12 Wartime Penetrating Injuries

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Historical Background

The current treatment of penetrating brain injury in military conflict has evolved from the principles established at the end of World War I (WWI) by Dr. Harvey Cushing.[1] Since that time, the strategy of radical debridement utilized in World Wars I and II,[2] the Korean War,[4] the Vietnam War, and the Iran–Iraq War[5] has been followed by an approach of conservative debridement during the Israeli-Lebanon conflict of the 1980s.[6] During Operation Iraqi Freedom (OIF), a method of early radical decompression through the use of hemicraniectomy with conservative debridement and duraplasty has been applied to blast-induced penetrating brain injuries. Although a formal analysis of all casualties is not complete, the immediate impression is that early decompression results in increased survivability and neurological improvement.[7] Ultimately, long-term follow-up will be necessary to determine if early decompression actually improves functional outcome (see **Fig. 12.1**).

The multitude of head injuries associated with trench warfare in WWI challenged early neurosurgeons unlike any prior civil-military conflict.[8] The field of neurosurgery was in its infancy and was unprepared for the complexities of these injuries. Cushing's observations and reports were instrumental during this time in establishing guidelines for treatments. He noted that decreased infection rates limited the major cause of mortality at the time.[1] However, due to the lack of axial imaging and delays in the evacuation process, few operations were actually performed for immediate "life-saving" interventions. Despite these obstacles, Dr. Cushing developed a process of radical debridement of the scalp and skull and irrigation of the track with a catheter, attempting to remove all foreign bodies. This was then followed by a watertight scalp closure without drains. The application of these techniques in a well-equipped center, usually remote from the front, was preferable in his mind to the "frontline" surgery that risked overwhelming infectious morbidity. His classification of penetrating injuries provided the foundation for the concept of limiting secondary injury and promoting eventual reconstruction (**Table 12.1**).

These concepts evolved with improved training and technology during WWII. In a summary of procedures from WWII, Dr. Donald Matson clearly outlined the purpose of far-forward neurosurgery.[9] The tenets of those lessons still hold true in today's interventions and are summarized as follows: (1) the immediate saving of life (hematoma evacuation, brain stem decompression), (2) the prevention of infection, (3) the preservation of the nervous function, and (4) the restoration of anatomic structure.[9] He also attributed the success of medical care in WWII to forward neurosurgical care with specialized equipment, rapid evacuation of casualties to these hospitals permitting early surgery, availability of blood in large amounts in the forward area, and the universal application of antibiotics. The application of these lessons in the current conflict will be the focus of this chapter (**Table 12.2**).

Over the past 5.5 years, our experience has included the treatment of nearly 200 severe, penetrating brain injuries. This population includes a total of 38 patients with severe, traumatic vasospasm, 40 patients with

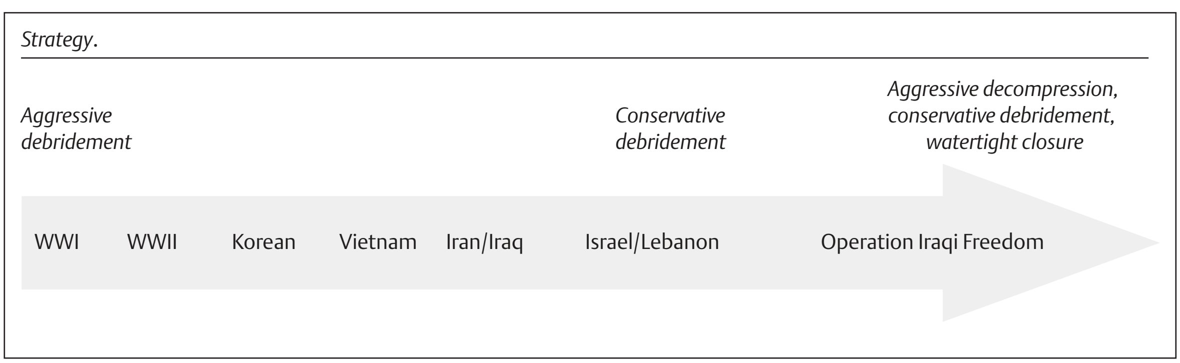

Fig. 12.1 Evolution of neurosurgical approach to wartime penetrating brain injury.

The views presented are the professional opinions of the authors and do not represent the views of the Department of Defense, Department of the Army, or Department of the Navy.

Table 12.1 Cushing's Classification of Penetrating Brain Injury (1918)[1]

Grade	Description	No. of WWI Cases	% Mortality
I	Scalp lacerations with intact skull	22	4.5
II	Wounds with skull fractures/intact dura/ ± depression	54	9.2
III	Wounds with depressed skull fracture/dural laceration	18	11.8
IV	Wounds (guttering type) with in-driven fragments, usually protruding brain	25	24
V	Penetrating wound, lodged projectile, brain usually protruding	41	36.6
VI	Wounds penetrating ventricles with either (a) bone fragments or (b) projectiles	a)14 b)16	a)42.8 b)100
VII	Wounds involving orbitonasal or auropetrosal region with extruding brain	15	73.3
VIII	Perforating wounds, cerebral injury severe	5	80
IX	Craniocerebral injury with massive skull fracture	10	50

traumatic aneurysms, and well over 100 patients who have received decompressive hemicraniectomy. The addition of routine cerebral angiography and transcranial Doppler ultrasonography (US) has augmented patient care. A specific review of our population has revealed that 30% of patients presenting with an initial Glasgow Coma Scale (GCS) of 3 to 5 have good functional outcomes; 60% of patients with GCS >5 have good functional outcomes.

Missiles and Mechanisms of Wartime Penetrating Injuries

The effect of penetrating trauma to the nervous system is dependent on multiple factors (**Fig. 12.2**). As seen in recent conflicts, the incidence of survivable missile injuries (i.e., AK-47 round) to the brain remains low. Recent engagements have identified the use of even higher velocity rounds with longer metal jackets and higher muzzle velocities (i.e., AK-74), which are used as a sniper's weapon of choice. The majority of these wounds is still fatal. This is related to the high likelihood of perforation, global cranial vault disruption, and high cavitation pressures. However, the majority of injuries during Operation Iraqi Freedom have been from roadside "IEDs" or improvised explosive devices. These include vehicle-borne delivery systems commonly referred to as either "car bombs" or "suicide bombers." These munitions are variable in their design and delivery of injury. The injuries are dependent on the explosive that is used, the distance from the explosion, the shape of the projectile, and lastly the viscoelastic properties of the impacted tissue. Such projectiles are propelled by enormous blast-overpressure forces, which may account for the injury force beyond the flying projectiles or the terminal impact. Syndromes of central nervous system (CNS) dysfunction associated with blast injuries have been identified and classified since WWII.[10] During the explosion of such devices, flying projectiles include the materials used to make the bomb (primary projectile) and additional materials (i.e., nails and other metallic objects, rocks, glass, body parts) packed around the device by the enemy (secondary projectiles). These fragments, although traveling with lower terminal velocity compared with the sniper's round, inflict significant destruction due to their abnormal size, shape, and porosity.

Unlike the previously discussed metal fragments, nonmetallic fragments may lead to delayed abscess formation and secondary sepsis. In the case of a vehicle-borne IED (VBIED), the metal from the auto can act as a secondary projectile (**Fig. 12.3**). Debris from surrounding buildings

Table 12.2 Matson's Tenets

Matson's Tenets[9]	Current Application
I. Save life	Application of ATLS/ACLS/far forward homeostasis and hemicraniectomy
II. Prevent infection	Watertight dural closure
III. Preserve nervous system function	Prevention of secondary neurologic injury through advanced neurocritical and neurointerventional care (i.e., meningitis, seizures, stroke)
IV. Restore anatomic function	Restore anatomic protection and contour (i.e., cranioplasty)

Abbreviations: ACLS, advanced cardiac life support; ATLS, advanced trauma life support.

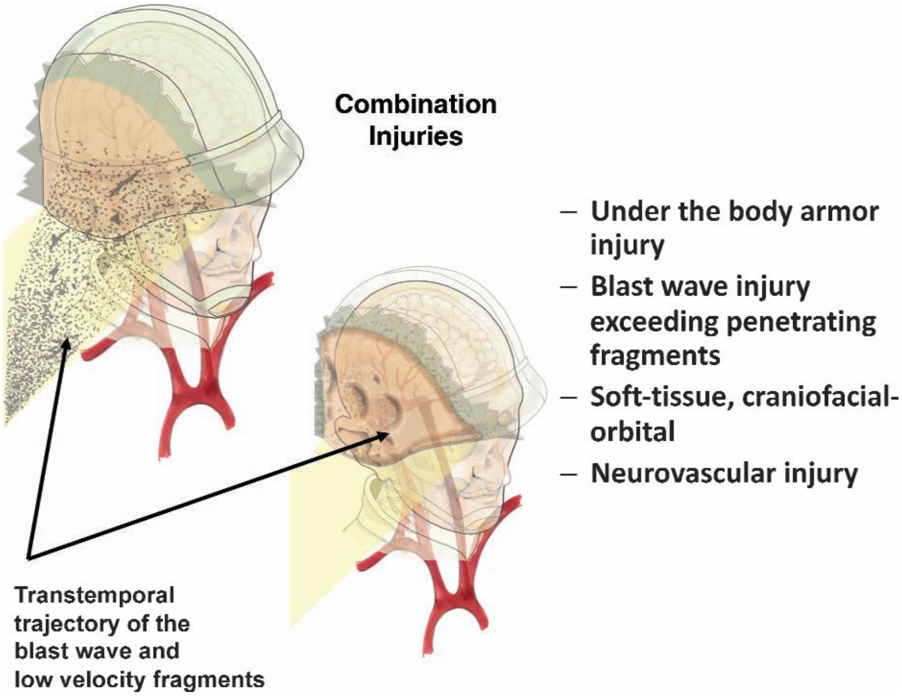

Fig. 12.2 The effect of penetrating trauma to the nervous system is dependent on multiple factors. Four injury patterns are described. Under the body armor injury occurs when the inner portion of the armor delaminates and impacts the underlying scalp, skull, and brain. This creates a piston-like high-energy impact that reverberates through the cerebral tissue and cranial vault. The propelling blast waves exceed the visual identified fragments and lead to remote injuries in the cerebral tissue and surrounding structures. Those structures with immediate and delayed injury (within 2 weeks of impact) include a selective vulnerability of the cerebral conducting arteries. This includes traumatic pseudoaneurysm typically perpendicular to the fragment track, and large conducting vessel injuries at the skull base and circle of Willis. In particular, the supraclinoid carotid artery, where it is fixed at the distal dural ring, has the highest incidence of delayed vasospasm.

in the form of glass or stone can also be propelled and penetrate the calvarium (**Fig. 12.4**). Some of the most lethal of these “antipersonnel” devices include the use of small spherical bolts (**Fig. 12.5**). Reported by the Israelis to have significant lethality when penetrating the cranial vault, these small round fragments have been noted to cause well-delineated anatomic damage as well as minor deficits.[11] In one case, the Israelis identified acute hydrocephalus when the fourth ventricle was occluded by a spherical bolt. In cases in which the cranial base or sylvian or interhemispheric fissure has been penetrated, these fragments can rupture major vessels, create pseudoaneurysms, or even lodge into the venous sinuses. During the initial assessment of patients with metallic and

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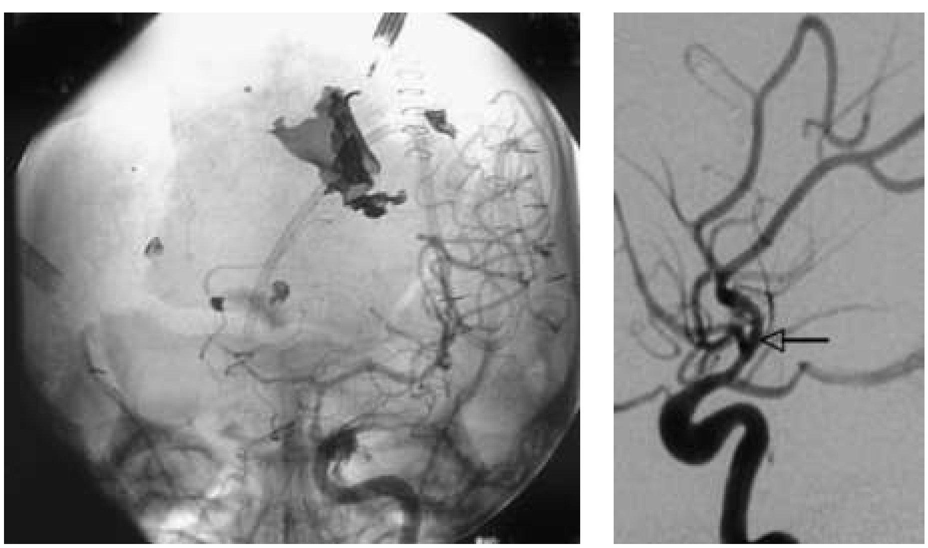
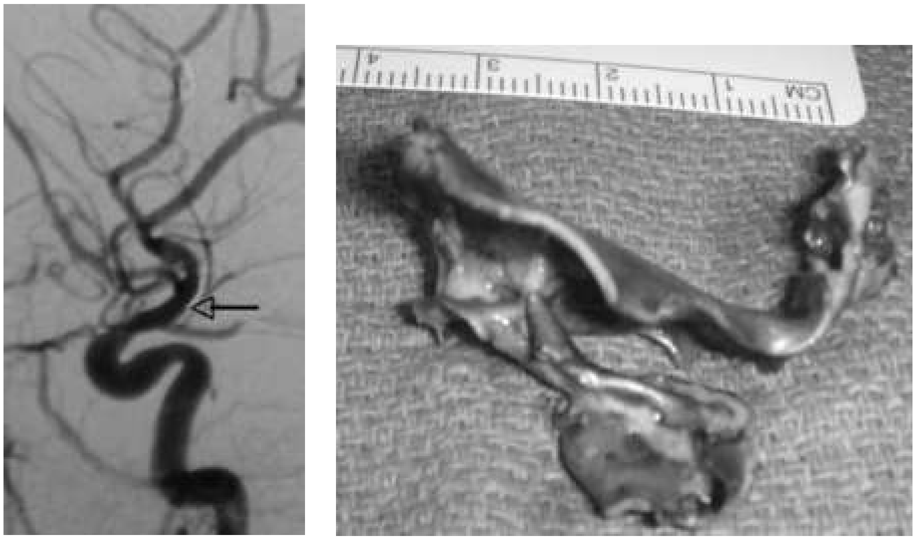


B

Fig. 12.3 (A) This patient initially presented with a Glasgow Coma Scale score of 3 with severe burns and scalp tissue loss with a large penetrating fragment from a car bomb crossing the midline above the diencephalon into the interhemispheric fissure. He underwent an immediate right hemicraniectomy, evacuation of a subdural hematoma, and placement of a ventriculostomy. **(B)** He developed delayed severe bilateral vasospasm (*black arrow*) treated with



C D

Fig. 12.3 *(Continued)* **(C)** microballoon angioplasty and nicardipine (*black arrow*). **(D)** He was taken back to the operating room for removal of the large metal fragment measuring ~4 cm. He underwent a cranioplasty with tissue expanders previously placed, yet required a latissum dorsi flap due to tissue breakdown. At 36 months postinjury, he is ambulating independently, effectively communicating, and feeding himself.

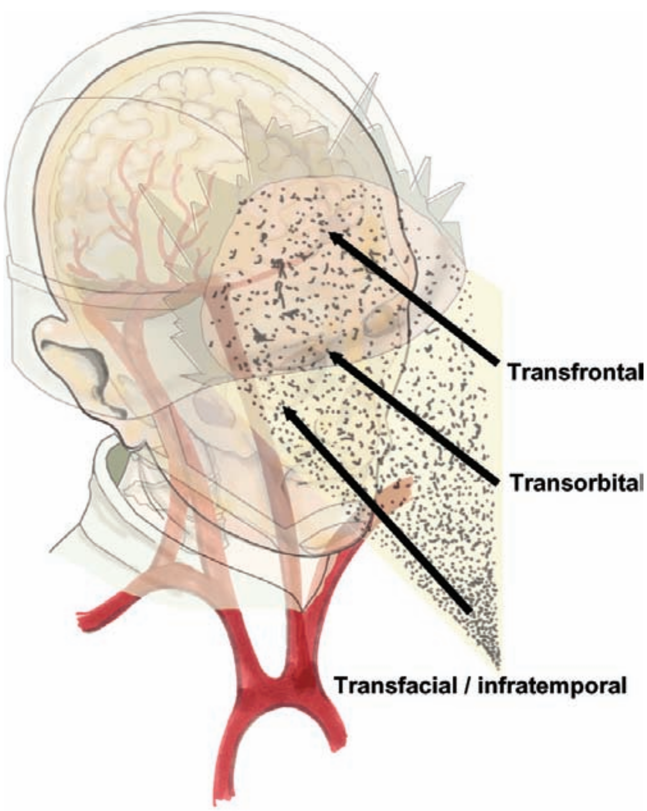


Fig. 12.4 Debris surrounding the explosion is propelled as secondary fragments. In a vehicle or building this occurs in the form of twisted metal, glass, or roadside stones and can penetrate the calvarium via the orbit and midface. In a frontal direction significant anatomic disruption results to the anterior skull base, orbit, midface, airway, and bilateral frontal lobes as well as the anterior cerebral artery complex in the interhemispheric fissure. The soft tissue, supporting bony framework, and anatomic continuity are lost from the skull base to the orbit and infratemporal fossa.

nonmetallic foreign body penetration, the question of removal must be considered and may be influenced by multiple variables. Ventricular or paraventricular location of such metallic or nonmetallic porous material has been associated with delayed infections and late neurological deterioration.[12] Overall, if there is evidence of fragment movement, contact with the cerebrospinal fluid (CSF) within either a cisternal or ventricular location, or location adjacent to a vascular structure, it may be advisable to remove the foreign body (**Table 12.3**). The exception may be interhemispheric bone fragments without vessel abnormality. Regardless of approach, the fragments should be followed radiographically to assess for any evidence of delayed movement or abscess formation. This conservative approach is acceptable because reoperation to remove fragments has not been shown to reduce the seizure rate or the incidence of late infections but has increased the neurological morbidity.[6,13]

Management of Wartime Penetrating Injuries

Initial Resuscitation

The application of Matson's tenets begins at the point of injury. Combat medical personnel are faced with multiple challenges, not least of which is resuscitating the patient while under enemy fire. Unlike the civilian environment, the care of the military casualty is often hindered by the ongoing threat to the unit. Medical teams are specifically targeted by the enemy to discourage, demoralize, and

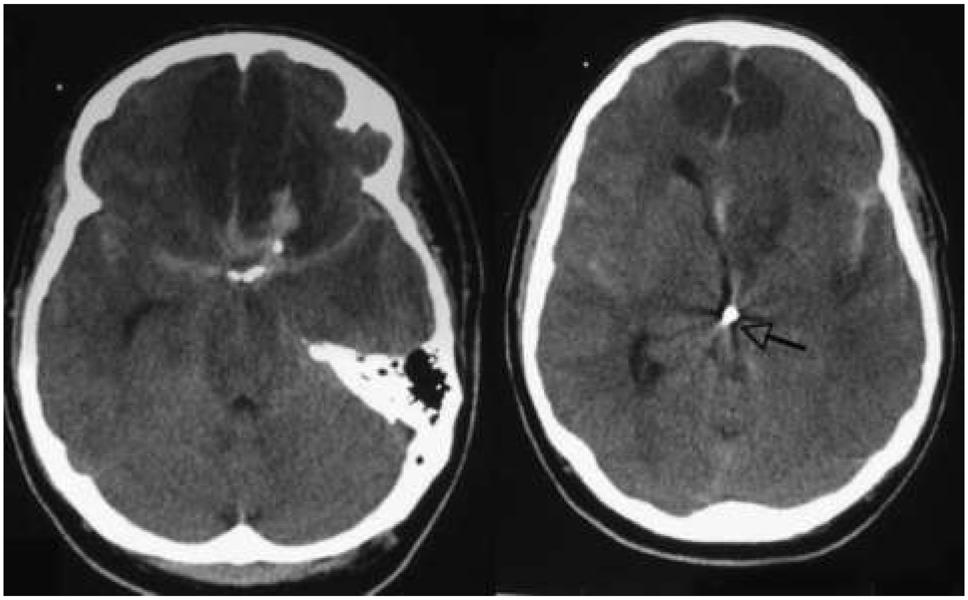


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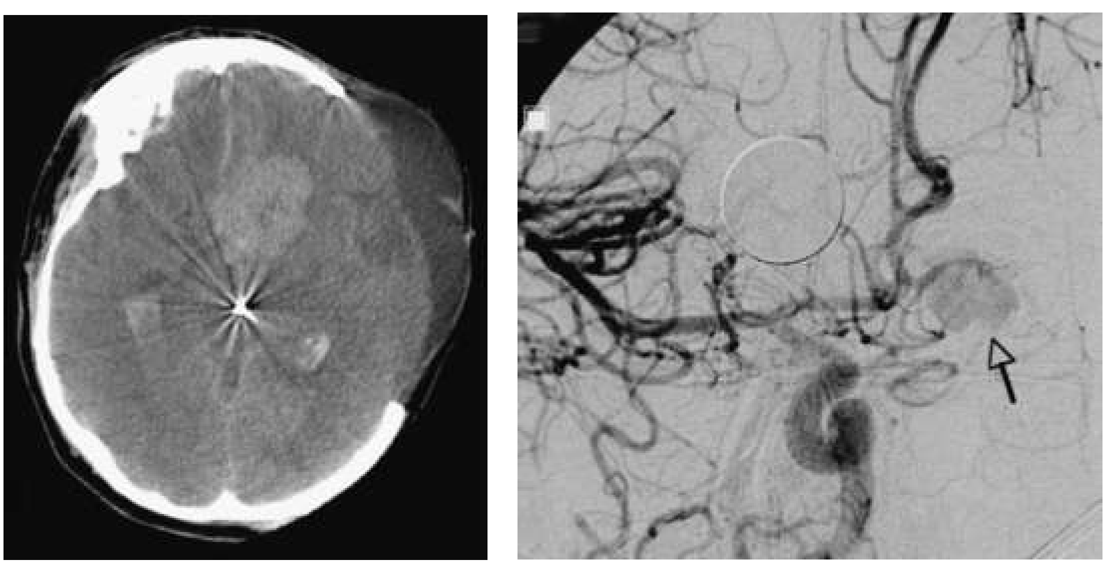
Fig. 12.5 (A) This soldier had an initial Glasgow Coma Scale score of 7 with a transorbital spherical bolt penetration deposited into the pineal region (*black arrow*, **B**). **(C)** He received a ventriculostomy then delayed left hemicraniectomy and **(D)** subsequent cerebral angiogram demonstrating an anterior communicating artery pseudoaneurysm. The patient reruptured this pseudoaneurysm following rapid enlargement and expired.



C

D

Table 12.3 Criteria for Removal of Intracranial Fragment

- Movement of fragment
- Abscess formation
- Vessel compression or contact
- Porous material in contact with cerebrospinal fluid (i.e., rock, wood)

deter the unit's combat effectiveness. Therefore, a concept of removing the casualty from the “kill-zone” is essential prior to focused resuscitation. In a direct firefight, the medic's first priority may be to return fire in an attempt to suppress the enemy before evacuating the casualty. Because most of the injuries during OIF have occurred from unmanned roadside bombs (i.e., IEDs), the medical plan is typically adjusted. Unlike civilian trauma and previous military conflicts, immediate evacuation from the “kill box” is of the utmost importance. After mobilization to a safer area, initial resuscitation and medical evacuation to the next level of care are conducted.

Early airway and hemorrhage control combined with rapid evacuation is the first stage in the resuscitation of a casualty with severe neurotrauma. Direct transport to neurosurgeons located in the combat support hospital (CSH) has allowed immediate intervention, leading to improved survivability. The exact magnitude of increased survival is difficult to evaluate because, with such rapid evacuations, a higher proportion of expectant wounds are seen by the neurosurgeon than in prior conflicts.

Far Forward Neuroimaging and Neurosurgery

The challenges of complex, severe military penetrating brain injury (PBI) are addressed by the coordinated efforts of physicians, nurses, and technicians at the CSH. In the United States military medical model, the CSH is the first location where both neurosurgery and computerized tomography (CT) scanning are available. After the initial airway, breathing, and circulation have been managed, a hemodynamically stable patient must undergo appropriate imaging. At this stage, it is imperative that no unnecessary delay prevents appropriate cranial decompression for a life-threatening lesion. Occasionally, life-threatening extracranial bleeding must first be treated. Multiple options exist with the most practical and efficient including simultaneous cranial/corporeal intervention or delayed imaging after hemodynamic stability has been achieved. Delayed neuroimaging is used when faced with a closed injury, a neurologically stable patient, or patients undergoing prolonged extracranial procedures without the benefit of an immediate postoperative examination.

The approach to the severely brain injured patient has evolved throughout the current conflict. Because of the long transport flights that must occur, the practice has changed to include wide decompressive hemicraniectomy with subsequent duraplasty and watertight closure as early as possible. The thought is that the decompression may mitigate or reduce incidence of secondary neurological deficits that occur from malignant intracranial hypertension. Nevertheless, as in civilian neurotrauma, most cranial interventions will include early postoperative imaging and intracranial pressure (ICP) monitoring where appropriate.

Medical Evacuation

The medical evacuation of the severely injured soldier or marine to the United States currently involves a stop in Germany and includes over 7,200 miles of travel. The medical hazards of this trip must be taken into consideration and include the effects of delayed cerebral edema, hydrocephalus, or hemorrhage, which may occur during transfers or flight. To address these issues, critical care air transport teams have been instrumental in the strategic evacuations of patients from Baghdad to Germany and beyond. Management of elevated ICP, hypoxia, and hypotension is their primary focus; each team consists of a physician, nurse, and respiratory technician and is rarely supplemented with a neurosurgeon or neurologist. Out of over 21,000 casualties, over 500 intubated neurotrauma patients have been transported in this fashion. Additional operational challenges include enemy activity, weather, and airframe function.

Description of Injuries

Patterns of penetrating trauma in both civilian and military have been classically described based on the fragment path. The key element is the unseen force propelling the fragment. Rarely is this force completely characterized in a bomb blast. Typically, all that is seen are the fragments, spall, or retained overlying clothing driven into the cranial vault. A complete physical examination allows the ability to identify points of foreign body entry or exit. The most commonly missed region of fragment entry includes the retroauricular and suboccipital regions. Fragment entries from these sites are particularly hazardous, with the increased risk of vascular, cranial nerve, or brain stem injury.

Perforating

These injuries typically carry the worst prognosis, especially when associated with high-velocity injuries or when the injuries cross the midline or are transhemispheric. In a large series of civilian gunshot wound (GSW), the lateral penetrating injury had a poorer outcome compared with anteroposterior injuries. Lateral perforation wounds typically have the poorest outcomes. Despite early emergent surgery, functional survivability is rare among these combat casualties. The high-energy force propelling the missile or fragments through the cranial vault creates an immense deforming force. In some cases, this force is so powerful it can deform the entire cranial vault and can be typically seen with injuries from AK-47 rounds (**Fig. 12.6**). The high muzzle velocity can create perforating injuries that will transfer enough injury to "burst" the cranial vault. Such expansive forces will ovalize the skull, resulting in fractured plates of the cranial vault. The centripetal forces explode outward creating deformation of the cranial cavity. Patients with this type of injury may initially present awake, moving spontaneously, and sometimes talking. Invariably, however, many will do poorly despite aggressive surgical intervention. Despite hemicraniectomy and bifrontal decompression, the degree of neuronal disruption rarely leads to functional

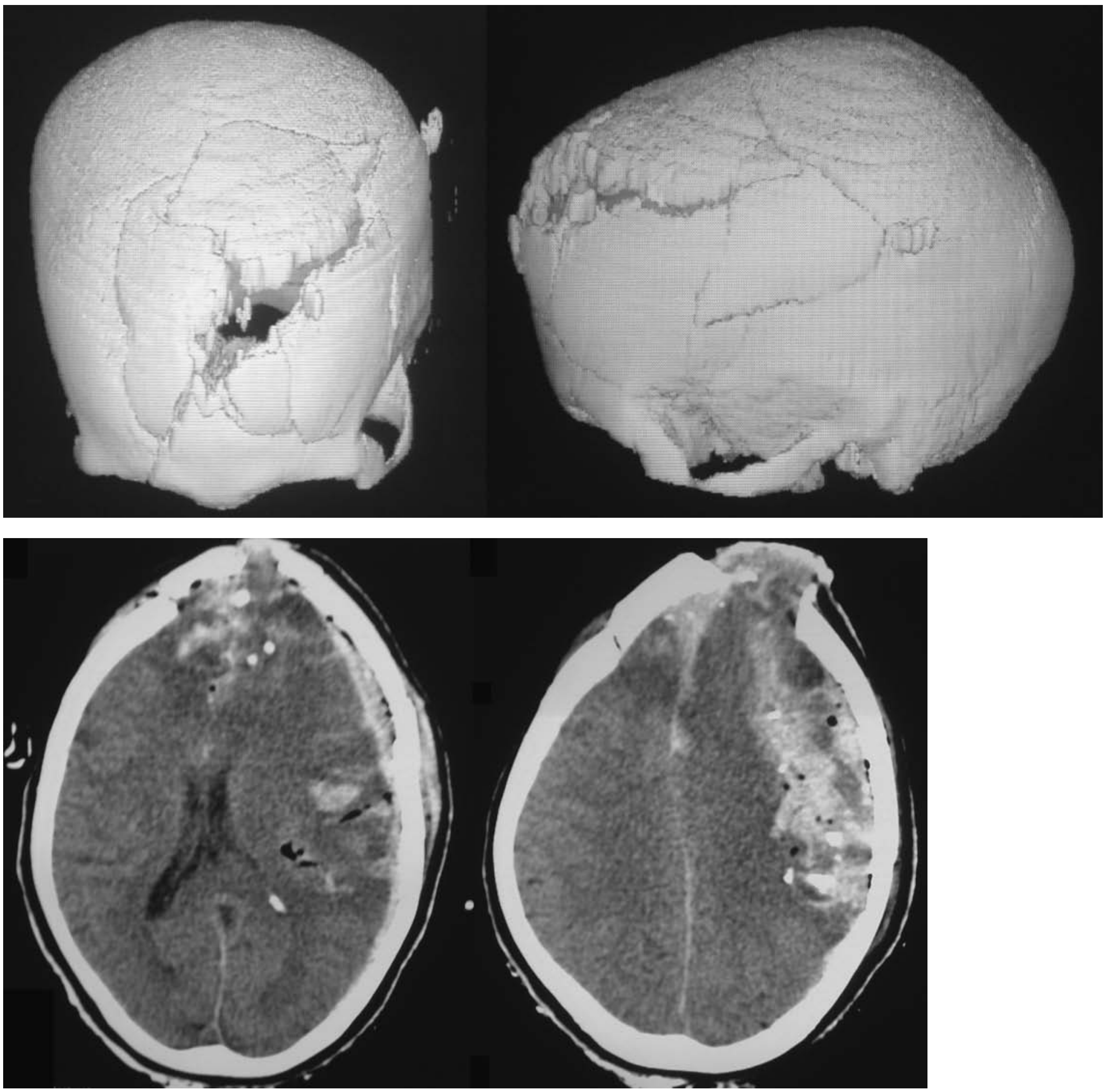


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Fig. 12.6 **(A)** This civilian victim of a suspected AK-47 perforating round was without body armor and was evacuated to the combat support hospital within 20 minutes of her injury localizing on examination with open, herniating brain through a complex scalp defect. **(B)** Computed tomography demonstrated evidence of global deformity with "bursting pattern" of an expansile skull fracture deforming the skull shape **(A)**. Patient underwent left hemicraniectomy, repair of the anterior aspect of the sagittal sinus, duraplasty, and placement of a monitor. Patient later deteriorated from a coagulopathy on post-operative day (pod) #4.

survival. In some cases, rapid decompression may lead to an associated hypotension especially in hypovolemic patients whose blood pressure will typically drop during decompression. Communicating with your anesthesiologist will allow appropriate anticipation of this response.

Penetrating

The most lethal of the penetrating injuries include those through the central region of the brain, referred to as the zona fatalis (**Fig. 12.7**). This region includes the suprasellar area comprising the third ventricle, hypothalamus, and thalamus. As in civilian wounds, the mortality is near 100%, with functional survival <2% from wartime wounds in the region. Trajectories that pass through this region with a significant force may disrupt the midline vascular structures, including the anterior communicating artery and the deep venous system, and can result in significant intraventricular hemorrhage. The greatest damage, however, comes from the cavitation track or direct damage to the surrounding reticular activating system, the hypothalamus, and the thalamus. Patients who survive these injuries are typically in a persistent vegetative state. A characteristic sign seen

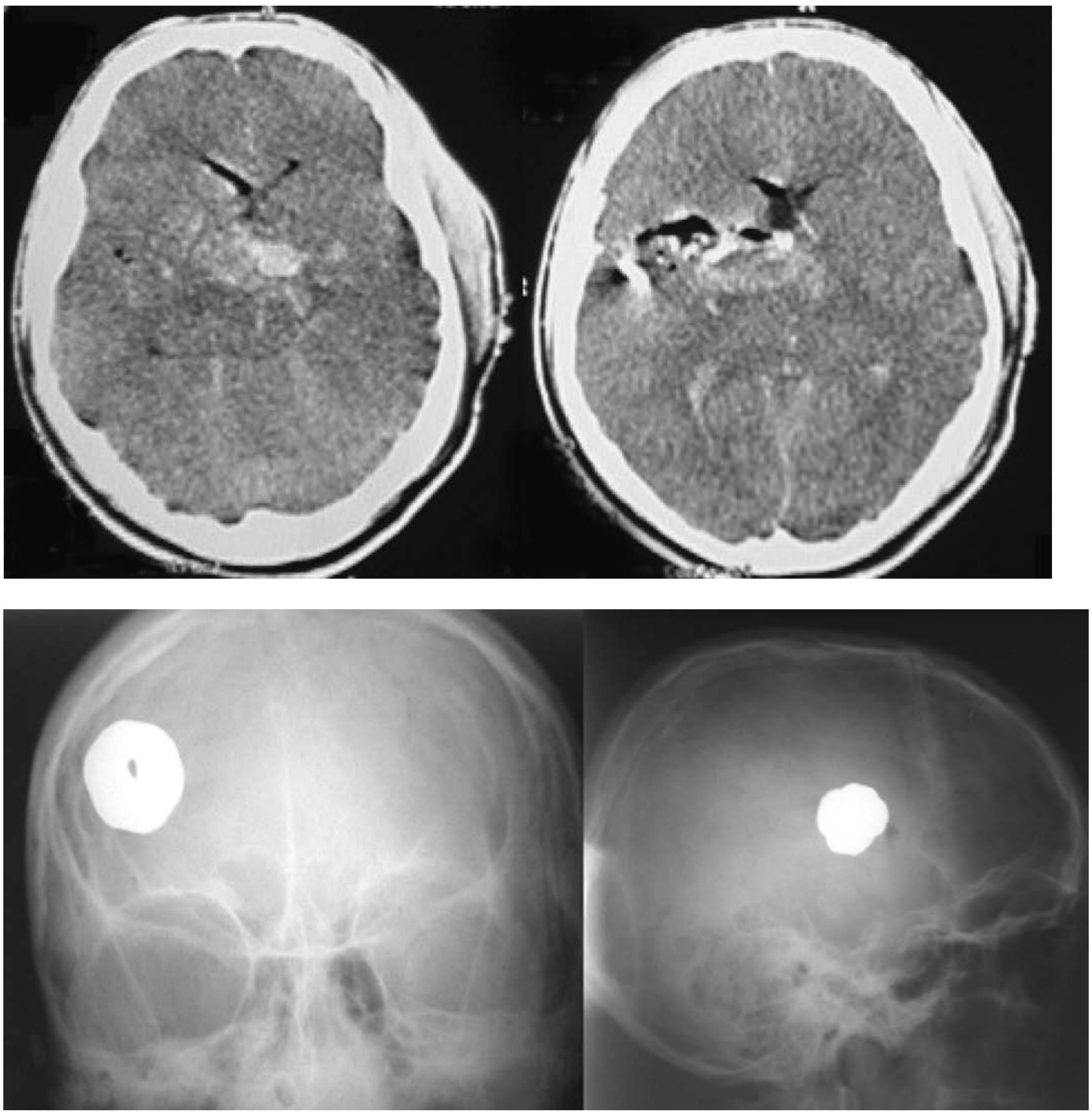

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Fig. 12.7 (A, B) Soldier struck by an improvised explosive device (IED) explosion with a flying hexagonal nut coursing from the left temporal region through the diencephalon bilaterally and into the contralateral right frontal region. On examination, he was initially localizing at the scene then deteriorated to extensor posturing at 30 minutes without a focal new hematoma. He expired within 4 hours of his injury after a conservative course.

Table 12.4 Complications of Wartime Penetrating Brain Injury

Time	Type of Complications	Treatment
0–24 h	ICP increased	Hemicraniectomy
	Hematoma	Evacuation/coagulation correction
	Ischemia	Decompression/ID occlusion
	Anatomic defect	Anatomic closure
	Hypoxia	Airway/pulmonary correction
	Hypotension	Overt or occult EBL
		PRBC/FFP/PLTS vs. whole blood vs. hypotonic saline
24–48 h	ICP increased	Hemicraniectomy
	Hematoma	Evacuation/coagulation correction
	Hydrocephalus	Ventriculostomy
	Edema	Decompression
	Seizure	Antiepileptics/cEEG monitoring
72 h–1st wk	Edema	Medical/surgical decompression
	ICH (Contusion)	Correct coagulopathy
	Hydrocephalus	Ventriculostomy
	CSF leak	Repair/CSF diversion
	Ischemia	Medical/endovascular Tx
	Pseudoaneurysm	Surgical/endovascular Tx
	Seizures	Antiepileptics/cEEG monitoring
2–3rd wk	Infections	R/O abcess, CSF infection
	Vasospasm	TCDs, PbO_2, cEEG, CBF monitoring with combined HHH versus angioplasty
	Pseudoaneurysm	Endovascular versus microsurgery
	Seizures	Antiepileptics
	Delayed hydrocephalus	VP shunt (low-pressure consider use of programmable valve)
1–6 mo	Infection	R/O abscess, meningitis
	Low-pressure hydrocephalus	VP shunt (programmable valve)
	Syndrome of trephine	Reconstructive cranioplasty
	Seizures	Antiepileptics
	Cranioplasty complications	
	Temporalis atrophy	Resuspension/implant/fat graft
	Infection	Prosthesis removal
	Hydrocephalus	VP shunt
	Epidural/subgaleal	Drainage
	Hygroma/hematoma ICH	Evacuation
	Scalp necrosis	Free-flap

Abbreviations: CBF, cerebral blod flow; cEEG, continuous electroencephalogram; CSF, cerebrospinal fluid; EBL, estimated blood loss; FFP, fresh frozen plasma; ICP, intracranial pressure; ICH, intracranial hematoma; HHH, hypervolemic, hypertensive, hyperdynamic; PLTS, platelets; PRBC, packed red blood cells; R/O, rule out; TCD, transcranial doppler; Tx, treatment; VP, ventriculoperitoneal.

in civilian injuries, and occasionally in lower-caliber wartime injuries, is the “tram-track” sign. This represents the cavitation tract and is associated with significant energy transfer, significant edema, and poor outcome. This outcome is commonly repeated in the transhemispheric, transventricular wound. Multiple hemisphere injury and crossing the midline at the level of the corpus callosum or below portends a high mortality and poor functional outcome.[14] As stated earlier, these missile tracts have been associated with pseudoaneurysms. Typically occurring perpendicular to the long axis of the tract, they are associated with ischemia or delayed rupture if not appropriately treated. The M1 segment is particularly vulnerable in some of these paths. Deeply embedded metals are not classically retrieved unless they are in the ventricular system, in motion, compressing a large vascular structure, creating hydrocephalus, or associated with a delayed abscess. Again, the early use of radical hemicraniectomy with duraplasty has allowed a higher survival and earlier, improved functional outcome in this population than previously predicted. In many of these cases, a majority may have presented initially talking before massive edema, shift, and cerebral dysfunction occurred. The patients typically have a poorer examination after the first 48 to 72 hours, usually due to delayed cerebral edema or hydrocephalus. In selected cases, delayed blast-induced vasospasm may occur, although this is typically seen after the first week.

Injury Patterns and Management

Complex cranial–facial injuries are typical in the OIF conflict. Comparable to WWI trench-warfare, the head and neck is a region of selective vulnerability. Injuries that bridge the craniocervical junction, associated orbitofacial injuries, and injuries to the neck have been particularly challenging to treat. Cranial-basal injuries have a tendency to have a higher association with neurovascular injuries with a profound risk for delayed stroke and death. Additionally, this region is also associated with a high rate of CSF leaks, fistulae, and infections. The disruption of the cranial base with communication with the orbit, pharynx, and infratemporal fossa may be associated with cranial nerve injuries, blindness, and globe disruption. Avoiding associated complications begins with a high index of suspicion followed by an aggressive role for neuroangiography, meningitis monitoring, and cranial nerve evaluation (**Table 12.4**).

Orbitofacial Injuries

Orbitofacial injuries in this conflict are highly associated with neurovascular injuries, CSF leakage, and death[15] (**Fig. 12.5**). Biomechanical studies of penetrating trauma to the maxilla and mandible have demonstrated significant force transmission to the brain. In particular, the pressure waves in the brain were greatest when Chinese M193 or M56 military bullets were used in animal models compared with 1.03 grain spheres at 1,400 m/s or at 800 m/s.[16] Transorbital intracranial entry risks injury to the internal carotid, cavernous sinus, anterior communicating artery complex, optic nerve, and cranial nerves II to VI (**Fig. 12.8**). This is most common when the medial aspect of the orbit is penetrated. Diffuse intracranial air associated with a transorbital injury strongly increases irreversible brain stem injury, transorbital cerebral herniation, and increases the risk of death. Disruption of the orbital roof can create a communication with the intracranial cavity, leading to associated CSF leaks, encephalocele, intracranial abscesses, or delayed orbital reconstruction difficulties. In extreme blast cases, the maxillary sinus, orbit, and anterior cranial vault will all communicate through a traumatic disruption, exposing the brain to the sinus mucosa. In such cases, it is usually necessary to re-create surgically the cranial base, orbit, and maxillary sinus to protect the brain and obtain a cosmetically acceptable result. The use of titanium mesh fixation for the anterior skull base floor in theater has allowed subsequent surgeons to then use that foundation to keep the cerebral-orbital spaces separate. This closure is reinforced with pericranium (when available), fascia lata, temporalis fascia, fat, and occasionally split-thickness skull bone graft.

Surgical Considerations

The overall management goals include acute decompression and hemorrhage control. This is typically accomplished with a bifrontal craniotomy or craniectomy. In cases with disruption of the anterior cranial floor and frontal sinus with obvious risk for CSF leakage, a sinus exenteration, skull base reconstruction with watertight dural closure is usually performed. In restricted situations such as those akin to combat conditions involving mass casualties, lack of imaging, and lack of ophthalmology support, a limited procedure may be initially performed. This includes epidural hematoma evacuation followed by transfer to another neurosurgeon within 24 hours for a more definitive anterior skull base reconstruction. This was the case during the attack on the United Nations headquarters in Baghdad where over 150 casualties arrived at the combat support hospital and 30 underwent open surgeries. Half of these required cranial or cervical surgery to remove glass embedded within the cranial vault, face, orbit, or neck. The possible array of penetrating fragments includes glass, rocks, metal, and occasionally the fragments of the suicide bomber. Plain films and the

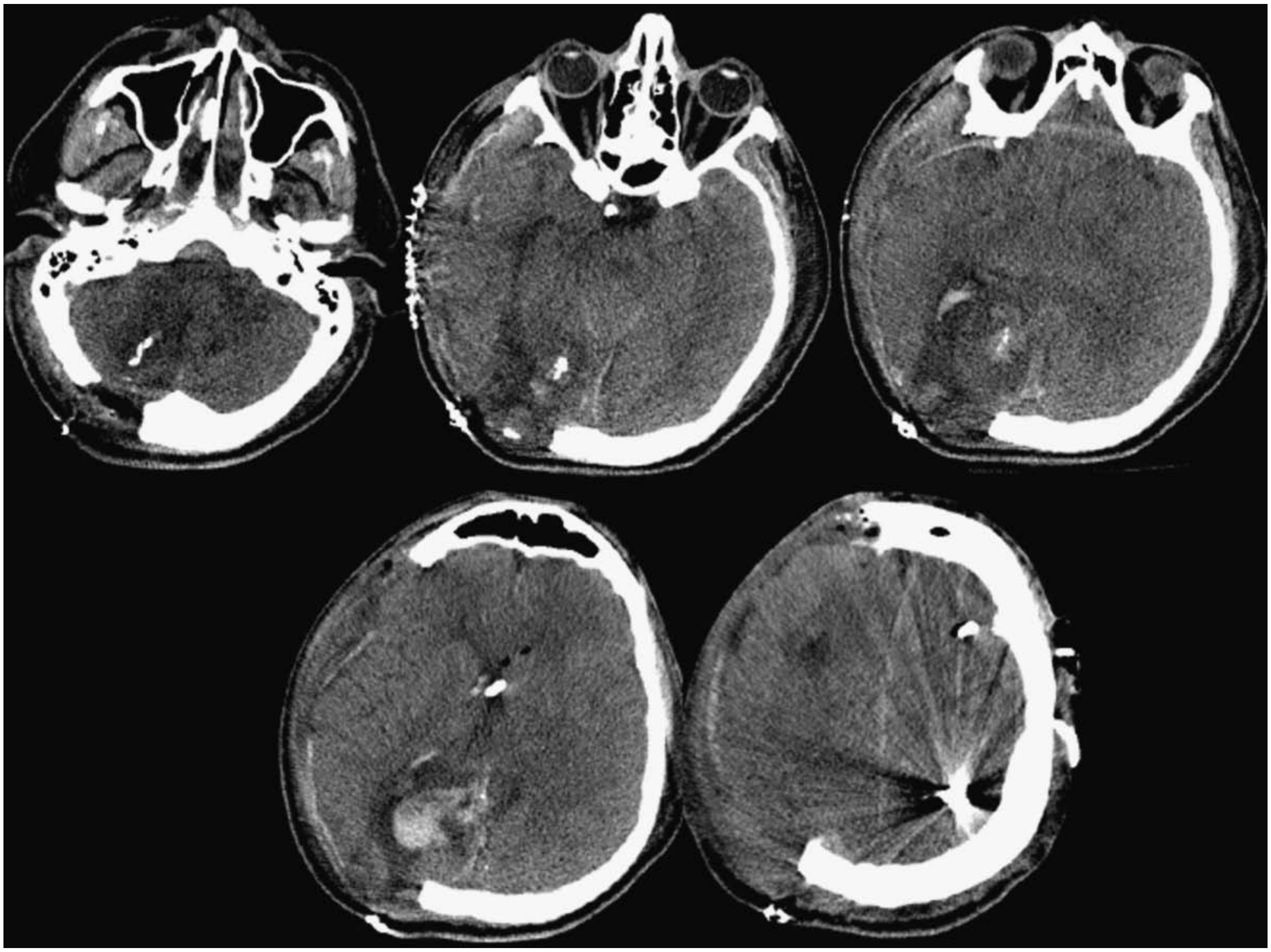


Fig. 12.8 This patient had an initial Glasgow Coma Scale score of 3 with a penetrating right suboccipital fragment passing transtentorially into the occipital lobe on the left, then into the right occipital parietal junction. The patient underwent a suboccipital craniectomy, right hemicraniectomy, transverse sinus ligation preserving the vein of Labbé, and placement of a ventriculostomy. He demonstrated delayed recurrent severe bilateral internal carotid artery, middle cerebral artery vasospasm requiring microballoon angioplasty and nicardipine. His examination improved with following commands, speaking spontaneously, and moving all four extremities. He demonstrated delayed hydrocephalus requiring a ventriculoperitoneal shunt.

physical examination are particularly helpful in understanding the global distribution of the fragments, the path of injury, and the best surgical approach. Unlike metal, an attempt is made early to remove glass, depressed bone over air sinus, clothing, body armor, and rocks from the cranial vault. However, deeply embedded fragments are not pursued unless there is documented delayed movement or vascular compromise. This is in keeping with avoidance of secondary injury through missile tract exploration.

Transtemporal Injuries

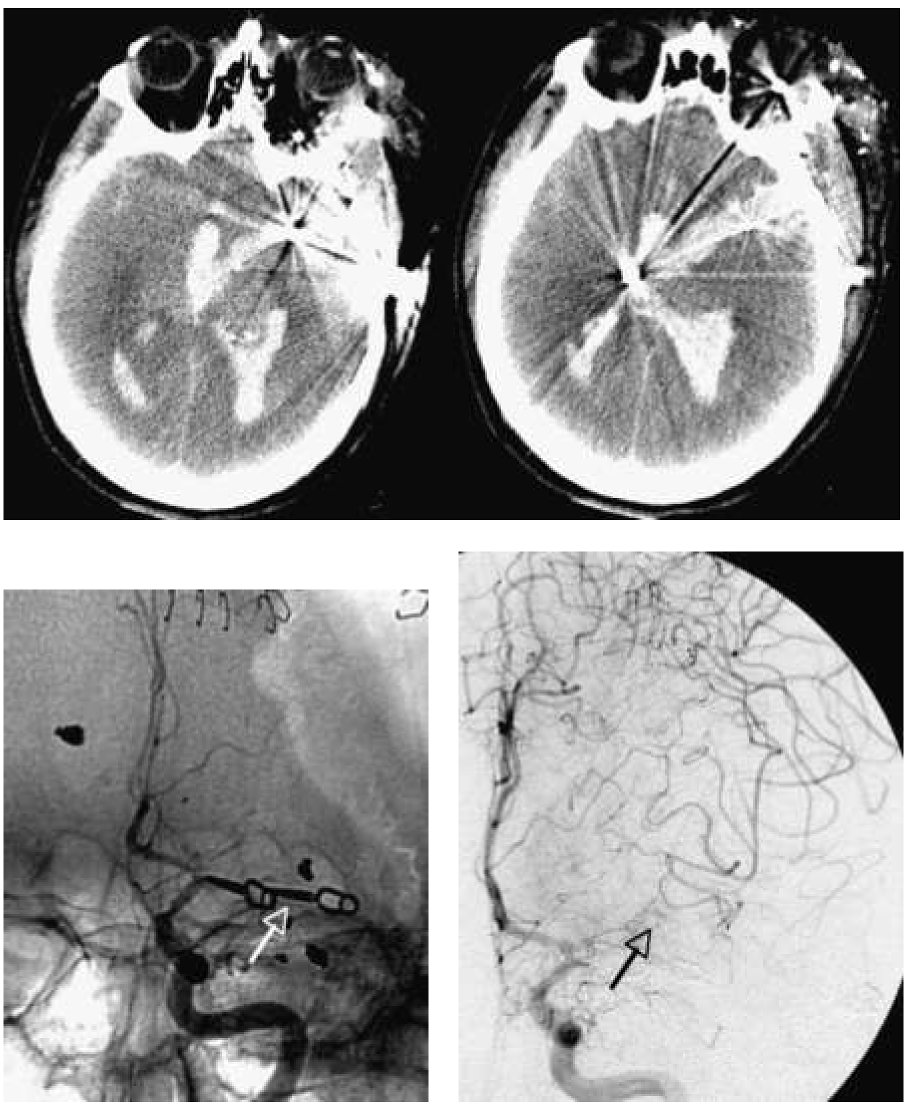
Those injuries that penetrate the frontotemporal region of the cranial cavity may include underlying injury to the frontotemporal lobes, internal carotid and middle cerebral arteries, and lateral ventricles with intraventricular hemorrhage (**Fig. 12.9**). Additionally, those associated with a significant force to the skull base may destroy the petrous bone; petrous carotid artery; facial, auditory, and trigeminal nerves as well as the lateral orbit and optic nerve. This can lead to CSF leaks, pseudoaneurysms, blindness, loss of usable hearing, and facial paralysis.

Surgical Considerations

Injuries in the region of the lateral skull base should include proximal exposure and control of the cervical carotid artery and its branches. In cases of intractable epistaxis, endovascular methods are preferred to obtain proximal control but may not be possible in an austere environment. Reconstruction of the petrous carotid artery is particularly challenging in a combat environment. Multiple constraints include the lack of intraoperative angiography, the absence of a high-definition operating microscope and microinstruments, the reduced availability of grafts due to extremity injuries, and most critically, the presence of a swollen, edematous, and hemorrhagic brain. In some cases, it may be more reasonable to perform a proximal and distal supraclinoid internal carotid artery (ICA) ligation to prevent a thromboembolic middle cerebral artery (MCA) stroke.

Laterally displaced entrance wounds may create a significant amount of soft tissue loss. This will challenge both the initial closure as well as the delayed reconstruction. In an attempt to preserve the known vascular pedicles, it may be preferable to base a curvilinear incision behind the ear to the anterior forehead (**Fig. 12.10**). The superior temporal artery will play an important role in scalp viability with a large hemicraniectomy flap.

Preservation of the vein of Labbé and viable MCA branches is an important part of the surgical decompression. Adequate bone removal insures that venous compromise from swelling at the bone edge will not occur. Following dural opening, a careful examination of the sylvian and cortical MCA branches should take place because the branches of the middle cerebral artery most



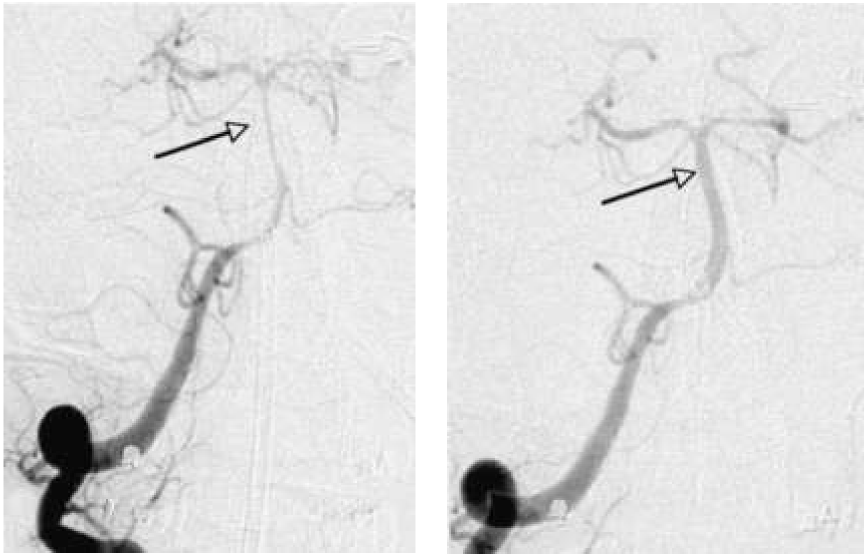
A

B

C

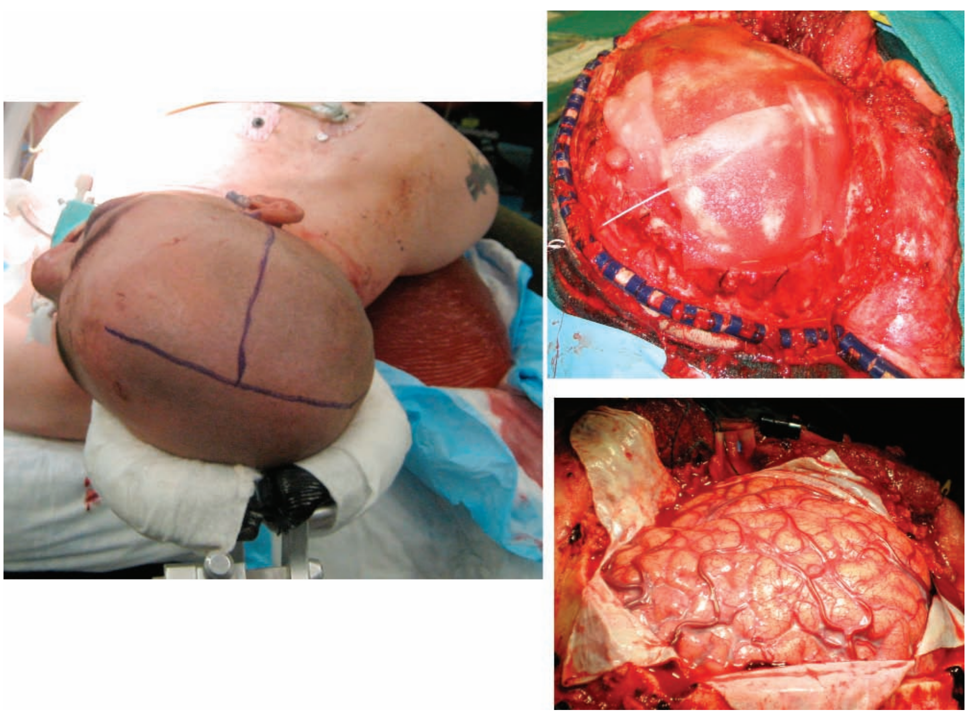
Fig. 12.9 **(A)** This soldier presented with a Glasgow Coma Scale score of 3 with a lateral temporal penetrating fragment coursing through the sylvian fissure, central diencephalon bilaterally, and third ventricle with significant SAH, IVH, and temporal lobe hematoma. He underwent a left hemicraniectomy, clipping of a transected left middle cerebral artery **(B**; *white arrow*, **C**; *black arrow***)**, evacuation of the temporal lobe hematoma, and placement of a ventriculostomy **(B, C)**. The postoperative course was complicated by posterior circulation delayed severe vasospasm requiring microballoon angioplasty and intraarterial nicardipine 1.

(Continued on page 250)



D E

Fig. 12.9 *(Continued)* **(D, E)**. Delayed cranioplasty was performed at 6 months and required ventriculoperitoneal shunting for delayed hydrocephalus. The patient's best examination at 8 months remains minimally reactive localizing, but the patient is noncommunicative with a right hemiplegia.



A B C

Fig. 12.10 **(A)** Alternative hemicraniectomy incision with midline curvilinear incision with vertical bisecting incision to the root of the zygoma. Originally described by Dr. Ludwig Kempe at the Walter Reed Army Medical Center during procedures for hemispherectomy and reintroduced in the current conflict by Major Jon Martin, MD, while serving in Balad, Iraq, in spring 2007 [Kempe, L. Operative Neurosurgery Vol 1. New York: Springer Verlag; 1968; 180–189]. Brain is covered by synthetic dura after placement of an ipsilateral intracranial pressure monitor, tunneled at the midline, a large 7fr subgaleal drain is then placed before closing the scalp **(B, C)**.

commonly injured include those in the distal cortical surface or lateral fissure. Typically, pseudoaneurysms are perpendicular to the fragment path in the zone of cavitation adjacent to the track and, if encountered, should be excluded from the normal circulation. Suspicion for traumatic aneurysms should arise when a sylvian fissure hematoma, focal parenchymal blood (i.e., gyrus rectus hematoma), or a hematoma remote from the fragment are present.

Delayed complications from injuries in this region include CSF leaks, pseudoaneurysm rupture, thromboembolic strokes, and flap necrosis associated with devascularization (**Table 12.4**). Commonly, CSF leaks include a disruption of the petrous skull base with underlying low-pressure hydrocephalus. In the presence of a hemicraniectomy, a distended flap may lead to CSF egress through the disrupted petrous ridge, subgaleal space, and possibly through the wound. In an effort to decrease this occurrence, we routinely place ventriculostomies to decompress the hemicraniectomy flap and afford another pathway for CSF egress while the disrupted skull base is sealing. Except in extreme cases with multiple ventriculostomies, we have avoided the routine use of early lumbar drainage due to concerns with cranial spinal pressure dissociation, meningitis, and lumbar overdrainage.

Pseudoaneurysm management has challenged current practice patterns during the current conflict. More pseudoaneurysms have been detected and treated in the first 2 years of this war than in the entire 10 years of the Iran–Iraq conflict. [3,17] Unfortunately, early in the conflict, delayed rupture resulted in death, coma, progressive paralysis, and near-fatal cardiac arrest from epistaxis in patients demonstrating early recovery from their initial neurological injury. This observation has prompted a concerted effort toward early detection and treatment. An aggressive screening process composed of early CT and cerebral angiography performed upon arrival to a stateside hospital by an experienced neurointerventionalist is now our standard of care. CT angiography (CTA) alone has been inadequate secondary to technical limitations stemming from metal artifacts, poor timing of the contrast bolus with venous contamination, and contrast diverted from stenosed conductance vessels. The criteria for a screening angiogram are outlined in **Table 12.5**. If the pseudoaneurysm is associated with a well-defined neck and is endovascularly accessible, the preference at our institution is early exclusion with either coils or stent-assisted coiling. In cases with distal pericallosal or MCA aneurysms, early microsurgery is the preferred treatment. The recurrence rate for endovascularly treated aneurysms approaches 30% in the senior author's series and requires close follow-up (**Fig. 12.11**). Repeat angiography at 3 months followed by either repeat endovascular treatment or open microsurgery has been the current strategy.

Suboccipital or Occipital Injuries

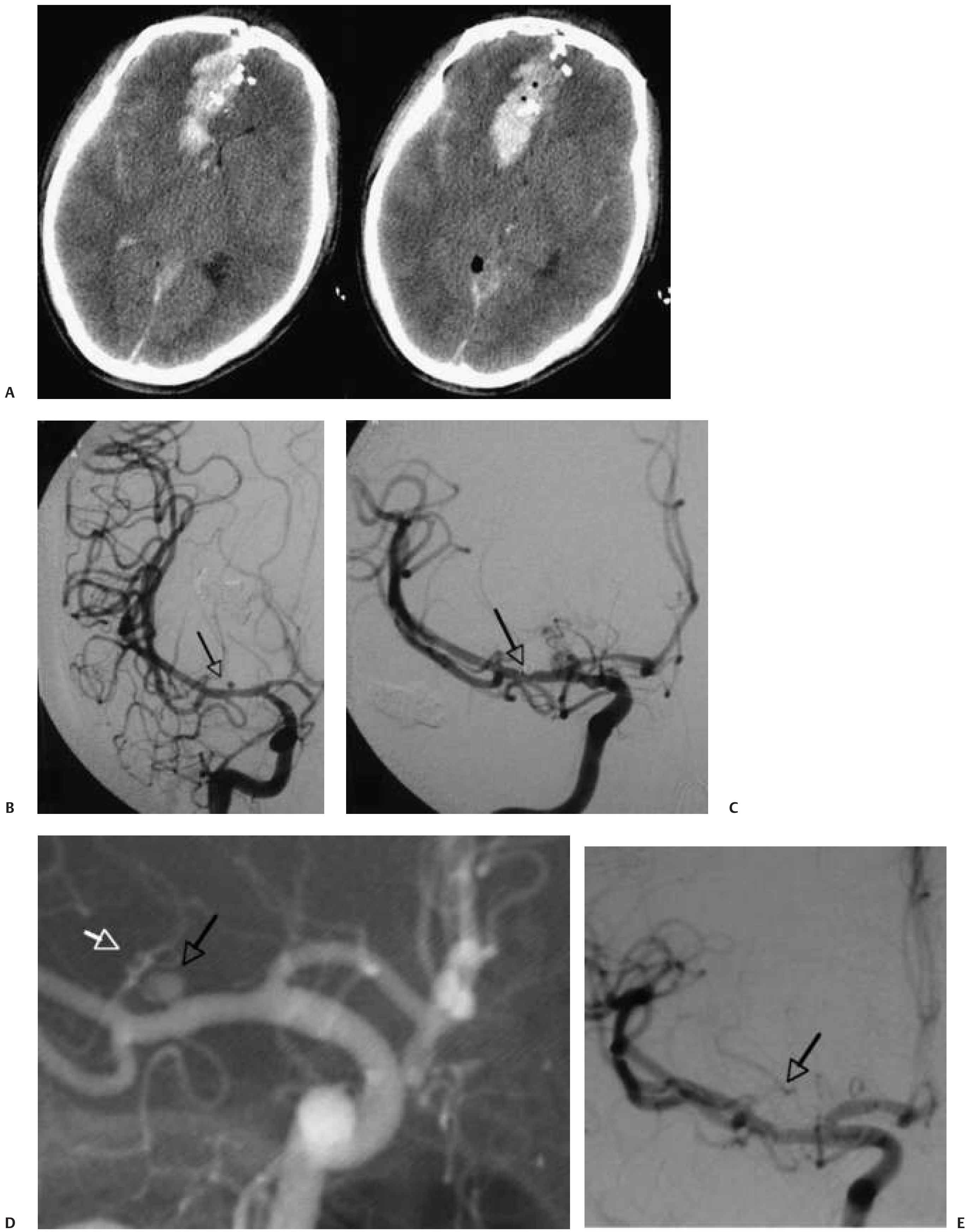
These injuries can be some of the most lethal due to the extent of injury to the brain stem, venous sinuses, and multiple intracranial compartments. Low-velocity fragments or high-velocity missiles that pass from the posterior fossa into the supratentorial compartment may create a path of injury that includes as many as three cerebral compartments (i.e., the ipsilateral cerebellum, occipital-temporal lobe, and contralateral parietal-occipital lobes) (**Fig. 12.8**). Additional injuries to the cervical spinal cord, vertebrobasilar circulation, and cranial nerves are possible. In one specific case in our series, an extracranial, suboccipital fragment resulted in a proximal posterior inferior cerebellar artery (PICA) traumatic aneurysm that subsequently ruptured.

Table 12.5 Evolution of Criteria for Intracranial Angiography following Penetrating Injury

Iran–Iraq War*	Operation Iraqi Freedom†
Penetrating injury through pterion, orbit, posterior fossa	Previous criteria plus:
Penetrating fragment with intracranial hematoma	Known cerebral artery sacrifice and/or pseudoaneurysm at the time of initial exploration
	Known cerebral artery sacrifice and/or pseudoaneurysm at the time of initial exploration
	Blast-induced penetrating injury with GCS <8
	TCD evidence of posttraumatic vasospasm
	Spontaneous decrease in $PBrO_2$

Source: Data from *Aarabi B. Traumatic aneurysms of brain due to high velocity missile head wounds. Neurosurgery 1988;22(6 Pt 1):1056–1063 and †Armonda RA, Bell RS, Vo AH, et al. Wartime traumatic cerebral vasospasm. Recent reviews of combat casualties. Neurosurgery 2006 Dec: 59: 1215–1225. Discussion 1225.

Abbreviations: GCS, Glasgow Coma Scale, $PBrO_2$, partial pressure brain tissue oxygen; TCD, transcranial doppler.



A B C D E

Surgical Considerations

Operative exposure, decompression, and homeostasis are all challenging in this area. The incision should allow exposure above and below the transverse-sigmoid sinus and allow decompression of the supratentorial hemisphere. A large C-shaped incision based on the mastoid to the subocciput to the midline forehead may provide the greatest needed exposure. Vascular injuries may include both major arterial and venous structures. The vertebral artery is typically prone to injury just proximal to the sulcus arteriosus and between C2–C3. The venous sinuses and the torcula are particularly vulnerable to spreading bone fractures that may displace the underlying bone through the outer wall of the venous sinus. In the subocciput, a "guttering" wound as described by Cushing can result in disruption of the jugular foramen with bony fracture through the jugular bulb and a delayed venous epidural hematoma of the posterior fossa. Homeostasis around the venous sinus can be obtained with the use of multiple strategies including muscle and dural elevation, sinus ligation, and oversewing with an attempt to preserve the sinus when possible, especially if dominant and including the vein of Labbé or the torcular. Additional hemostatic agents such as fibrillary Surgicel (Johnson & Johnson, New Brunswick, NJ) combined with Gelfoam (Pfizer, Inc., New York, NY), Surgicel, and cottonoid patties can be used.

Vertex or Parietal Entrance

Due to modern body armor, these are the most infrequent types of injuries seen in the current conflict. When occurring, they are usually associated with a delamination of the underlying body armor with a secondary skull fracture and rarely any metallic penetration of the cranial vault. The kinetic energy of the missile or fragment is transmitted from the helmet to the skull to the underlying brain. These injuries are associated with a range of scalp, bone, dural, and diffuse brain injuries. In extreme life-threatening cases, there is a gaping stellate scalp laceration, open-depressed skull fracture, and herniating brain from the defect. The CT scan may demonstrate significant bony fragments propelled deep into the brain. In some cases, the bony fragments act as secondary projectiles tearing through brain tissue creating secondary hematomas. When these bony fragments are propelled with such tremendous force, they can also create pseudoaneurysms in their path with disruption of the interhemispheric branches of the callosomarginal and pericallosal vessels. Occasionally, these forces are displaced over a venous sinus; techniques for exposing, securing, and repairing the sinus should be employed as well as precautions to avoid inadvertent air-emboli. The use of bilateral exposures allows the neurosurgeon to have the ability to adequately expose the longitudinal sinus, decompress both hemispheres, and control bleeding from either side of the falx cerebri. A coronal incision also helps facilitate wound closure and if necessary releases of scalp tension with partial-thickness scalp incisions, which can be skin-grafted and allow the primary wound to heal without tension.

Conclusion

The neurosurgical care of the penetrating brain-injury patient has evolved significantly since World War I. In early conflicts, a penetrating brain injury usually resulted in mortality. Today, we have seen an unprecedented functional survival from even the most severe penetrating injuries. A combination of factors has led to this outcome: the use of technologically advanced body armor, far forward brain stem decompression, and rapid strategic evacuation of patients to specialized and sophisticated neurocritical care. The lessons learned from our experience and from the conflicts that have preceded Operation Iraqi Freedom stress that patient selection for aggressive interventions is critical in maximizing outcome and avoiding vegetative survival (i.e., intervention in the setting of bihemispheric midbrain perforation may not be advisable). Additionally, the anticipation of late complications like pseudoaneurysm rupture, delayed stroke from vasospasm, and hydrocephalus in viable survivors could be the difference between vegetation or good functional recovery.

Fig. 12.11 **(A)** This soldier was struck by an improvised explosive device with penetrating fragments coursing from the forehead transhemispherically from the frontal pole to the occipital lobe. Patient was initially awake, then deteriorated to localizing with contralateral hemiparesis. In theater, patient underwent a bifrontal craniotomy, frontal sinus exenteration, dural repair with placement of a ventriculostomy. Despite a trajectory above the sylvian fissure, he developed a low-density in the anterior aspect of the head of the caudate. **(B)** A cerebral angiogram demonstrated evidence of a traumatic middle cerebral artery pseudoaneurysm (*black arrow*) and subsequent delayed severe vasospasm. **(C)** This was initially treated with endosaccular coiling and angioplasty. **(D)** Eight weeks later the aneurysm recurred (*black arrow*) with coil compaction (*white arrow*) and was **(E)** then microsurgically clipped. At 6 months, he has returned to normal activity without any deficits.

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