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

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

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

**Wartime TBI**

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

Following injury, battlefield medical care rendered by fellow soldiers and combat medics is classified as Level I care. The first priority of Level I care is establishing scene security to avoid additional injury to either the injured individual or the caregivers. Subsequent Level I care includes hemorrhage control frequently using extremity tourniquets, airway establishment, field dressing...
application to protect wounds from continued contamination, and intravenous access to initiate fluid resuscitation. Casualty evacuation from the scene occurs as rapidly as the tactical situation allows to Level II or III medical facilities by rotary wing aircraft, typically a UH-60 Blackhawk helicopter, or ground transport ambulance. Arrival of the injured individual at higher levels of care within the “golden hour” after injury is a DoD priority.

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

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

**United States Air Force CCATT**

Development of the US Air Force CCATT Program in the early 1990s was driven by a new DoD requirement...
to effectively evacuate critically ill and injured patients in potentially large numbers from austere forward locations rearward through the levels of care to the US. The CCATT concept is the capacity to transport stabilized, intensive care patients who have undergone initial management by ground-based medical personnel. A “stabilized” patient is operationally defined for aeromedical evacuation as having 1) the airway secured, 2) accessible hemorrhage controlled, and 3) extremity fractures immobilized. Physiological stability, although preferred, is not implied in the definition, and the patient may be undergoing continued resuscitation and stabilization en route depending on the circumstances at the sending location.

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

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

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

**Intercontinental Aeromedical Evacuation**

**Patient Selection, Mission Preparation, and Movement**

As in any complex patient intervention, mission planning and preparation are crucial for maximizing the potential for CCATT mission success. Because no dedicated aeromedical evacuation aircraft exists in the US Air Force inventory, missions are flown on “aircraft of opportunity” with no intrinsic medical capability. Most commonly, cargo aircrafts such as the C-130 Hercules for tactical missions (short-range, within a theater of
operations) and the C-17 Globemaster III for strategic missions (long-range, between theaters of operation) are used. After cargo and passenger off-load, these aircraft can be rapidly reconfigured for patient movement. The CCATTs must be aware of aircraft-specific variations such as patient litter positioning and accessibility, oxygen and electrical supply, airspeed, flight range, and cabin temperature regulation. The C-17 Globemaster III can be configured to accommodate 54 ambulatory and 36 litter patients with 360° access. The aircraft cabin is relatively comfortable and well lit and the aircraft’s on-board systems deliver pressurized medical oxygen at 50 psi and 60 Hz AC electrical power through standard 110-V outlets. It flies at a speed of 450 kn at 28,000 feet and has an unlimited range with aerial refueling. During flight, available clinical expertise, medical equipment, and supplies to include medications are limited to those brought aboard by the CCATT itself (Fig. 3). Nonstandard medications such as hypertonic saline solutions (3% or 23.4%), desmopressin, and phenobarbital must be obtained from the sending facility prior to departure.

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

remains problematic. If the situation allows, the provision of several days of ICP stability is strongly preferred because CCATT management is limited to maximizing medical therapy. In flight, the CCATT is unable to repeat brain CT imaging or to intervene should a surgically correctable lesion exist.

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

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

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

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

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

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

Respiratory. Extubation is avoided in the interval immediately preceding air transport. The hypobaric aircraft environment may potentiate hypoxia and worsen secondary brain injury. In the absence of an artificial airway, short-term hyperventilation to manipulate PCO₂ and to dampen acute ICP elevations is no longer an option. An aircraft is also an extremely challenging location to attempt emergency intubation without backup expertise or equipment. Verification of endotracheal tube position is difficult without the ability to obtain a chest radiograph, visualize the airway with a fiberoptic bronchoscope, or auscultate breath sounds. Closed tube thoracostomies should not be removed within 24 hours of flight to minimize the risk of in-flight reaccumulation of an occult pneumothorax resulting in hypotension and hypoxemia. Chest tubes are carefully inspected to confirm patency, placement, and function. Review of a recent (< 12 to 24-hour) chest radiograph is mandatory prior to departure to verify endotracheal tube and chest tube placements in patients for whom these tubes were required. Continuous end-tidal CO₂ measurement and in-flight arterial blood gas sampling (Portable Clinical Analyzer Model 200, Abbott Point of Care, Inc.) are useful tools to ensure adequacy of mechanical ventilation.
Infectious Disease. Patients receive prophylactic antibiotics for ventriculostomy drains and penetrating brain injuries (1 g cefazolin intravenously every 8 hours), but not for fiberoptic ICP monitors. For malaria prophylaxis, doxycycline (100 mg intravenously/nasogastrically/orogastrically) is administered daily for patients evacuated from OEF. Other antimicrobials are administered depending on associated traumatic injuries or microbial culture results. Ventilator-associated pneumonia—prevention practices continued in-flight include head-of-bed elevation, oral care, caregiver glove wear, and in-line tracheal suctioning. Because febrile episodes increase cerebral metabolism, cooling measures are initiated for temperatures exceeding 99.5°F.

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

Research

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

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

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

Conclusions

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

Disclosure

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

The views and opinions expressed in this manuscript are those of R. Fang et al.
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