AACN Advanced Critical Care
Volume 21, Number 3, pp.260–276
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CE Advancing Critical Care

# Joint Combat Casualty Research Team and Joint Theater Trauma System

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## ABSTRACT

Despite the severity and complexity of injuries, survival rates among combat casualties are equal to or better than those from civilian trauma. This article summarizes the evidence regarding innovations from the battlefield that contribute to these extraordinary survival rates, including preventing hemorrhage with the use of tourniquets and hemostatic dressings, damage control resuscitation, and the rapid evacuation of casualties via MEDEVAC and the US Air Force Critical Care Air Transport Teams. Care in the air for critically injured casualties with pulmonary injuries and traumatic brain injury is discussed to demonstrate the unique considerations required to ensure safe en route care. Innovations being studied to decrease sequelae associated with complex orthopedic and extremity trauma are also presented. The role and contributions of the Joint Combat Casualty Research Team and the Joint Theater Trauma System are also discussed.

**Keywords:** biomedical research, critical care, military, nursing, performance improvement, war

Despite austere conditions and 7000-mile air transport, outcomes for critically injured combat casualties in Iraq and Afghanistan are comparable to or better than those in the most sophisticated trauma systems in the United States.[1] Gawande,[2] in his book *Better*, attributes this success to the military making a science of performance, that is, "to investigate and improve the knowledge and technologies at hand."[2(p56)] The authors of this article had the privilege of contributing to these efforts. In 2009, Col Bridges served as the first Director, Joint Combat Casualty Research Team (JC²RT)–Afghanistan and MAJ Biever served as the Trauma Program Manager for the Joint Theater Trauma System (JTTS) in Iraq and Afghanistan.

This article reviews the characteristics of combat casualties and highlights the important contributions of the JTTS and JC²RT to advancements in critical care, including preventing hemorrhage, damage control resuscitation, and the rapid aeromedical evacuation of casualties via MEDEVAC and the US Air Force (USAF) Critical Care Air Transport teams.

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## Characteristics of Critically Injured Combat Casualties

Understanding the characteristics of combat casualties is essential in identifying areas of care for research and practice improvement and to serve as a basis for discussing innovations that have come from current military operations. For this article, the term *casualty* indicates personnel (military and civilian) evacuated from the theater (ie, war zone—Iraq and Afghanistan) because of a medical reason.

In contrast to civilian trauma, combat injuries are primarily due to penetrating trauma (11% vs 68%), with a majority of the injuries caused by explosive fragments.[1] These combat injuries are complex, with 69% of critically injured casualties suffering polytrauma (Table 1).[3] For example, among 1556 US casualties there were 6609 wounds (average, 4.2 wounds per casualty).[4]

Although the primary focus of most research and reports involve US and coalition military casualties, more than 40% of patients cared for at US facilities are host nationals (eg, Afghan/Iraqi military, police, and civilians), who may account for more than 75% of intensive care unit patients.[5] Host national patients generally have a different mechanism of injury (gunshot wounds followed by improvised explosive devices [IED]) or blunt trauma compared with US/coalition military (IEDs).[6] Noncoalition casualties also tend to be very severely injured, and because they cannot be evacuated they have a longer length of stay compared with US and coalition casualties.

### Pediatric Trauma

One of the greatest challenges faced by providers in the deployed environment is the care of pediatric patients. Children account for 7% to 10% of all hospital admissions, with 75% of pediatric admissions for trauma.[7,8] At a British military hospital in southern Afghanistan, there was at least one critically injured child in the intensive care unit 66% of the time.[9] The pediatric trauma patients primarily suffer severe penetrating trauma from gunshot wounds and explosions, with injuries to their extremities (38%), torso (24%), and head, face, and neck (24%). Thirteen percent of pediatric patients suffered burns.[10] In contrast, in the United States only 17% of pediatric admissions are for trauma, which is primarily from a blunt mechanism or as a result of a blunt injury.[11]

**Table 1: Injury Type Among Patients Transported by Critical Care Air Transport Teams From Iraq/Afghanistan to Landstuhl Regional Medical Center, Germany, from October 2001 to May 2006 (n = 1491)[a]**

| Injury type | Total no. (%)[b] |
|---|---|
| Soft-tissue trauma | 948 (64) |
| Orthopedic | 636 (43) |
| Fracture (upper extremity) | 170 (11) |
| Fracture (lower extremity/pelvic) | 323 (22) |
| Fracture (upper and lower extremities) | 131 (9) |
| Pulmonary/thoracic | 523 (35) |
| Skull fracture | 296 (27) |
| Neurologic | 475 (32) |
| Neurologic (brain injury) | 376 (25) |
| Neurologic (spinal cord) | 50 (3) |
| Neurologic (neurovascular) | 31 (2) |
| Neurologic (brain and spinal cord) | 11 (1) |
| Neurologic (overdose/toxic exposure) | 4 (0.3) |
| Neurologic (heat stroke) | 2 (0.1) |
| Vascular | 361 (24) |
| Abdominal/gastrointestinal | 328 (22) |
| Burns | 254 (17) |
| Ocular | 208 (14) |
| Amputation | 202 (14) |
| Vertebral fracture | 134 (9) |
| Genitourinary/renal | 114 (8) |
| Cardiac | 19 (1) |

[a]From Bridges and Evers.[3]
[b]Patients may have more than one injury (63% with polytrauma).

An innovative strategy[7] to prepare nonpediatric clinicians is the Hostile Environment Life-Saving Pediatrics (HELP) program,[12] which includes DVD and Web-based references in conjunction with pediatric simulator training. Additionally, the pediatric content has doubled in the Joint Forces Combat Management Course (a predeployment course), telemedicine consultation with pediatric experts in the United States is available 24 hours a day, and pediatricians are now assigned to all major combat hospitals. Further efforts are needed to tailor readiness preparation to address the unique nursing care requirements of combat casualties. As emphasized in the 2010 congressional testimony by Maj Gen Siniscalchi, Assistant Air Force Surgeon General, Nursing Services, the impact of caring for these children is profound: "A senior trauma surgeon said in describing the care provided to Afghan patients … and the kids, we will never forget the kids. At the time of discharge, they reached out their little hands and smiled as if to say, 'Thank you … I'll be okay'."[164]

### Blast Injuries

Blast injuries are most commonly associated with combat and terrorism. A majority of the blast injuries are characterized as secondary (soft-tissue trauma from fragments) or tertiary (long-bone fractures, blunt trauma, closed-head injuries).[13,14] However, primary blast injuries, which cause damage to gas-filled structures (ie, lungs, tympanic membranes, gastrointestinal tract) present a potential challenge for initial management and long-distance aeromedical transport.

Primary blast lung injury, which is characterized by alveolar overdistention and rupture and multifocal subpleural, intra-alveolar, and perivascular hemorrhages, is not as frequently diagnosed as secondary or tertiary injuries. For example, in 53 casualties injured by IEDs, 4% suffered primary blast injuries, and among the 12 fatalities, 2 had primary blast lung injuries.[15] Similarly, 26 of 524 ventilated patients evacuated by USAF Critical Care Air Transport Teams (CCATTs) had a documented diagnosis of acute respiratory distress syndrome, pulmonary contusions, pneumonia, or hypoxia.[16] However, an additional 167 patients had a $PaO_2/FIO_2$ ratio less than 300, which yields an overall incidence of acute lung injury or pulmonary impairment of 20% of all CCATT patients (182/901) transported during this period, and 35% of ventilated patients (182/524). Primary blast lung injury, which is somewhat analogous to numerous minipneumothoraces and acute respiratory distress syndrome, may be worsened by overresuscitation or during air transport because of decreased barometric pressure and hypoxia. The high incidence of undiagnosed blast lung injury or pulmonary insufficiency and en route risk indicates a need for the recognition of the injury patterns associated with primary blast injuries. Research is ongoing to determine if the presence of the concurrent injuries outlined in Table 2 and clinical criteria ($PaO_2/FIO_2$ ratio, degree of infiltrate on chest radiograph, and presence of barotraumas)[17] are useful in identifying patients at increased risk for pulmonary deterioration during aeromedical evacuation.

## Joint Theater Trauma System

One of the key factors associated with the success of operational military medicine is the JTTS, which was implemented across Iraq and Afghanistan in 2005.[23–25] The JTTS, whose goal is to ensure the right patient to the right place at the right time to receive the right care (R4), is modeled after civilian trauma systems and provides the leadership and structure to facilitate the standardization of care across the theater.[1] The JTTS personnel oversee the development of clinical practice guidelines (CPGs),[26] which ensure standardization and dissemination of evidence-based practice recommendations relevant to the care of combat

**Table 2: Blast-Related Injuries**

Injuries associated with increased morbidity and mortality[15]

- Long bone fractures
- Intracranial pathology
- Amputations
- Penetrating torso injuries
- Higher number of body areas involved with more injuries to torso, head, neck, face

Higher risk of mortality if two or more of these injuries occur[18]

Detection of primary blast injuries

- Tympanic membrane damage is not a consistent indicator of the presence or absence of primary blast injury,[19,20] but it may be an indicator of increased risk for a concussive brain injury[21]
- In victims of suicide bombings, physical injuries associated with higher risk for primary blast lung injuries included penetrating injury to the head or torso (OR, 4), burns >10% body surface area (OR, 11.6), and skull fractures (OR, 55.8)[22]

Abbreviation: OR, odds ratio.

**Table 3: Examples of Joint Theater Trauma System Clinical Practice Guidelines[a]**

| |
|---|
| Burn care |
| Compartment syndrome and the role of fasciotomy in extremity war wounds |
| Nutrition |
| Damage control resuscitation at level IIb/III treatment facilities |
| Hypothermia prevention, monitoring, and management |
| Infection control |
| Management of mild TBI/concussion in the deployed setting |
| Management of patients with severe head trauma |
| Prevention of deep venous thrombosis |

Abbreviation: TBI, traumatic brain injury.
[a]See the Web site in reference 26 for additional clinical practice guidelines.

trauma patients. Examples of some of the 29 CPGs are presented in Table 3.

Each week the JTTS also has a system-wide teleconference to discuss the care of casualties with personnel from every facility involved in their care, from the initial MEDEVAC transport to the Veterans Administration.[27] This teleconference provides a method for timely feedback on performance-improvement initiatives and allows for a discussion of the care provided and concurrent lessons learned. The teleconference also allows clinicians in the theater to know the status of the casualties they treated as they reach the next rung in their care.

The Joint Theater Trauma Registry (JTTR) was created as a longitudinal data repository to facilitate performance-improvement initiatives.[23,28] The JTTR contains demographic data, mechanism of injury, anatomic and physiologic data, and acute outcomes from point of injury through rehabilitative care. The Trauma Nurse Coordinators are nurses from the Army, Navy, and Air Force who are located at the major medical facilities in the theater, at Landstuhl Regional Medical Center, Walter Reed Medical Center, National Naval Medical Center-Bethesda, and many other stateside medical treatment facilities. The trauma nurse coordinators not only collect all of the data for the JTTR but also collaborate with all health care providers to facilitate performance of the evidence-based practice recommendations outlined in JTTS CPGs.[29]

The remainder of this article presents the operational research and lessons learned that inform the care provided in theater and the outcomes associated with the integration of this evidence-based care and the performance-improvement initiatives that are central to the success of operational care.

## Joint Combat Casualty Research Team

In 2005 formal approval was received to conduct human subject research in Iraq, and in 2009 the first researcher was placed at a US military base in Afghanistan.[30,31] The Joint Combat Casualty Research Team is a multidisciplinary team composed of clinical researchers from the Army, Air Force, and Navy. Many of the researchers on the JC²RT are critical care and emergency nurses. This clinical experience brings a distinct perspective as these nurse scientists blend their research and clinical expertise to direct and conduct operational research. The work of the team is coordinated by the US Army Institute for Surgical Research, and each study undergoes review and approval by a US Army Human Subjects Review Board and the Office of Research Protections, Fort Detrick, Maryland. Additionally, each team has a member whose sole responsibility is to ensure the protection of all individuals participating in research.[32,33] Examples of some of the research studies facilitated or performed by the JC²RT are discussed in this article.

## Innovations From the Battlefield

### Hemorrhage Control

Approximately 15% to 24% of battlefield deaths may be preventable.[34–36] The leading cause of potentially survivable death among combat casualties is hemorrhage, specifically noncompressible truncal hemorrhage, hemorrhage from extremity wounds that could have had a tourniquet placed, and potentially compressible hemorrhage of the axilla, neck, or groin. Innovations from the battlefield to address these potentially treatable causes of death are hemostatic dressings, tourniquets, and the implementation of damage control resuscitation.[30,35]

#### *Hemostatic Dressings*

Hemostatic dressings are used for the treatment of life-threatening hemorrhage from external wounds where bleeding cannot be controlled by a tourniquet but can be compressed (eg, groin wounds). Although most of the research on these various agents and dressings has been done in animal models,[37–40] results from the battlefield demonstrate their effectiveness in controlling hemorrhage.

For example, in 44 casualties who had a hemostatic agent applied to an extremity or truncal wound and were admitted to a combat support hospital, 2 died (Injury Severity Score [ISS] >75).[41] Among the surviving 42 casualties, the hemostatic agent either stopped or decreased bleeding. In another series of patients, the hemostatic dressings successfully achieved hemostasis in 62/64 (97%) of casualties after failure of a standard gauze dressing.[42]

Combat Gauze (Z-MEDICA, Wallingford, Connecticut) is the hemostatic dressing currently in use in the prehospital and combat hospital setting,[39,43] and is supplied in each personal first aid kit carried by all deployed military members. This kaolin-coated dressing is flexible and can be packed into a wound followed by placement of a pressure dressing. The Combat Gauze dressing adheres to the wound and activates the intrinsic clotting cascade. Because Combat Gauze activates the clotting cascade, it is most effective when a coagulopathy has been corrected. Of note, there are currently no published reports of its use or effectiveness in the treatment of combat casualties.

### *Tourniquets*

Hemorrhage from extremity wounds is one of the leading causes of preventable deaths on the battlefield.[34,35,44] In response to this finding, under direct combat conditions, the use of tourniquets has gone from a last resort intervention to the first intervention for uncontrolled extremity hemorrhage.[45] Concern has been raised over the proper use of tourniquets, specifically application for inappropriate indications (tourniquets should be applied only to a wound where a pressure dressing did not work or under combat conditions, where it is not practical to maintain pressure to a wound), incorrect application (eg, application distal to the wound or failure to completely occlude distal blood flow), and secondary sequelae including limb loss or neurologic injury.[46]

Three studies have been conducted regarding outcomes from tourniquet use during current military operations. In 1375 severely injured casualties, 107 tourniquets were applied on 70 casualties, with 61/70 (87%) casualties surviving.[47] Five of 17 casualties had more than 1 tourniquet applied (12/17 bilateral tourniquets and 5/17 with 2 tourniquets applied for the same injury). Of the 9 who died, 3 were killed in action, 2 died in the field from nonbattle injuries, and 4 died of wounds after entering the medical facility. There were only 3 complications (2 cases of compartment syndrome and 1 case of nerve palsy) among the survivors.

A retrospective study[48] compared 67 casualties who were admitted to a US field hospital with a tourniquet in 2004 with a matched set of 98 casualties with severe extremity trauma without a tourniquet. Eighteen percent of the tourniquets were considered "nonindicated," which is relatively low compared with the 47% rate reported by the Israeli military.[45] Adequate control of bleeding was noted in 83% of the tourniquet group in contrast to 60% of the no-tourniquet (pressure bandage only) group. There were no significant differences in the incidence of secondary amputation or mortality between the 2 groups, and no secondary amputations were related to the tourniquet. Among the 7 fatalities it was determined that a tourniquet could have potentially prevented fatal hemorrhage in 4 cases.

The most recent series of studies included casualties admitted to a US Combat Support Hospital in Iraq over two 6-month periods in 2006.[49–51] There were 499 casualties who had a tourniquet placed (826 tourniquets on 651 injured limbs), with only 15/499 casualties (16 limbs) for whom a tourniquet was not indicated. Among the casualties with an isolated extremity injury where a tourniquet was indicated but not placed, the survival rate was 0% in contrast to an 87% survival rate in the casualties where a tourniquet was indicated and placed. There were 65 deaths among casualties who had tourniquets; among these casualties, 16 died from isolated extremity hemorrhage (suggesting a potentially preventable death), and in a majority of all deaths, the tourniquet was placed after the onset of shock. Among survivors there was a low incidence (1.7%) of secondary sequelae.

Three findings from this study suggest that tourniquet use decreased mortality: (1) there was a lower mortality among casualties who had a tourniquet applied prehospital (11% mortality) compared with casualties who had the tourniquet applied in the emergency department (22% mortality); (2) there was 90% survival in 477 casualties who had a tourniquet placed before the onset of shock, in contrast to 18% survival in casualties who were in shock at the time of tourniquet placement; and (3) there were 10 casualties for whom a tourniquet was indicated but not used, with a 0% survival in contrast to 87% survival rate in casualties who had tourniquets placed for an appropriate indication.

Based on this evidence, the current recommendations from the recently updated Tactical Combat Casualty Care guidelines and the British military[52] for tourniquet use during direct combat are that a tourniquet should be applied for all cases of life-threatening extremity hemorrhage as soon as possible (eg, before extrication), and when safe and feasible, a reassessment of the need for a tourniquet and, as appropriate, the conversion to a pressure or hemostatic dressing be undertaken. Before deployment, every military member demonstrates the correct use of a tourniquet, and a one-handed tourniquet is included in each personal first aid kit.

Given the high incidence of penetrating trauma, devastating extremity trauma from IEDs, and the rapid transport of casualties, the increased use of tourniquets may not be generalizable to civilian settings where blunt trauma predominates, the frequency of mangled injuries or traumatic amputations is lower, transit time to the hospital may be longer, and there is less experience with their use.[53,54]

### *Damage Control Resuscitation*

Damage control resuscitation is an innovation that includes the prevention of excessive bleeding with hypotensive resuscitation (ie, maintaining the systolic blood pressure <90 mm Hg until surgical control of bleeding is accomplished), tourniquets, and hemostatic dressings in the prehospital setting; the avoidance of hemodilution from excessive crystalloids; and the immediate reversal of hypothermia, acidosis, anemia, hypocalcemia, and coagulopathy concurrent with damage control surgery.[55,56]

A component of damage control resuscitation is the administration of blood products in a manner similar to a whole blood transfusion in what is referred to as *hemostatic resuscitation* or a 1:1:1 protocol (1 unit of fresh-frozen plasma [FFP] to 1 unit of packed red blood cells [PRBCs] to 1 unit platelets).[56] Observational data from the military suggest a potential survival benefit with higher plasma to PRBC and platelet to PRBC ratios. For example, in 246 combat casualties who received a massive transfusion, the higher the FFP to PRBC ratio, the lower the mortality (FFP to PRBC 1:8 – mortality = 65%; 1:2.5 – mortality = 34%; and 1:1.4 – mortality = 19%). The latter group received recombinant factor VIIa and less crystalloid and more cryoprecipitate and platelets than did the other 2 groups.[57] Similar survival benefits have been found in other military studies,[58] although results in civilian trauma have been mixed.[59–65] Recent synthesis articles support damage control resuscitation and a 1:1:1 transfusion strategy for patients requiring massive transfusion, although the exact ratios have not been established.[65–67] Caution must be taken as the recommendations for hemostatic resuscitation are based on observational data only, and there is an increased risk for acute lung injury or acute respiratory distress syndrome with transfusions.[65,68]

The recommendations for damage control resuscitation are outlined in a JTTS CPG.[69] At military field hospitals, a medic responds to each trauma call with a cooler of "shock packs" of PRBCs and thawed plasma, so that hemostatic resuscitation can be rapidly initiated. The initiation of this CPG along with other systemwide initiatives has been associated with improved outcomes for critically injured casualties. Before implementation of the damage control resuscitation CPG, there was a 32% mortality rate for casualties requiring a massive transfusion in contrast to a 20% mortality rate post-CPG implementation ($P < .05$).[1] Of note, current JTTR data indicate that the long-term survival rates for US and NATO casualties who receive a massive transfusion is 95% or more, which is in contrast to civilian trauma centers, where survival rates range from 40% to 71%.[59]

## Hypothermia

In the early phases of the war, hypothermia (temperature <35°C) was problematic even with ambient temperatures well over 37°C. In 2848 trauma admissions to a combat support hospital in Iraq in 2004, 18% of the casualties were hypothermic.[70] Among these casualties, there was an inverse relationship between admission temperature and mortality, and casualties who were hypothermic required more blood products.

In response to the task of reducing the incidence of hypothermia in combat casualties, a series of studies was conducted to identify hypothermia-prevention strategies that could be used in the field and on board military aircraft.[71–73] The results of these studies demonstrated the importance of not only preventing heat loss but administering heat to the severely injured casualty to prevent hypothermia. The technologies recommended by these studies were integrated in the Hypothermia Prevention and Management Kit (North American Rescue Products, Greenville, South Carolina), which contains a baffled space blanket (Blizzard Rescue Blanket, Blizzard Protection Systems, Gwynedd, United Kingdom), warming pads that activate upon exposure to air ("Ready-Heat" Blanket, TechTrade, New York, New York), and a hat (Thermo-Lite Hypothermia Prevention System Cap, Encompass TechStyles, Addison, Texas). The JTTS CPG: Hypothermia Prevention, Monitoring and Management[74] outlines the use of these technologies, as well as hospital-based warming strategies.

Temperature measurement is mandatory on all casualties, and the JTTR tracks compliance with initial temperature measurement and the incidence of hypothermia. In a review of 25 000 patients in the JTTR, there was an 84% compliance with the hypothermia prevention CPG. The success of efforts to prevent hypothermia in combat casualties is exemplified by data from the past year, which indicate that less than 1.5% of US casualties were admitted to level III trauma hospitals with a temperature 35°C or less. These findings are in contrast to US civilian trauma centers where 43% of severely injured trauma patients admitted to 7 major trauma centers were hypothermic on admission.[75]

This success demonstrates the translation of research into practice and the importance of ongoing evaluation of the effectiveness of innovation through the JTTS.[76] These technologies are effective in preventing hypothermia, but caution must be taken to prevent overwarming casualties, particularly those with a head injury. Refinement of temperature measurements and documentation in the theater is also needed.

## Guided Resuscitation

The most common causes of severe trauma in Operation Iraqi Freedom and Operation Enduring Freedom are explosions and gunshot wounds (Table 1).[3] Resuscitation of these casualties can be complex because of the multilayered nature of their injuries (see the article by Marshall[77] in this issue), particularly those injuries caused by an explosion.[13] Judicious fluid resuscitation is a recommendation in treatment protocols for patients with blast lung injury[78,79]; however, what constitutes judicious fluid administration is not defined, nor is there guidance on how to balance fluid requirements in a polytrauma casualty (eg, a casualty with a traumatic amputation, a traumatic brain injury [TBI], and a possible pulmonary contusion), and how to decide when to administer fluids versus the addition of a vasoactive medication to optimize perfusion. Standard methods of monitoring (eg, central venous pressure and blood pressure) do not accurately predict if a patient will respond to a fluid bolus.[80,81] Functional hemodynamic indices (eg, systolic pressure variation, pulse pressure variation), which have been found in other patient populations to accurately predict fluid responsiveness, may be beneficial in guiding fluid resuscitation in this patient population. A limitation of these functional indices is the need for an arterial catheter, which may not be feasible under operational conditions. The pleth variability index, which is also a functional hemodynamic indicator and is obtained noninvasively from a pulse oximeter, is also an accurate predictor of fluid responsiveness.[82,83]

None of these functional indices has been studied in severely injured patients. Research is under way to describe changes and potential utility of invasive and noninvasive functional hemodynamic indices during the resuscitation of critically injured combat casualties.

## Noninvasive Detection of Occult Hypoperfusion

Assessment of combat casualties in the field is focused on triage and the identification of patients who require life saving interventions.[84] Despite the potential utility of a minimal vital sign set (eg, radial pulse characteristics, Glasgow Coma Scale) to identify patients requiring prehospital life saving interventions,[85–87] standard vital signs and trends in vital signs may fail to identify a patient with occult hypoperfusion (hypoperfusion despite a systolic blood pressure >90 mm Hg).[88,89]

Skeletal tissue oxygen saturation ($StO_2$) monitoring allows for noninvasive monitoring of skeletal muscle oxygenation and thus perfusion. The potential utility of $StO_2$ monitoring in hemorrhagic shock and combat field resuscitation was evaluated in an animal model.[90] The $StO_2$ was an earlier indicator of hypoperfusion than base deficit or lactate. Two studies have been conducted under operational conditions to evaluate the utility of $StO_2$ monitoring. In a study[91] of 40 combat casualties, 8 (20%) had an initial $StO_2$ less than 70%. As demonstrated in Table 4, in the first 2 cases the $StO_2$ would have aided in the identification of occult hypoperfusion, and in the last 2 casualties the $StO_2$ confirmed the severity of the casualties' condition.

The utility of $StO_2$ to predict the need for life-saving interventions has also been studied.[92] In 147 combat casualties, the $StO_2$ differentiated between patients who did or did not require a life-saving intervention, a blood transfusion, or a massive transfusion. The $StO_2$ may also be a useful target as a part of damage control resuscitation.[55]

A limitation of these studies is the need to delay $StO_2$ monitoring until the patient arrives at a fixed medical facility. A recent study was conducted at a level I civilian hospital in the United States in which the transport vehicles (ground and aeromedical) were equipped with $StO_2$ monitors.[93] The $StO_2$ measurements were obtained on 41 trauma patients, 5 of whom died. The $StO_2$ was lower in those who died than those who survived, although there was a large amount of variability in $StO_2$ values among the patients who died. Of note, there were no reports of the $StO_2$ monitor interfering with electronic operations on the aircraft. Although this study demonstrates the potential use of $StO_2$ monitoring in the field (including on board aircraft), its operational application is limited by the use of a hospital-based piece of equipment that requires an external power supply. Research is ongoing in the field to evaluate the utility of a portable $StO_2$ device to augment clinical assessment and detect occult hypoperfusion in combat casualties, which may aid with triage and decisions about the urgency of transport.

**Table 4: Skeletal Tissue Oxygen Saturation on Admission to a Combat Support Hospital**

| Patient injury | BP | HR | $StO_2$ (%) |
|---|---|---|---|
| IED blast with bilateral amputations | 110/70 | 110 | 51 |
| GSW to abdomen | 90/60 | 120 | 50 |
| High-velocity GSW to hip on 100% $O_2$ | 56/30 | 150 | 54 |
| IED blast with massive right lower extremity injury, $SaO_2$ 91% | 69 | 150 | 52 |

Abbreviations: BP, blood pressure; GSW, gunshot wound; HR, heart rate; IED, improvised explosive device; $StO_2$, skeletal tissue oxygen saturation.

## En Route Care

The rapid evacuation of casualties by MEDEVAC (helicopter-based transport) or a CCATT is another factor associated with the dramatic improvement in survival observed in current military operations. A key concept underlying en route care is that it is seamless—that is, there is no decrease in the level of care at any point along the continuum.[94] An easy way to conceptualize this concept of operations is to view the continuum of care from Afghanistan and Iraq to the United States as one very large intensive care unit that crosses 7000 miles and 12 time zones.

### MEDEVAC

Although the transport of patients by helicopter is standard practice in civilian trauma centers, evacuation of combat casualties presents additional care considerations.[95] There is little research on the care requirements, shortfalls, and outcomes associated with MEDEVAC. The only published research on MEDEVAC from the current conflict[96] evaluated 149 MEDEVAC transports in Iraq from a role II or level II (field hospital) to a level III hospital (larger trauma hospital). Over 65% of the transports were for critically injured casualties (average ISS, 21 ± 11; range, 4–54). Among the trauma patients, 44% had undergone major surgery within the past 24 hours, and 20% had received a massive transfusion. Additionally, 53% of the casualties were ventilated, and 20% required a vasoactive medication. In-flight deterioration occurred in 30% of transports (eg, hypotension, desaturation, or arrhythmias). This research and the article by Higgins[97] in this issue highlight the critical care nature of these transports.

Research is ongoing to describe the types of care provided en route and to identify the skill level required to provide care during the phases of MEDEVAC transport (field to level II hospital/level II to level III hospital transport). Further research is also needed to describe the unique characteristics of MEDEVAC transport in Afghanistan, where over 90% of casualties are transported by helicopter. MEDEVAC in Afghanistan is particularly difficult and dangerous given the rugged geography of the country.

For example, in eastern Afghanistan the Hindu Kush (the foothills of the Himalayas) rise to 17 000 ft, necessitating high-altitude, circuitous transport routes, whereas the southern portion of the country is arid and extremely dusty (Figure 1).

Other research is needed to describe en route adverse events that are preventable versus expected sequelae, care requirements based on the type of injury, and the utility of predictive tools to guide decision making about the time of transport, personnel qualifications, and equipment requirements.

## Critical Care Air Transport Team

The USAF Critical Care Air Transport Team (CCATT) was first introduced in the early 1990s. The team, which consists of a physician (critical care intensivist, anesthesiologist, pulmonologist, or emergency specialist), a critical care nurse, and a respiratory therapist, has the ability to manage critically ill or injured patients who are stabilizing, but may not be stable. Several excellent reviews of the USAF CCATT and the British Royal Air Force Critical Care Air Support Team (CCAST) have been published.[94,98–103] Critically injured burn casualties are transported by both CCATT and the US Army Institute for Surgical Research Burn Transport Team.[104]

Casualties are rapidly evacuated from the theater by CCATT. Flying time to Germany is on average 6.3 ± 1.8 hours, with casualties arriving at Landstuhl Regional Medical Center on average within 24 hours of their injury.[3] During this initial 24 hours the casualty may have undergone 2 MEDEVAC transports and 1 or 2 surgeries before the 8-hour evacuation flight. Because of the rapid transport the casualties may be stabilized (ie, having a secured airway, accessible hemorrhage controlled, and extremity fractures immobilized) or are stabilizing but not yet stable, with resuscitation ongoing during the transport. The average length of stay for American casualties at Landstuhl Regional Medical Center is 48 to 72 hours.[105]

**Figure 1:** MEDEVAC ("dust-off") and chase helicopter landing at a medical facility in the Helmand Province in southern Afghanistan.

The casualties may then be evacuated to the United States for definitive care.[106] Excellent articles have been published on the critical care received at US military hospitals and the effect of providing this care on the nurses.[107,108] A summary of ongoing evidence-based critical care and rehabilitation of these casualties is provided in the article by McNeill[109] in this issue. Additionally, a recent article[110] provides a moving insight into the experience of this care from a family's perspective.

### *Stresses of Flight*

During the flight both patients and medical crew are exposed to stresses of flight, which include barometric pressure changes, hypoxia, noise, vibration, gravitational forces, thermal stress, dehydration, and third spacing. The article by Lamb[111] in this issue emphasizes the effects of these environmental factors on the performance of the medical crew during long-distance transport.

As an example of the effect of the stresses of flight on care, cabin altitude is on average 6000 to 8000 ft on board fixed-wing cargo aircraft used for CCATT transport, and during MEDEVAC the helicopter cabin altitude may be as high as 12 000 ft. With an increase in altitude, barometric pressure decreases (sea level = 760 mm Hg; 8000 ft = 565 mm Hg; 12 000 ft = 483 mm Hg), and as described by Boyle's Law gas expands (from sea level to 8000 ft, a gas bubble expands by 35%). This gas expansion may be problematic if a patient has air trapped in his or her body (eg, a simple pneumothorax on the ground may become a tension pneumothorax at altitude). Similarly, gas trapped in the abdomen, eye, or skull may expand and cause sequelae.

Decreased barometric pressure and gas expansion may also affect equipment used during air transport. For example, the fidelity of an invasive pressure monitoring system may decrease with ascent to altitude as microbubbles in the flush solution expand.[112] The use of a validated checklist to minimize the creation of microbubbles during setup of the equipment has been shown to optimize invasive pressure monitoring systems for both ground-based care and under conditions of decreased barometric pressure.[113] Research related to the long-distance aeromedical evacuation of critically ill patients with pulmonary insufficiency and head injuries is discussed as an example of the unique care provided by CCATT.

### *CCATT Transport of Casualties With Pulmonary Insufficiency*

With ascent to altitude barometric pressure decreases, as exemplified by the alveolar gas equation, $P_AO_2 = FIO_2 (P_{barometric} - P_{H2O}) - PaCO_2/0.8$. Therefore, at altitude a patient may require supplemental oxygen. For example, without supplemental oxygen, the alveolar partial pressure of oxygen ($P_AO_2$) decreases from 100 mm Hg at sea level to 59 mm Hg at 8000 ft because of the decrease in barometric pressure (Dalton's Law).

The effect of altitude on gas expansion-induced worsening of injuries and oxygenation requirements is exemplified by the care requirements for 11 casualties injured in the attack on the USS *Cole*.[114] Two of these casualties were ventilated before transport, and the remaining casualties were all spontaneously breathing and had a room air $SpO_2$ more than 90% at sea level. On ascent to altitude the remaining 9 casualties required supplemental oxygen and 1 casualty desaturated to 50%. The oxygen requirements of the casualties were so great the aircraft had to land to recharge their oxygen supply. Considering the location of these casualties at the time of the explosion (most likely below decks in an enclosed space), they may all have had a primary pulmonary blast injury that became apparent at altitude.

However, patients with pulmonary compromise can be safely transported with appropriate planning and understanding of their modified care requirements during transport, particularly for those who may have suffered a blast trauma.[115,116] For example, in 22 CCATT patients evacuated from the theater, the average ventilator parameters were $FIO_2$, 0.4 to 0.5 (7 patients required $FIO_2$ >0.5); tidal volume, 6.9 mL/kg; and positive end-expiratory pressure (PEEP), 6 cm $H_2O$ (range, 0–17 cm $H_2O$).[117] These parameters suggest a lung-protective ventilation strategy, which is important in casualties who may have suffered a pulmonary blast injury. During these 22 CCATT transports (117 hours of transport time), there were only 3 desaturation events ($SpO_2$ <90%), with the longest lasting 280 seconds and all events resolving spontaneously.

Similarly, results were observed in a study of 656 CCATT transports between March 1, 2007, and June 30, 2008.[118] During this period there were 656 patient moves from the theater. Among these casualties, 318 (49%) required mechanical ventilation, 68 (10%) required vasoactive medications, and 43 (7%) received a blood product transfusion en route. The 425 trauma patients were severely injured (average ISS, 21), primarily because of blast trauma. Despite the severity of injuries, there were only 75 events on 65 patient transports (10%), including desaturation (19 events), hypotension (29), decrease in neurologic status (3), and oliguria or anuria (23). It is not known if these events reflect the natural course of injuries or whether they reflect an exacerbation in the patient's condition caused by the transport.

Research is ongoing to further optimize en route care, including the evaluation of the safety and effectiveness of autonomous closed-loop systems to monitor oxygen saturation, adjust mechanical ventilator parameters, and guide fluid resuscitation.[119–121] Research has also demonstrated that ground-based suction protocols are effective in preventing suction-induced hypoxia at altitude.[122,123] The optimal suction pressure for suctioning at altitude is 120 mm Hg; however, the use of a higher suction pressure (>120 mm Hg) should be avoided, as this may cause the ventilator to shut off as a protective measure.[124]

## Acute Lung Rescue Team

Another innovation is the Acute Lung Rescue Team (ALRT).[16] The ALRT, which is composed of a critical care physician, nurse, and respiratory therapist with extensive expertise in the management of ventilated patients, is tasked to safely transport patients whose ventilatory requirements exceed the capabilities of standard CCATT equipment.

The ALRT carries a standard CCATT ventilator (Uni-Vent Eagle 754, Impact Instrumentation Inc, West Caldwell, New Jersey), in addition to specialty ventilators, such as the LTV1000 (Pulmonetics Systems, Minneapolis, Minnesota) and the Volumetric Diffusive Respirator (VDR-4; Percussionaire Corp, Sandpoint, Idaho). Extracorporeal support is also available using the Novalung Interventional Lung Assist (Novalung iLA; Hechingen, Germany). In 2005–2006 the ALRT was alerted to transport less than 1% of all CCATT patients. Although the need for the ALRT is limited, the severity of pulmonary failure among patients requiring ALRT is exemplified by their ventilator parameters ($FIO_2$ 0.92 ± 0.11/PEEP 19 ± 2.2 cm $H_2O$) in contrast to 524 ventilated CCATT patients ($FIO_2$ 0.53 ± 0.14/PEEP 6.5 ± 2.4 cm $H_2O$). Of the 11 ALRT patients, 5 were successfully transported (mean $PaO_2$/ $FIO_2$ = 71), and 4 survived to hospital discharge. Of the remaining 6, three died before arrival of the team, 2 stabilized sufficiently that the ALRT was canceled, and 1 died in the theater despite aggressive extracorporeal support.

### *Transport of Casualties With Neurotrauma*

Traumatic brain injury is the signature injury of the current war[125]; however, TBI-related hospitalizations involve less than 0.3% of all deployed military personnel.[126] Although the overall incidence of hospitalization for TBI is small, many of these injuries are severe. Approximately 16% to 25% of all CCATT patients have TBI (Table 1).[3,127]

Among 2898 soldiers admitted for TBI to field hospitals in Iraq and Afghanistan (2001–2007), 46% were categorized as type 1 or the most severe, which indicates an intracranial injury, a moderate or prolonged loss of consciousness, or optic nerve injuries.[128] Similarly, in another study of combat casualties from Operation Iraqi Freedom (March 2004 to September 2004), 49% of the casualties with TBI had an intracranial injury and concurrent injuries of the head (facial fractures, open head wound).[125]

These casualties are managed according to the Guidelines for the Field Management of Combat-Related Head Trauma[129] and the JTTS CPG: Management of Patients With Severe Head Trauma.[130] There may be additional en route care challenges for these complex injuries, because air trapped in the sinuses or a pneumocephalus may be problematic at altitude when gas expands and theoretically may cause an increase in intracranial pressure.[131] However, 21 casualties with pneumocephalus were evacuated out of the theater without sequelae.[132] These cases suggest that it is possible to safely transport these patients, but caution should be taken to avoid rapid changes in barometric pressure and to monitor the patient during ascent. Similar caution needs to be taken when transporting patients with frontal sinus injuries.[133]

Preliminary analysis of 68 critically injured patients with isolated head injury transported by CCATT provides insight into the severity of these isolated injuries.[134] The first recorded vital signs for these casualties were, on average: Glasgow Coma Scale (GCS), 8.5 ± 5.1 (51% GCS <8), Glasgow Motor Score, 3.6 ± 2.3; ISS, 14.3 ± 6.8 (47% ISS ≥15, 17% ISS >25), and Revised Trauma Score, 5.9 ± 1.7. Based on the Revised Trauma Score the predicted mortality rate for this group of patients is 9%, in contrast to the observed mortality rate of 5.8%.

Limited research exists on the longer-term outcomes of combat casualties with severe TBI. Recently, a study[135] was published of long-term outcomes among 408 casualties with TBI who were admitted to the intensive care units at Walter Reed Medical Center or National Naval Medical Center–Bethesda. These casualties arrived an average of 7.4 ± 9 days after their injury. Among this cohort, 56% had penetrating head trauma primarily related to blast injury (56%) or gunshot wound (14%); among the patients with closed head trauma, the majority of injuries were due to an explosive blast and the remainder due to blunt trauma. Their initial field GCS was 8.8 ± 4.4, and on admission to the US medical facilities their GCS was 10.6 ± 4. The average ISS on admission was 30 ± 11, which is consistent with polytrauma, in contrast to the isolated head injury group previously reported, whose average ISS was 14.3 ± 6.8.

The Glasgow Outcome Scale (GOS; Table 5) was used to evaluate outcomes at discharge, 6, 12, and 24 months. Among the 42 casualties whose initial GCS was 3 to 5, their GOS at discharge was 2.8 ± 1.2 and on average remained unchanged at 2 years (2.8 ± 1.6), although 17 patients had a 2-year GOS greater than 3. Among casualties with less severe TBI, their GOS improved over time: initial GCS, 6 to 8 (GOS at discharge: 3.1 ± 0.6/GOS at 1–2 years: 4 ± 0.7), initial GCS, 9 to 12 (GOS at discharge: 3.1 ± 0.6/GOS at 1–2 years: 4.1 ± 0.9); initial GCS, 13 to 15 (GOS at discharge: 4.0 ± 0.7/GOS at 1–2 years: 4.5 ± 0.6).

Although these results are important and they provide the first systematic analysis of long-term outcomes for these patients, they also highlight the ongoing challenges the patients and their families may face.

An unexpected finding in the casualties with penetrating trauma was the high incidence of aneurysms and vasospasm,[135,136] which along with the complex nature of their injuries may have implications for en route monitoring and care. Further research is needed to link data on the casualties with TBI (or any other injury type) from the point of injury through rehabilitation to identify areas in which further research or modification of care is needed.

Additionally, there are no studies addressing the integration of nursing therapeutics into the plan of care. There are several excellent summaries of the acute and rehabilitative nursing care provided to these casualties at Walter Reed Army Medical Center and National Naval Medical Center-Bethesda.[109,137,138] These summary articles may stimulate the identification of research topics and areas for care improvement that are specific to the unique environment as well as the need to modify care, as these casualties undergo rapid evacuation to the United States.

Key to improving outcomes for casualties with TBI is to prevent hypotension, hypoxia, and hyperthermia, which cause secondary brain injury.[139,140] There is evidence for the overall safety of CCATT transports,[127] and the transport safety of these unique patients is exemplified by the rare occurrence during CCATT transport of hypotension or hypoxemia (n = 4) or a need for more aggressive ventilation (n = 3).[3]

Research is ongoing to evaluate en route care for casualties with polytrauma including TBI. Of note, 33% of the casualties with isolated head injuries had a temperature greater than 38°C in the first 72 hours of their injuries. Hyperthermia is associated with worse outcomes, and the general recommendation is to implement interventions to maintain normothermia in patients with TBI.[141–143] However, treating hyperthermia en route may be difficult, as the use of external cooling devices is restricted by size, electricity, and safety considerations. The environmental characteristic on board cargo aircraft may be exploited as a part of hyperthermia management if other technologies are not available. For example, the ambient temperature on military cargo aircraft used by CCATT may decrease to 58°C at cruising altitude, and in certain areas of the aircraft an airflow may be as high as 5 m/s,[144] which creates conditions comparable to a cooling blanket or a fan. The evaluation of the feasibility and effectiveness of civilian hyperthermia treatment protocols is warranted.

**Table 5: Glasgow Outcome Scale**

| | | |
|---|---|---|
| 5 | Good recovery | Resumption of normal life despite minor deficits |
| 4 | Moderate disability | Disabled but independent. Can work in a sheltered setting |
| 3 | Severe disability | Conscious but disabled. Dependent for daily support |
| 2 | Persistent vegetative | Minimal responsiveness |
| 1 | Death | Nonsurvival |

Unique questions regarding the transport of casualties with severe neurologic injuries are currently being studied. (1) Which way should the casualty be positioned on the aircraft to minimize gravitational effects during takeoff and landing: feet to the front or to the back of the aircraft? (2) When to evacuate a casualty, or, more specifically, when is the brain fit to fly? (3) Is there an optimal window of opportunity for safe evacuation?[145]

## Extremity Trauma

Extremity trauma is the most common combat injury. Approximately 24% of the 34 006 patients evacuated out of the theater between 2004 and 2007 had a musculoskeletal injury,[146] and among critically injured patients, 63% had extremity trauma, with 71% of these injuries involving fractures.[3] Among casualties with battle injuries, extremity injuries are often complex (Figure 2).[147–150] For example, in 3155 casualties with orthopedic injuries, 80% to 85% of all extremity fractures were open, and 48% of lower extremity injuries involved tibia/fibula fractures.[149] These casualties also tend to have injuries to other areas of their bodies. For example, 665 casualties suffered 2640 injuries, with 62% of the injuries involving the extremities.[151]

### Detection of Compartment Syndrome

The high incidence and complexity of extremity trauma in combat casualties are important,

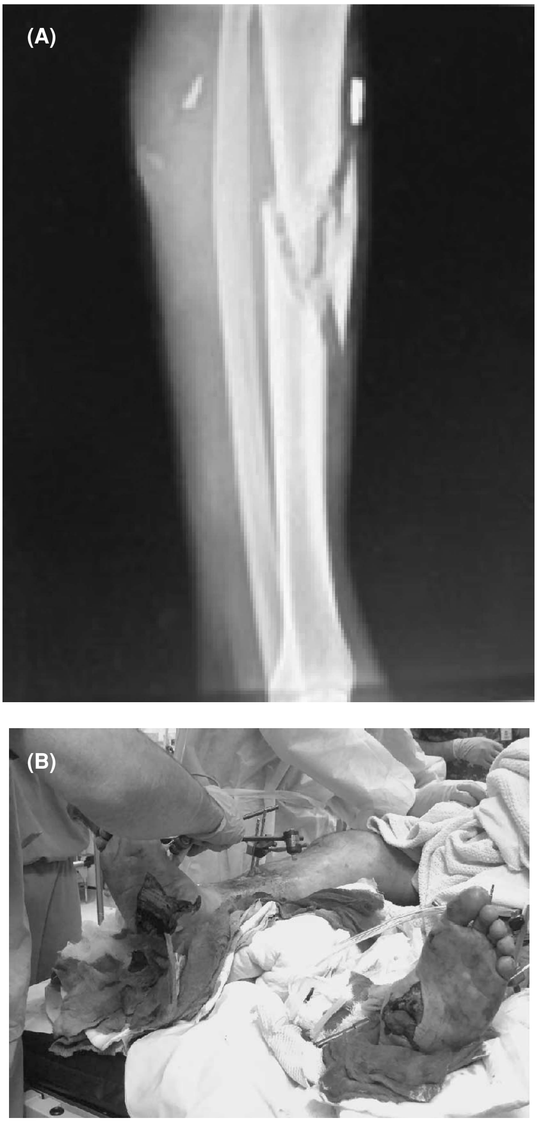

Figure 2: Examples of the complex nature of extremity trauma. (A) Gunshot wound. Note that there was minimal external injury. (B) Extensive lower extremity trauma caused by an improvised explosive device.

as extremity trauma is the most common cause of compartment syndrome.[152,153] Extremity compartment syndrome is detected by clinical presentation or extremity compartment pressures. However, clinical assessment is intermittent, subjective, and may be difficult to perform if the patient is unable to communicate or the sensation is diminished by the use of analgesia or peripheral anesthesia. Thus, clinicians may fail to detect early subclinical deterioration. Early identification of compartment syndrome is crucial, as muscular damage occurs within 4 hours and irreversible changes may occur within 4 to 12 hours.[154] This time frame is critical, as a casualty with subclinical compartment syndrome who is evacuated from the theater (a 6- to 8-hour transport) may not have the condition detected until after irreversible changes have occurred. In a study of 336 combat casualties who underwent a fasciotomy, casualties who underwent fasciotomy after evacuation had higher rates of muscle excision (25% vs 11%), amputation (31% vs 15%), and mortality (19% vs 5%) compared with casualties who received their fasciotomy in theater.[155] Thus, it is paramount to identify and treat patients before evacuation from the theater.

Two innovative technology solutions to augment the clinical diagnosis of compartment syndrome in combat casualties are being studied. One technology under investigation in the theater, which has been previously evaluated in civilian trauma,[156] is infrared imaging to detect differences in surface temperature in legs that develop compartment syndrome. Another possible technology solution is the use of $StO_2$. Several studies in civilian trauma have demonstrated differences in $StO_2$ in legs with and without compartment syndrome and before and after fasciotomy.[157–160] Studies are ongoing to evaluate the use of $StO_2$ to identify vascular compromise in casualties with extremity trauma following revascularization, and to determine the utility of $StO_2$ monitoring in detecting developing compartment syndrome before aeromedical evacuation.

## Innovative Strategies to Translate Evidence Into Practice

As exemplified by this article, there are unique aspects of care that nurses would not be exposed to during their normal US-based practice. The JTTS CPGs provide one strategy to ensure evidence-based care is consistently provided across the theater. However, many of the CPGs are medically focused and do not provide evidence for nursing care. To facilitate evidence-based operational nursing care, the TriService Nursing Research Program funded the creation of the *Battlefield and Disaster Nursing Pocket Guide*.[161] This guide contains evidence-based recommendations for nursing care including acute management of an injury from a blast, how to dress an amputation, pain management, evaluation of a casualty for mild TBIs, and how to prepare casualties for aeromedical evacuation. More than 15 000 copies of the guide, which fits into the pocket on the field uniform, have been distributed to deploying nurses and medics. Research is ongoing to evaluate the utility of using this pocket guide and other evidence-based sources[162,163] to describe the required operational competencies for all critical care nurses, and to evaluate use of these evidence-based resources as the basis for readiness training.[76]

## Conclusions

The lessons learned from battlefield research and performance improvement have contributed to the extraordinary survival rates and outcomes for combat casualties. Many of the innovations discussed in this article are the direct result of large, tireless programs of military and civilian research ongoing in the United States and the theater. The authors are privileged to have been involved with these efforts and to have contributed in a small way to advancing critical care to ensure the highest quality care for our combat casualties.

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