Wartime decompressive craniectomy: technique and lessons learned

BRIAN T. RAGEL, M.D.,1 PAUL KLIIMO 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

1Department of Neurological Surgery, Oregon Health & Science University, Portland, Oregon; 2Neurosurgical Service, Wright Patterson Air Force Base, Ohio; 3Division of Neurosurgery, Connecticut Children’s Medical Center, Hartford, Connecticut; 4Department of Neurosurgery, Brooke Army Medical Center, Fort Sam Houston, Texas; 5Department of Neurosurgery, Madigan Army Medical Center, Fort Lewis, Washington; and 6Department 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.5,23 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).3,13,17

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 hours from the war zone. 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).3,13,17

Abbreviations used in this paper: CJTH = Heathcote 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.
hours from the war zone. 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. 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. 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. 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
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when performing wartime DCs: the midline sagittal incision with “T-bar” extension (the hemispherectomy incision of Ludwig G. Kempe)\(^1\) (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).\(^1\) 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).\(^1\) 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 superi-orly 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-
accomplished 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...
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, steriley wrapped, and stored at −30°F for later autologous cranioplasty.

Results

Decompressive Cranietomy

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.
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, Kirschberg, Germany. United States soldiers were subsequently transported back to the US 3–4 days after injury.2,22 Afghan soldiers 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.

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

<table>
<thead>
<tr>
<th>Injury &amp; Mechanism†</th>
<th>PHI</th>
<th>CHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCs (% of Craniotomies)</td>
<td>FTP</td>
<td>BF</td>
</tr>
<tr>
<td>NATO</td>
<td>19</td>
<td>8 (42)</td>
</tr>
<tr>
<td>AMSF</td>
<td>43</td>
<td>14 (33)</td>
</tr>
<tr>
<td>enemy combatants</td>
<td>7</td>
<td>1 (14)</td>
</tr>
<tr>
<td>local Afghan civilians w/ war-related injuries</td>
<td>21</td>
<td>5 (24)</td>
</tr>
<tr>
<td>total</td>
<td>90</td>
<td>28 (31)</td>
</tr>
</tbody>
</table>

* 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.
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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.

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).1–3,37 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.5 Because of the high incidence of cerebrovascular injury,
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.

Frontotemporal parietal DCs were performed for unilateral injuries and/or swelling, whereas bifrontal craniotomies 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 imbolded bone fragments and foreign bodies were not chased. Second or third operations were sometimes necessary for further debridement of necrotic brain tissue, and it was found that deep imbolded 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 lambdaid 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 Ludwing 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 bandage and skull base reconstruction (Fig. 8). Bone flaps from US
patients were routinely discarded because of fear of infection and because of the excellent cosmetic results obtained with 3D custom-fit prosthetic implants.\textsuperscript{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.\textsuperscript{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.\textsuperscript{7} After analyzing World War II and Korean War head trauma data, Matson\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{3} This difference in GCS scores was not noted on hospital discharge to rehabilitation indicating that DC was associated with improvement in GCS scores.\textsuperscript{3} Bell et al.,\textsuperscript{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.\textsuperscript{3} These patients were often extubated postoperatively with the ability to follow their clinical neurological status prior to transfer out of the war theater.\textsuperscript{3} In comparison, patients with low GCS scores, diffuse brain injury, and exposure to explosive injuries (for example, IED injuries) were

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**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.
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 loss substitutes for dural closure.

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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.