Management of Battlefield Injuries to the Skull Base

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Abstract

High velocity skull base injuries on the battlefield are unique in comparison to most civilian sector trauma. With more than 43,000 United States military personnel injuries during Operations Iraqi Freedom (OIF) and Enduring Freedom (OEF), the most recent conflicts in Iraq and Afghanistan have significantly expanded the understanding of the physiology of modern battlefield trauma and how to appropriately address these injuries. The acute care principles of effective triage, airway management, and hemorrhage control in these injuries can be life saving and are reviewed here. Specific injury patterns and battlefield examples are reviewed as well, with a review of some of the lessons learned while providing care in a deployed setting. Utilization of the knowledge learned in Iraq and Afghanistan, which have improved casualty care of deployed service members, can be used both in future military conflicts and in civilian trauma care.

Keywords

- battlefield injuries
- skull base trauma

Introduction

While most of the traditional teaching of managing skull base injuries in the civilian sector can be applied to wartime trauma, there are unique aspects of battlefield trauma that warrant further discussion. With more than 43,000 U.S. military injuries during Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF), the most recent conflicts in Iraq and Afghanistan have significantly expanded the understanding of the physiology of modern battlefield trauma and how to appropriately address these injuries.¹ Two important considerations regarding battlefield trauma include the kinetics of the weaponry used in war and the injury patterns typically sustained.

Basics of Ballistics

In OIF and OEF, there have been many causes of head and neck injuries that include gunshot, mortar/rocket, mine, motor vehicles, and improvised explosive devices (IEDs).¹ There are various types of IEDs that include roadside explosives or blast mines, explosive formed projectiles designed to breach armored vehicles, and suicide bombings.^{2,3} In previous con-

flicts, blast injuries accounted for less than 10% of the wounded, but now IEDs are the most common battlefield injuries and account for 76% of combat injuries in Iraq and Afghanistan.^{4,5} Unfortunately, these IEDs also cause the most devastating injuries.⁶ The reason for this can be explained by considering the kinetic energy of these weapons.

The mechanism of injury by different weapons/projectiles is dependent on the kinetic energy transferred to the tissues.⁷ The equation for determining kinetic injury is

$$KE = \frac{1}{2} m (V1 - V2)^2$$

where *KE* is kinetic energy, *m* is missile mass, *V1* is entering velocity, and *V2* is exiting velocity of projectile.⁸ The most lethal projectiles are high-velocity missiles that impart all their energy into the tissue, with a high entering velocity and without exiting the tissue (*V2* = 0).⁸ High-velocity weapons project a bullet at greater than 610 m/s, a characteristic typical of close-range shotgun wounds, rifles, mortars, and IEDs.

High-velocity projectiles form two wound cavities on impact—a permanent cavity is caused by the direct impact

Fig. 1 Dining hall in Mosul, December 21, 2004, after a suicide bomber with an IED killed 27 American service members and severely wounded 50 soldiers.

and a temporary cavity proportional to the kinetic energy of the projectile. This temporary cavity can be up to 30 times the cross-section of the projectile, causing extensive tissue damage.⁸ IEDs, as a high-velocity weapon, generate a significant amount of kinetic energy with a complex chain of events. This chain of events includes the initial shock front of the blast (termed the *primary injury*), followed by the blast wind propelling multiple penetrating fragments (*secondary injury*), the latter of which is the predominant wounding agent. The wind also propels large objects into people, or people into large objects, causing blunt or crush injuries (tertiary injuries). Finally, heat, flames, gas, and smoke cause burns, inhalation injuries, and even asphyxiation (quaternary injuries).² The more extensive damage caused by high-velocity weapons and explosions is unique in comparison to civilian trauma, which is more typically characterized by low-velocity weapons (knives, handguns) and blunt trauma.¹

Mass Casualty Incidents and Management of Medical Assets

A *mass casualty incident* (MCI) is defined not by any specific number of patients seen in a discrete period of time, but instead is described as a situation in which the need for emergency medical care exceeds the available resources. As a result of their high kinetic injury, IEDs cause multisystem trauma and typically wound many patients within a large area around the detonation site. Preparation for potential MCI is a priority for any military medical treatment facility. With more than 9,000 MCIs in the United States in 2010, the importance of handling these situations is also very relevant to civilian trauma care.⁹ In a review of three mass casualty events that happened during OIF, Salinas et al noted that one-third of mass casualty patients suffered injuries to the head and neck. Surgeons must be familiar with the management of

these injuries to be integral to the health care team of any MCI.¹⁰

One example of the devastation a single IED can cause took place on December 21, 2004 when a suicide bomber with an IED killed 27 American service personnel and severely wounded more than 50 soldiers who were in a dining hall in Mosul (→Fig. 1). The lessons learned during MCIs such as this one provide unique insights that could be used in civilian trauma practice, especially in those situations where MCIs overwhelm the resources of local civilian medical facilities.¹¹ Critical to appropriate management of these devastating situations is the appropriate triage of patients with the priority being stabilization of acute life-threatening injuries by controlling hemorrhage and securing the airway.

Triage

When medical resources are overwhelmed, triage is essential to prioritize medical care appropriately given limited time, equipment, supplies, personnel, and evacuation capabilities.¹² The principles of triage, as described in *Emergency War Surgery*, are as follows:

- Injury priority/severity (airway > breathing > circulation > neurologic changes)
- Salvageability
- Available resources/personnel
- Treatment time/distance/environment (aero-evacuation or capability/availability)¹²

Consideration of these principles allows the physician to provide the most benefit to most patients, which is the key obligation in such difficult situations.¹³ The military triage categories help prioritize care for the patients who need care most acutely, while preserving resources for patients with the best chance of survival (→Fig. 2). These categories include the following:

Fig. 2 Emergency room triage doctor with clips for categorizing patients into triage groups. Clips can be marked with labels or color coded (for example red for immediate, yellow for delayed, green for minimal, and black for expectant patients) for quick identification.

- Immediate (red)
- Delayed (yellow)
- Minimal (green)
- Expectant (black)¹²

Immediate patients should have a high chance of survival but require lifesaving surgery, such as those patients with acute traumatic airway obstruction.¹² *Delayed* patients can tolerate a delay in surgical treatment without endangering their lives.¹² Such operations include panfacial fracture repair in a patient with a secure airway. *Minimal* patients have minor injuries and can care for themselves or can be helped by nonmedical personnel.¹² Last, *expectant* patients have devastating injuries and their survival would be unlikely even with the benefit of massive medical resources.¹² Expectant patients should be given adequate analgesia and cared for in a private setting.

Priorities of Care during Mass Casualty Events

Concurrent with appropriate triage, as they arrive at a care facility, a patient's needs must be individually considered. In this respect the two most important considerations are airway management and hemorrhage control.

Airway Management

After compressible hemorrhage and tension pneumothorax, airway compromise is the third leading cause of preventable

death on the battlefield.^{11,14} Penetrating face and neck trauma accounted for more than 75% of the injuries that necessitated critical airway control in OIF.¹⁵ High-velocity trauma causes acute hemorrhage, tissue prolapse, and massive edema that may result in significant airway obstruction necessitating emergent airway control.^{11,16} A simple and efficient way to assess airway patency is for the surgeon to ask the patient to talk.¹⁵ By producing intelligible and appropriate responses, the patient demonstrates a patent airway and a Glasgow Coma Scale greater than 8 that indicates brain perfusion and a high likelihood of being able to maintain their airway.¹⁵

Patients requiring airway support can be classified into three groups: red airways, yellow airways, and green airways.¹⁷ Red airways demonstrate acute airway compromise and require airway control within 5 minutes. Immediate recognition of these patients and having prepositioned emergency cricothyroidotomy sets readily available are vital for successful management. Yellow airways require urgent airway control within 12 hours. These are patients with progressive or impending airway compromise, active head and neck bleeding, and symptomatic penetrating neck trauma.¹⁷ The third category, green airways, require a surgical airway that can be delayed for 12 hours or more after being seen, such as in those patients with respiratory failure on long-term ventilatory support or with closed head trauma. Ten percent of OIF patients with high-velocity head and neck injuries required critical airway intervention. Classifying the airways into these three categories allowed the surgeons to be most effective with limited time and resources.¹⁷

Hemorrhage Control

Devastating soft tissue injuries caused by IEDs to the head and neck are frequently accompanied by extensive bleeding that can be life threatening. With significant skull base trauma, surgical control of the internal and external carotid arteries and the jugular vein can be required urgently in the operating room. A retrospective review of U.S. service members treated at the Air Force Theater Hospital in Iraq from October 2004 to September 2007 revealed that massive facial trauma (involving 3+ facial aesthetic units) was associated with higher injury severity scores, transfusion rates, and an increased risk of eye and brain injuries.¹⁸ The association with increased transfusion rates underscores the importance for having a well-planned blood transfusion protocol in any MCI, as this can be lifesaving treatment that allows time for hemorrhage control in the operating room.

Injury Patterns of Recent Conflicts

In OIF and OEF, between 25 and 40% of American wounded sustained injuries to the head, face, and neck.^{19,20} The high incidence of head and neck trauma is due to the lack of head and neck protection provided by the body armor currently used by troops in the field. Body armor typically prevents torso, abdominal, and pelvic wounds. However, with the exception of ballistic goggles and a helmet that protect the eyes and skull, the face and neck are unprotected.^{11,21} Nevertheless, body armor has significantly decreased the number of

soldiers presenting with concomitant potentially fatal chest and abdominal injuries. The success of body armor can be demonstrated by considering that only 10% of U.S. Marines wearing body armor sustained torso wounds, whereas 24% of Iraqis without body armor sustained torso wounds.²² With the prevention of potentially lethal chest and abdominal injuries, there is an increased rate of survivable injury to the head and neck. Wartime physicians can expect a higher incidence of skull base trauma secondary to an increased frequency of injury to the head and neck, as well as the higher kinetic injury caused by contemporary wartime weapons.

Areas of Skull Base Injury in Battlefield Trauma

Frontal Sinus

The frontal sinus is a paranasal cavity lined by mucosa located between the anterior cranial fossa and the naso-orbito-ethmoidal (NOE) region of the frontal bone. Normal sinus drainage is through the outflow tract that drains into the middle meatus of the nasal cavity. While the bone of the posterior table that separates the sinus from the cranium is relatively thin, the anterior table is the densest bone in the facial skeleton. It has twice the thickness of the posterior table and requires 800 to 1,600 lb of force to fracture.²³ Frontal sinus trauma is frequently seen in the combat setting with either blast or penetrating injuries. An initial thorough physical examination is critical to evaluate any concurrent neurologic injury, given the significant amount of force required to fracture the frontal sinus. It is also essential to look for any evidence of cerebral spinal fluid (CSF) rhinorrhea as this has important implications for medical and surgical management. Computed tomography (CT) of the sinus fractures delineates the extent of anterior table, posterior table, and frontal sinus outflow tract involvement, as well as any related intracranial complications of the injury.

The degree of compromise of the outflow tract is important, given that an occluded nasofrontal outflow tract risks the formation of a mucocele. In this setting, surgical cranialization or obliteration should be considered. Animal models have demonstrated that patients with unobstructed nasofrontal outflow tract can be managed expectantly, given appropriate medical care availability, as there should be no gross, radiologic, or histologic evidence of mucosal ingrowth into the posterior table after 6 months have passed.²⁴ The consideration of cranialization versus obliteration in a deployed setting must also factor in surgical capabilities at the treatment facilities, as a cranialization procedure is not advisable without neurosurgical support.²⁵

Patients with isolated anterior table fractures, without involvement of the frontal outflow tract, are repaired for cosmetic purposes only. The degree of displacement is an important consideration. Displacement of less than 4 mm does not lead to a noticeable contour abnormality.²⁶ Several approaches can be used for the repair that include access through existing lacerations, prominent forehead wrinkles, or a gull wing brow incision. Most favor a bicoronal approach as it offers the best exposure without any visible facial incision.²³

Midface Fractures

The midface is typically described in terms of buttresses that help maintain the structure of the face and protect the oral and nasal cavities, orbits, and paranasal sinuses.²⁷ The zygomaticomaxillary, nasomaxillary, and pterygomaxillary buttresses form three paired vertical buttresses. The horizontal buttresses include the superior orbital rims, infraorbital rims, zygomatic arch, maxillary alveolus, and palate. The pattern of fracturing and the degree of force are dependent on the condition of the bones as well as the mass, projection, and velocity of the fracturing force. Classically, fractures of the midface were described by René Le Fort over 100 years ago as following three patterns.²⁸ Le Fort I fractures involve the nasal septum, the nasomaxillary buttresses, and the zygomaticomaxillary complexes as they travel through the maxilla and piriform aperture above the maxillary dentition. Le Fort II fractures disrupt the NOE region, fracturing through the nasofrontal junction, orbital floor, medial orbital rim, and zygomaticomaxillary suture line. Le Fort III fractures are described as a craniofacial separation, as the fracture separates the facial skeleton from the skull base through the nasofrontal and zygomaticofrontal suture lines. These fractures typically extend to involve both medial and lateral orbital walls as well.²⁸

With any midface fracture, a thorough ocular examination must be performed. Entrapment of the ocular muscles in fractures of the orbital walls make surgical repair more urgent. Retro-orbital hematoma threatens vision and must be addressed quickly with a lateral canthotomy and cantholysis. A full discussion of orbital fractures is beyond the scope of this article. Nevertheless, recognition of signs and symptoms of orbital injury is important so that they can be addressed in a timely fashion and further complications prevented. CT evaluation again is critical for evaluation of midface fractures and 3D reformating is also useful when planning surgical interventions.²³

Surgical reconstruction of the midface should restore occlusion, facial projection, and facial height.²⁷ Reestablishment of preinjury occlusion by maxillomandibular fixation with either arch bars or four-point fixation can be a critical starting point with attention to palatal fractures.²⁷ In cases complicated by comminuted mandibular fractures, the “base” or mandible fracture should be repaired first. After the “base” is set, a “top-down” approach can be considered by establishing a frontal bar and building sequentially down the midface with the proper positioning of the malar eminence being the key to successful reconstruction. Loss of tissue or bone is common with high-velocity injuries. Bone loss of more than 5 mm is an indication for grafting with plate fixation to ensure tolerance of masticatory forces.²⁷

Naso-orbito-ethmoid Fractures

Naso-orbito-ethmoid (NOE) fractures are a subtype of midface fracture that warrants unique attention given the complexity of the area. The NOE region is at risk with current ballistics protection and is frequently involved in facial and anterior skull base trauma. Apart from potential damage to the frontal outflow tract, fractures and penetrating trauma can also cause displacement or disruption of the medial

canthal ligaments. These fractures are typically categorized as type I, a single large fracture with an intact connection to the medial canthal tendon; type II, comminuted fractures of the NOE with the canthal tendon remaining fixed to bone; or type III, comminuted fragments with detachment of the medial canthal tendon.^{29,30} Instability of the medial canthal ligaments can be assessed by palpating the medial canthus while applying traction on the lateral canthus (bowstring test).²⁵ Measuring the intercanthal distance can be helpful if disruption secondary to fracture is suspected. A normal measurement is around 30 mm, whereas a distance of greater than 45 mm is defined as telecanthus.²³

A frequently unrecognized sequela of NOE fractures is injury to the lacrimal system. If injury is identified, early repair with Crawford stents within the first 24 hours after injury results in the best outcome.²³ Delayed manifestation of injuries typically include epiphora and dacryocystitis. If recognized initially, a dacryocystorhinostomy should be considered and can provide long-term patency of the lacrimal system in greater than 90% of cases.³¹ Other aspects of NOE fractures include evaluation of uncontrolled epistaxis and evidence of CSF leak. Clear rhinorrhea after sitting forward is especially suspicious for a CSF leak. Testing for β_2 -transferrin in the nasal secretions confirms the diagnosis. However, this test may take up to 1 week to process and receive results, and, in the setting of a high clinical suspicion, care should not be delayed.²³ If small, a leak may be amenable to conservative measures with strict bed rest, sinus precautions, and the consideration of a lumbar drain.²³ Surgical repair is indicated if the leak has not settled within 5 to 7 days of conservative management. Surgical repair of NOE fractures should also be considered for all displaced or unstable fractures so that the normal intercanthal distance and nasal projection can be restored.

Temporal Bone Trauma

Temporal bone fractures are common battlefield injuries caused by the blast trauma of IEDs. The management of these fractures is detailed elsewhere in this issue.^{31,32} Temporal bone fractures caused by penetrating trauma is frequently seen in combat injuries and facial nerve palsy is present in up to 50%.³³ In both the combat and the civilian trauma settings, the temporal bone trauma will rarely be an isolated injury, so the initial focus will be on Advanced Trauma and Life Support (ATLS) principles. Initial evaluation, however, should be performed when medically safe and can be helpful in guiding later treatment. Though surgical management of facial nerve injury can be delayed while more immediate injuries are addressed, documenting the severity of paresis or paralysis upon presentation is important in treatment management decisions. Similarly, the immense shearing forces in battlefield injuries often lacerate the external auditory canal. Placing an expandable wick in the ear canal early after injury can prevent subsequent stenosis.

Special Considerations in Reconstruction of Battlefield Skull Base Injuries

With the significant extent of battlefield injuries to the head and neck, reconstruction is an important consideration once

the more acute concerns of the injury are addressed. There are several more obvious considerations: the availability of surgeons with reconstructive skills, equipment limitations, and the sterility of the environment. Unique to modern military battlefield injuries is the ideal timing of any repair that has been learned over decades of bloody conflict, particularly the last decade.

As discussed previously, battlefield injuries seen in recent conflicts are more typically characterized by penetrating high-velocity trauma rather than blunt, low-velocity trauma that is commonly seen in civilian trauma. The high kinetic energy of projectiles is accompanied by a large concussive wave that partially devitalizes a large area of soft tissue surrounding the wound that can extend up to 30 times the cross section of the projectile.⁷ This secondary area of injury has important implications with regard to the timing of repair. Even with the great blood supply to the face, “doing too much too soon” extensive soft tissue undermining and flap rotation may result in a poor outcome.⁶ An example of this happened when a police chief was struck in the face by an AK-47 and sustained extensive facial injuries that included the loss of most of the left zygomaticomaxillary complex, a shattered left zygomatic arch, orbital rim and floor, loss of most of his nose, and a gaping wound of the left midface (►Fig. 3). A “home run” surgery was undertaken through a planned, bicoronal flap. This gave sufficient access for an open reduction internal fixation (ORIF) of the zygomatic arch, orbital floor implant, and cranial bone grafts to reconstruct the orbital rim and maxilla. A large cervicofacial advancement/rotation flap was used to cover the left cheek and nasal base defect. Septal flaps lined the nasal cavity. Conchal cartilage was harvested to replace the missing upper and lower lateral nasal cartilages and a paramedian forehead flap was used to cover the nasal skin defect (►Figs. 4, 5). Within a few weeks of this surgery, the medial portion of the cervicofacial flap died and the patient exposed midface plates and craniofacial grafts (►Fig. 6). This case demonstrated that the full extent of soft tissue injury from high kinetic energy wounds is difficult to appreciate early, and a staged

Fig. 3 Extensive facial injuries after the patient was injured by an AK-47 round.

Fig. 4 Multiple procedures were performed to reconstruct and close the wound, to include ORIF, cervicofacial advancement flap, paramedian forehead flap, and septal flap.

reconstruction can often be a more prudent choice. In situations with extensive soft tissue and bony injuries, initial surgery should be limited to irrigation, debridement, and conservative wound closure.

The primary goal of soft tissue reconstruction for high-velocity trauma should be primary closure of the wound with coverage of the bone and plates. Because of the temporary cavity trauma, extensive tissue undermining and flap rotation will almost always result in dead tissue. These principles were used to close a massive soft tissue injury in an Afghani soldier who suffered an IED injury (►Figs. 7–10). Needless to say, these extensive soft tissue injuries will need revision surgery

Fig. 6 Exposure of midface plates and wound breakdown after failure of cervicofacial advancement flap.

after the initial wounds heal and the surrounding temporary cavity injury resolves (►Fig. 11).

Kumar et al described other considerations during skull base reconstruction that they learned between 2003 and 2011 while treating service members evacuated from OEF

Fig. 5 Completed midface reconstruction.

Fig. 7 Massive soft tissue injuries sustained by an Afghani soldier after IED injury.

Fig. 8 Initial 3D reconstruction of facial CT demonstrating extensive facial fractures.

Fig. 10 Postoperative 3D reconstruction of facial CT.

and OIF. They used a variety of reconstructive techniques that included dermal/fat grafts, cranial bone autografts, and free-flap reconstruction. Despite published successes of alloplastic implants in the civilian literature, their experience was notable for an unacceptably high failure rate of cranial alloplastic implants placed near the facial sinuses, under poor-quality scalp, soft tissues, or over large underlying dead space.³⁴ As a result, the Bethesda Cranial Facial Reconstructive Protocol was developed to address the unique concerns of battlefield trauma (—Fig. 12).

In the series by Kumar et al, restoration of the fronto-orbital bar region with autogenous cranial bone grafts, separated from the facial sinuses by free flaps or dermal fat grafts, provided a

safe, valuable, and reproducible technique for complex staged cranial reconstruction.³⁴ A multilayered closure is advantageous whichever method of reconstruction is used. Delaying the definitive skull defect reconstruction until the upper orbit, frontal bone, and facial sinus injury had been addressed proved a successful strategy for high-risk cranial defects.³⁴

Fig. 9 Intraoperative view of facial fracture repair.

Fig. 11 Intraoperative view after soft tissue closure was completed.

Fig. 12 Bethesda Cranial Facial Reconstructive Protocol. (Reprinted, with permission, from Kumar AR, Tantawi D, Armonda R, Valerio I. Advanced cranial reconstruction using intracranial free flaps and cranial bone grafts: an algorithmic approach developed from the modern battlefield. *Plast Reconstr Surg*. 2012;130(5):1101–1109.)

Conclusion

During the past 10 years in Iraq and Afghanistan, over 30,000 head and neck injuries have been treated at American medical facilities in both war zones.¹ During the past 150 years, military personnel wounded in action have had a survival rate of about 80%.⁴ The survival rate in the Iraq and Afghanistan conflicts from 2001 to 2014 was 92%.³⁵ With medical advancements, improvement of evacuation protocols and increased access to care, well-trained interdisciplinary teams of neurosurgeons, otolaryngologists/head and neck surgeons, maxillofacial surgeons, and ophthalmologists have been able to improve the survival rate significantly. The experience of these teams over the last decade has led to efficient triage with a focus on hemorrhage, airway control, and practicing the lessons learned regarding the unique physiology of blast trauma. These lessons learned in combat, which have improved casualty care of service members in Iraq and Afghanistan, can be used both in future military conflicts and in civilian trauma care.

Note

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