the BCI, neuronal plasticity leads to a tuning of ensemble signals such that activity in more discrete populations of neurons becomes the best determinant of action commands.[8,30]

Depending on the source from which they derive their neural signals, BCIs can be classified into those that use noninvasive, invasive, and partially invasive platforms (Fig. 1). Electroencephalography, which obtains electrical signals from the scalp, has been the dominant method of recording used for noninvasive BCIs due to its relative safety and practical technical requirements. Invasive BCIs retrieve signals from single-neuron recordings via microelectrodes implanted in the cortical layers. Partially invasive BCIs use ECoG readings that come from sensors at the cortical surface placed either above or below the dura mater.[10,32,40,48] Platforms that belong to the latter 2 classes require neurosurgical implantation.

Using an EEG-based system, humans with motor debilities, including those that result from spinal cord injury or amyotrophic lateral sclerosis, have been able to control a computer cursor in 2 dimensions.[29,60] This technology has also been used by motor-intact individuals to command robots to manipulate objects, and has the potential to be applied in operating limb prosthetics.[3] The EEG devices, however, are fundamentally limited by their signal content, which does not convey information about components of movement such as position and velocity, and recordings are prone to interference from the electromyographic activity of cranial musculature.[10,32]

Invasive BCIs, on the other hand, can acquire more informative signals that enable higher performance limits.[50] For instance, human patients with locked-in syndrome are able to move cursors on a 2D keyboard to communicate using typed messages after undergoing implantation of electrodes that attract growth of myelinated nerve fibers.[24,25] With the aid of a 96-microelectrode array that records signals from primary motor cortex, tetraplegic patients have been able to move a 2D cursor as well as to execute basic control over robotic devices, such as opening and closing a prosthetic hand, years after their initial spinal cord injury.[21] Subsequent reports on tetraplegic patients who were enrolled in a pilot clinical trial of BCIs have demonstrated modest improvements in cursor control, thereby achieving greater functionality for practical tasks.[13,26]

More recently, ECoG has proven to be a useful tool in detecting input signals for BCIs.[33,51] Unlike EEG, ECoG can detect high-frequency gamma wave activity that is the product of smaller cortical ensembles and correlates with discharge of action potentials from cortical neurons.[19,32] Because they are not embedded in brain parenchyma, ECoG electrodes inflict less damage to the cortex and also experience less signal deterioration than invasive electrodes.[32,34] In patients with intractable epilepsy who required invasive monitoring, ECoG signals have been used for 2D movement control at a level of performance similar to that achieved with invasive BCIs.[51] Although this approach has not been tested in patients with motor impairment, it can be applied more safely than invasive electrodes, and produces greater information content than EEG systems.[32]

Although invasive and partially invasive BCIs hold great potential for functional recovery, the current risks and limitations associated with device implantation prevent BCIs from widespread use. One of the major shortcomings of the current technology is associated with the loss of signal reliability over time. In response to damage incurred by microelectrode penetration of the cortex, microglia and astrocytes begin a reactive process that ensheaths the prosthesis and disrupts its initial impedance properties.[5,16,45,58] Neural and vascular damage at the site of insertion can also lead to development of infections.[5,23] As a result, the length of time over which an implantable electrode is able to produce signals is measured in months, and typically does not make it over 1 year without significantly losing quality.[48,53] Moreover, motion between the implanted electrode and brain parenchyma, as is often caused by changes in brain volume or physical activity, can influence signal production.[49]

The Future of BCI Therapeutics: Restoring Function After Combat Injury

Although BCI technology at present has had a narrow scope of application in a small group of severely impaired patients, robust research efforts are underway to overcome current limitations and to boost the effectiveness of invasive electrode platforms. For instance, the design of biocompatible microelectrode coatings[27] and algorithms that can adapt to vigorous movement[9] promises to endow BCIs with the durability needed to withstand commonplace disturbances encountered outside the confines of a controlled laboratory environment. Additionally, development of ECoG-based platforms constitutes an important investigative avenue, given their lower risk profile when compared with single-neuron electrodes and their higher information content than EEG studies.[32] These properties would allow ECoG BCIs to be implanted in patients harboring less severe injury, and may make this the modality of choice in the future when restoring function to wounded soldiers.

The comparatively greater success of BCIs in animal studies further substantiates the potential for these devices to become functional prostheses. Rhesus monkeys implanted with electrodes recording from as few as 18 cortical neurons are able to move a cursor in 3 dimensions while also receiving visual feedback from their brain-controlled environment.[54] In follow-up studies, implanted monkeys have also been trained to control a multijointed robotic arm to exert variable grip strength and perform 3D movements to feed themselves.[55] These results have been achieved with motor prostheses, which continuously process cortical signals to guide movement and speed.[48] Their counterparts, communication prostheses, which extract information from higher cortical areas about intended goals, have also been successful and promise to enhance BCI performance as it might be applied to humans executing more complicated goal-oriented tasks.[17,37,48,50] The end point of the ongoing advances in BCIs lies in the translation of such functionality from preclinical studies to humans, and thus BCI research deserves continued academic and clinical attention as well as government funding to help those who risk their lives for their country.

Combat casualties from the wars in Afghanistan and Iraq have a marked propensity to present with the types of injuries that may be addressed with new developments in BCIs. Possibly in connection with increased use of body armor,[15,28,44] the number of combat-related extremity injuries has been on the rise, representing 54% of all combat injuries and 63% of primary diagnoses for admission.[41] In a recent analysis, Masini and colleagues[35] concluded that extremity injuries are the leading cause of disability among soldiers not returning to duty, and have the greatest projected disability benefit costs. In addition, spinal cord injuries represent a significant proportion of casualties,[56] occurring in nearly 10% of the entire caseload of closed or penetrating head trauma seen by military neurosurgeons in the US.[4] Neuroprosthetic use of BCIs can directly address the major clinical problems affecting active soldiers, improve quality of life for those injured in combat, and ultimately reduce the individual, fiscal, and social impact of disability.

In the face of new developments in the field of BCIs, whether to take on the risks of surgery and implantation must remain a question of utmost clinical and ethical importance for a military neurosurgeon. Up to the present moment, BCI devices have been able to benefit only the most severely injured patients, such as those with locked-in syndrome or tetraplegia.[21,24] It is only with improvements in the safety, longevity, and effectiveness of BCIs that neurosurgeons can begin to consider routine use of such devices, even for significantly disabled and willing soldiers. In any future discussion with a potential patient regarding BCI implantation, expectation management must be a central element of the conversation, because the clinical trial stage will still consider BCIs to be an experimental therapy rather than a treatment with confirmed benefits. Furthermore, in light of the increasing incidence of posttraumatic stress disorder and psychiatric issues experienced by veterans of recent wars,[36] it will be crucial for military neurosurgeons to take into account the influence of mental health on decision making as well as any preconceived assumptions held by the patient about BCI treatments. Irrespective of the situation, any application of BCIs in humans must be conducted in accordance with the guiding principles of patient autonomy and informed consent as well as physician beneficence and nonmaleficence as espoused by the Hippocratic Oath, the Belmont Report, and the Declaration of Helsinki.[14,38,61]

Military Enhancement With BCIs

Alongside therapeutic interventions, rapid advances in BCI technologies will also create opportunities for neurosurgeons to participate in improving military training and operations, particularly through combat performance modification and optimization. In fact, the use of neuroscientific approaches for achieving these goals is already an evolving area of research. During the last decade, the Pentagon's DARPA launched the "Advanced Speech Encoding Program" to develop nonacoustic sensors for speech encoding in acoustically hostile environments, such as inside of a military vehicle or an urban environment.[12] The DARPA division is currently involved in a program called "Silent Talk" that aims to develop user-to-user communication on the battlefield through EEG signals of "intended speech," thereby eliminating the need for any vocalization or body gestures.[11] Such capabilities will be of particular benefit in reconnaissance and special operations settings, and successful applications of silent speech interfaces have already been reported.[12]

Enhancements of soldiers' perception and control of vehicles or heavy machinery with BCIs are also within the realm of possibilities. A recent DARPA proposal for a "Cognitive Technology Threat Warning System" includes a requirement for operator-trained high-resolution BCI binoculars that can quickly respond to a subconsciously detected target or a threat. Such biological vision devices can have detection ranges of up to 10 km against dismounts and vehicles, and can expand soldiers' field of view to 120°.[11,57] Thus, future generations of auditory and visual neuroprostheses may allow soldiers to perform better during combat situations through automated detection and interpretation capabilities.[52] The concept of telepresence, in which a soldier is physically present at a base or concealed location, but has the ability to sense and interact in a removed, real-world location through a mobile BCI device, is also being actively investigated and has even been projected to be available in limited applications by 2015.[1] These expectations are substantiated by recent advances in the operation of robots using EEG signals,[3] such that control of cargo-loading machines, demolition robots, or unmanned aerial vehicles, as enabled by BCIs, is more than a progressive goal; it is also a realistic expectation.[1,20,47] In its earliest stages, this type of BCI could be used in manned vehicles, vessels, and aircraft to make their operation more efficient by reducing the need for manual input of key functions as required by today's navigation and weapons deployment protocols.

The ethical considerations of employing BCIs for performance modification depend largely on the type of intervention required to implement the device. Because a majority of unclassified DARPA projects are based on noninvasive BCIs, use of such platforms will not be associated with additional risks and can be viewed in a similar manner as the use of night-vision goggles or radiofrequency signals. However, the application of invasive or partially invasive BCIs in soldiers presents an ethically challenging scenario that raises concerns of surgical risk as well as issues of neurocognitive enhancement and alteration of personal identity. Unlike the use of BCIs for therapeutic interventions, cognitive, physical, and psychological enhancement of healthy individuals does not fall under the principle of physician beneficence that obligates doctors to restore health to normal levels through the treatment and prevention of disease. Nevertheless, the ability of BCI devices to expand human capacities must also be viewed in light of the advantage they grant soldiers to perform and succeed in combat missions. In this context, development of BCIs can be seen as making a paramount contribution to the national security, which citizens, including physicians, have a social duty to support. Equally important is the distribution of this technology: in the hands of a responsible military, BCIs can protect national interests and the population at large, but if obtained by rogue groups, they can promote terrorism and instability. On a further level, if an existing BCI application had the potential for significant benefit in a much wider population, such as through therapeutic uses, it would be ethically questionable to sequester its use without justly distributing it to the society at large. All these and other considerations make the role of a neurosurgeon in the development of BCIs particularly complex. Nevertheless, ethical considerations must be foremost applied to the most realistic expectations, such as BCI therapeutics, and deferred in those that are presently more speculative.

Conclusions

Brain-computer interfaces and their potential applications engender great excitement. However, it must be stressed that in their present state, it remains to be seen how far, and in what direction, applications for BCIs will develop. In the near future, guided by a responsibility to the patient and civic duty, the military neurosurgeon can meet the clinical and ethical challenges presented by the field of BCIs to make optimal decisions for those who put themselves in harm's way to serve their country.

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Address correspondence to: Christopher P. Kellner, M.D., Columbia University College of Physicians and Surgeons, The Neurological Institute of New York, 710 West 168th Street, Room 404, New York, New York 10032. email: cpk2013@columbia.edu.