Dismounted Complex Blast Injury Patterns: A Review of Current Management and Outcome Literature.*

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RESUME
Caractéristiques des blessures causées par des explosions sur des hommes à pied : revue des pratiques de soins et conclusions de la littérature.

Les engins explosifs improvisés (EEI) ont été responsables de morbidité et de mortalité importantes tant en Irak qu’en Afghanistan. Les EEI à haute efficacité ont causé des blessures critiques mettant au défi les soins prodigués par les médecins militaires. Les études et recherches originales issues de l’expérience aussi bien des militaires Américains que Britanniques au cours de ces deux conflits ont été passées en revue.

Les blessures désignées comme « Dismounted complex blast injury (DCBI) » sont les blessures dont ont été victimes des soldats à pied. Il s’agit d’asymptômes traumatiques uniques ou bilatérales des membres inférieurs associées à des lésions des tissus mous du pelvis, du péroné et de la région fessière. Les lésions les plus importantes concernent les organes creux et pleins ainsi que les atteintes les plus proximales. Ces DCBI ont vu leur fréquence augmenter au cours des opérations Enduring freedom (OEF) et Irak freedom (OIF) et par conséquence un besoin d’amélioration des connaissances dans le domaine du traitement.

Les soins des soldats victimes de DCBI ont évolué avec les soins aux blessés en situation de combat (TCCC), l’évacuation rapide vers les services chirurgicaux des rôles II et III OTAN et le renforcement des capacités de traitement en cours d’évacuation. Les procédures chirurgicales de base sont restées courtes et ciblées; les interventions non vitales ou de sauvetage des membres ont été différées en attendant la stabilisation des patients.

Ces DCBI se sont accompagnées de complications telles que la déhiscence des plaies, les infections fongiques invasives, la maladie thromboembolique, l’ossification hétérotopique et la mort. On a pu montrer que la déhiscence des plaies était associée à un profil de sécrétion locale et systémique de cytokines particulier au moment de la suture. Des modèles prédictifs d’infection fongique invasive pouvant aider la décision chirurgicale ont été élaborés. La prévalence des complications thromboemboliques est plus élevée dans les blessures de guerre qu’en traumatologie civile en dépit des mesures chimio prophylactiques. L’application de mesures strictes de prévention a permis de diminuer les complications thromboemboliques chez les blessés de guerre. La mortalité des DCBI se situe entre 8 et 10 %. L’évolution de ce type de blessés a été améliorée grâce à de meilleures pratiques issues de l’expérience que ce soit la prévention, l’entraînement ou les progrès de la réhabilitation.

KEYWORDS: Blast, Trauma, Combat, Amputation, Military.

MOTS-CLÉS : Explosion, Traumatisme, Combat, Amputation, Militaire.

INTRODUCTION

As the wars in Iraq and Afghanistan progressed, enemy combat tactics evolved from conventional small-arms fire and explosive missiles and projectiles to more extensive use of improvised explosive devices (IEDs) of increasing yield. Blasts were the mechanism of injury for nearly three-quarters of all combat wounds and wounding patterns differed significantly based on whether or not the injured casualty was in a vehicle (mounted) or on foot (dismounted). As the wars progressed in Iraq and particularly in Afghanistan, dismounted injuries became a higher proportion of all blast injuries and occurred in predictable patterns with accompanying morbidity and mortality.

Blast injuries are classified by the specific component of blast mechanism responsible for damage. In primary blast injuries, blast overpressure transmits directly onto the person. Injuries are most commonly hollow viscous injuries (lungs, tympanic membranes, gut). Secondary injuries are caused by fragmentation and debris; these materials are transmitted over a larger distance (approximately 100 times the distance at which primary blast injuries would be expected). Tertiary injuries reflect acceleration/deceleration injuries of a body onto nearby large objects, or alternately, nearby large objects onto a body. Quaternary injuries are those received from exposure to harmful products such as burn or inhalation injuries. Quinary blast injuries refer to consequences of exposure to the post detonation environment and include bacterial inoculation, radiation exposure, and reactions of tissues to blast components fuels or metals.

Injury patterns in dismounted IED blasts are roughly categorized into two categories; low-energy and high-energy. Low-energy injury patterns can result either from a blast that emits relatively less energy or by increased relative distance from blast. These injury patterns include lower extremity open wounds, open or closed fractures, and/or lower extremity amputations. Perineal or genitourinary soft tissue injuries sustained from this mechanism are in general less severe.

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Injuries sustained by occupants of a mine-resistant vehicle, referred to as a mounted IED blast, tend to be primary or tertiary in nature. Penetrating injuries are common only in the setting of un-armored vehicles or blasts from explosive formed penetrators (EFP), which concentrates the fragmentation into a specific vector compared with the diffuse spray of common IEDs. Hallmarks of high-energy blast injury patterns are pelvic ring injuries, more severe perineal or genitourinary soft tissue injuries, and intra-abdominal solid organ or hollow viscus injuries. Thoracic and CNS injuries are also more common in high-energy blasts. Among service members with multi-extremity amputations it was found that the highest percentage of associated injuries were musculoskeletal (31%), skin and soft tissue injuries (18.8%), and GU injuries (17.4%). Other less common injuries included: pelvic and perineal injuries (5.6%), abdominal injuries (4.7%), thoracic injuries (3.7%), spinal injuries (3.2%), neurologic injuries (2.9%), and vascular injuries (2.7%). The relative paucity of thoracic and abdominal injuries is likely attributable to the effect of modern Kevlar helmets and ceramic plate body armor worn by U.S. service members in Iraq and Afghanistan. Even smaller proportions of facial fractures, ophthalmic injuries, and oropharyngeal injuries were also seen. Unsurprisingly, the proportion of spinal injuries correlated with increased severity of injury. This severe wounding pattern with multiple injuries became more evident throughout the progression of OEF.

The DCBI pattern in Afghanistan occurred with increasing frequency correlating with escalating combat operations and adaptations in tactics. The pattern and severity was unlike any injury in previous wars and therefore standardized care had not been previously well defined and specific treatment protocols had not developed. However, these issues were quickly addressed by the Department of Defense Joint Trauma System (JTS), which allowed for real time international morbidity and mortality communications. The JTS also provided the impetus for the evolution and development of military trauma Clinical Practice Guidelines (CPGs), a common core of principles and treatment strategies for all deployed medical providers of all skill level and expertise to follow. Treatment of DCBI patients is resource-intensive and therefore smaller facilities can be quickly depleted of supplies if patients are not evacuated rapidly to higher levels of care. In this paper, dismounted complex blast injury (DCBI) patterns and their initial and ongoing management are discussed. Major complications and efforts to decrease their severity are reviewed. In addition, short and long-term outcomes and areas of performance improvement are explored. Finally, representative findings influencing the care of combat casualties from retrospective review of OEF/OIF data is presented.

**INITIAL TREATMENT OF DISMOUNTED BLAST INJURY CASUALTIES**

**Trauma Bay Evaluation**

DCBI casualties are frequently critically ill in the pre-hospital setting and in need of rapid evaluation and resuscitation. Depending on the tactical environment and number of casualties, pre-hospital care may be provided in the form of self-aid or bystander (combat life saver care), which may be the initial and only treatment provided in the field particularly if the injuries are less severe. Typically though initial treatment of DCBI casualties in the field is provided by service members trained in Tactical Combat Casualty Care (TCCC). TCCC was adapted from ATLS-based training given to special operations medical providers to support battlefield relevant principles of pre-hospital care. In consultation with special operations providers, TCCC was fashioned by Naval Special Warfare Command to provide tactical trauma care in a small-teams environment. TCCC is divided into three phases: Care Under Fire, Tactical Combat Care, and Casualty Evacuation Care. These phases delineate the principles of TCCC; namely, return suppressive fire, provide immediate tactically feasible hemorrhage control and remove the casualty to safety followed by airway control, treatment of open and tension pneumothorax, fluid resuscitation, re-assessment and control of hemorrhage, prevention of hypothermia, protection of eye injury, pain management and rapid evacuation. TCCC is discussed in more detail later.

Current Advanced Trauma Life Support (ATLS) guidelines and U.S. Army Institute of Surgical Research Clinical Practice Guidelines provide the framework for initial trauma bay management. The Defense Medical Readiness Training Institute (DMRTI) based in Fort Sam Houston, TX has worked to integrate tactical training into the ATLS framework in its ATLS – Operational Emphasis (OE) course. The OE supplement contains additional lectures on tactical damage control resuscitation, military trauma systems, and team concepts. A practical course in proper tourniquet use was also included. This course is intended to be provided to all medical, nursing, and allied health professionals in the U.S. military.

Given the likelihood of multiple severe traumatic amputations, hemorrhage control is an immediate priority with dismounted complex blast casualties. Initial assessment by providers includes assurance that tourniquets are in place and tightly secured. For bleeding not amenable to tourniquet control such as high above knee amputations, junctional mechanical hemostatic devices should be applied. Given the association between lower extremity amputation and pelvic fractures, pelvic instability should also be assessed and a pelvic binder placed if not already secured in the field. Airway patency is assured or secured with intubation or surgical airway, while preventing untoward anesthetic related hypotension. Etomidate is the recommended induction agent and ketamine is given for analgesia in hypotensive patients. Optimal pain management remains a controversial issue; concerns among medics regarding hypotension with opioids and lack of familiarity with Ketamine has led to pain medication frequently being withheld at the point of injury. Severely injured patients will typically arrive with supraglottic, endotracheal, or surgical cricothyroidotomy airway devices placed by pre-hospital providers. Vascular or intra-osseous access for resuscitation has
often been placed prior to presentation to the Role II or III facility. With the amount of soft tissue destruction and hypotension sustained by blast casualties, intraosseous access is frequently obtained in the field or en route to the receiving facility. In the emergency room additional peripheral large-bore intravenous access is obtained if possible otherwise central venous access is placed. Patients rapidly undergo balanced resuscitation with blood products. Patients arriving with CPR in progress are assessed for signs of life (cardiac activity on FAST, EKG, pupillary reactivity, spontaneous respirations) and are often treated with a resuscitative thoracotomy (RT) in the trauma bay.

RT allows for proximal vascular control by cross-clamping the descending thoracic aorta while permitting open cardiac massage (OCM) in an attempt to improve perfusion to the heart and brain. [For the highest probability of survival, the general indications for an ED RT are blunt trauma patients arriving to the trauma bay with less than ten minutes of pre-hospital cardiopulmonary resuscitation (CPR), penetrating torso trauma patients with less than fifteen minutes of pre-hospital CPR, and penetrating neck or extremity trauma with less than five minutes of CPR. In recent US combat operations, the survival rate reported for RT performed on casualties arriving with signs of life after penetrating trauma, including bilateral amputations, was 11%, similar to survival rates in civilian trauma. The Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) device can also be inserted, which is being placed with increased frequency in the civilian trauma population, as an alternative or in conjunction with a resuscitative thoracotomy and OCM. However, with the adoption of Damage Control Resuscitation (DCR), rapid blood product transfusion, and tourniquet placement for DCBI casualties RT was often not necessary.

INDEX SURGICAL PROCEDURE PRIORITIES

Vascular Control

Following initial resuscitation, patients are taken emergently to the operating room. Life-threatening hemorrhage remains one of the top causes of potentially survivable death in combat trauma; therefore, hemostasis is paramount. Hemorrhage from extremity amputations are managed by tourniquets until the casualty undergoes operative exploration. Field tourniquets are converted to pneumatic tourniquets either in the trauma bay or upon arrival in the operating room. Hemostatic packing material placed in the field is removed from the wound while exploring the wound in the operative theater. Vascular control is then obtained by placing vascular clamps initially as proximally as possible in clear vascular planes and then “marching the clamps” distally to isolate and localize the area of injury. Vascular management varies depending on the level of amputation or vascular injury. Depending on resources and presence of other life-threatening injuries options for repair of vascular injuries include primary repair, exploration and placement of a vascular shunt, thromboectomy, or repair with an interposition autologous or prosthetic graft. Proximal traumatic amputations or junctional vascular injuries are managed by aortic or common iliac vessel control through a transperitoneal or retroperitoneal approach. In certain instances, primary ligation or even amputation may be warranted based on the amount of soft tissue destruction and physiologic status of the patient. The severe nature of DCBI often made limb salvage prohibitive. If temporary vascular shunts are used in extremity arteries, fasciotomies should be performed. Owing to the potential risks of vascular complications while undergoing aeromedical evacuations, fasciotomies should be completed in this setting as well.

Pelvic stabilization

In patients with high bilateral lower extremity amputations consistent with DCBI, the rate of concurrent pelvic fracture approaches 30% with bilateral lower extremity amputations and 39% with bilateral transfemoral amputation. Unstable pelvic fractures are potentially life-threatening injuries due to the potential for retroperitoneal hemorrhage and exsanguination. Initial treatment of unstable pelvic fractures in the field or en route includes placement of a pelvic binder, which works by reducing pelvic volume and providing a tamponade effect. Unfortunately physical exam historically has not been very accurate in identifying pelvic fractures, thus, recommendations for empirically placing a binder in the field include casualties with bilateral lower extremity amputations. At Role II or III facilities with orthopedic capabilities rapid application of an external fixation (ex-fix) device can be life-saving, especially in casualties presenting with a malpositioned binder or no binder at all. Placement of an ex-fix can occur in the emergency department or the operating room. Similar to a binder an ex-fix achieves hemostasis by reducing pelvic volume and stabilizing bony elements thereby providing a tamponade effect. External pelvic fixation also allows for prone positioning of patients which may be required for management of extensive perineal, gluteal, or flank soft tissue injuries. Ongoing pelvic hemorrhage despite appropriate pelvic stabilization with an ex-fix presents a unique challenge in an austere environment. Endovascular embolization may not be routinely available even at Role 3 facilities. In this instance, pre-peritoneal packing has been found to be of benefit in preventing further hemorrhage. Bilateral internal iliac artery ligation during laparotomy and in conjunction with pelvic packing is an additional damage control tool for massive life threatening retroperitoneal hemorrhage. Hemorrhage control and pelvic fixation are the key points of this aspect of the index surgical procedure.

Fecal diversion

In the setting of pelvic disruption or open pelvic wounds it is recommended to perform fecal diversion. At the time of the index procedure the sigmoid colon is stapled at the pelvic brim and left in discontinuity if performing damage control surgery. A colostomy can be matured at subsequent operations once physiologic derangements have been corrected. A loop colostomy may be acceptable in the absence of evolving rectal injuries but
should be not performed during a damage control procedure59, 60, 61. It is important to keep in mind potential future orthopedic incisions in these casualties when selecting ostomy placement to prevent future wound contamination17.

In the civilian trauma literature, performance of diverting colostomies for open pelvic fractures has been losing favor62. It is felt that due to the extensive nature of injuries seen in DCBI casualties that civilian data on open pelvic fractures may not be applicable. Emerging data from the UK among blast-wounded service members in Afghanistan has begun to question the need for colostomy for preventing infection in perineal wounds. A small series demonstrated that rates of perineal wound infections among patients whose fecal streams were diverted by colostomy versus by rectal tube were not significantly different56. In civilian trauma colostomy reversal within two weeks has been shown to be safe provided the patients' wounds are healing, sepsis is resolved, and the patient is stable63. This is often not the case with combat wounds due to the destructive nature of the blasts; thus, few if any combat casualties are reversed early after injury. Exact timing of ostomy reversal in the blast population is unknown but data on appropriate timing and associated complications of colostomy reversal in combat casualties is forthcoming.

**Surgical debridement**

Dismounted IED blasts often cause large degloving injuries of the lower extremities and perineum. The blast itself inoculates soil and clothing deep into the wounds and produces a diffuse microvascular injury64. Non-viable tissues are sharply debrided and wounds are thoroughly irrigated of dirt and debris65. Copious irrigation of tissue decreases bacterial load and removes organic matter. Adequate debridement of non-viable tissue reduces substrate for bacterial growth, allows for eventual closure, and improves the overall clinical status of the patient66. Negative pressure wound therapy is used liberally to allow wounds to heal either by secondary intention or develop sufficient granulation tissue for skin or synthetic dermis grafting or for delayed primary closure65, 67. As discussed below, debridement at the index operation is the first of many serial debridements68.

**SECONDARY SURGICAL PRIORITIES**

As noted above, the intent of index operations is to attain hemostasis, stabilize pelvic fractures, divert fecal stream, and debride devitalized tissue in an unstable patient. Other injuries are temporized or protected until definitive care can be provided. Ocular injuries remain protected with eye shields or improvised devices such as disposable paper cups69-71. Emphasis is given to limb preservation in upper extremity injuries; avoidance of amputation is crucial to patients’ functional recovery72-74. Genitourinary injuries will have been controlled according to the level of injury75. Ureteral and bladder injuries in which primary repair over a stent is not feasible will be drained with percutaneous nephrostomy or distal ligation and ureterostomy76, 77. Urethral injuries will be temporized with suprapubic bladder catheter placement78. In later operations when patients are more stable, less urgent operative interventions can be undertaken. Secondary surgical priorities are repeated in numerous surgeries that are to follow the index operation.

**Serial debridements**

It is expected that patients will undergo serial returns to the operating room for repair of injuries and wound irrigation and debridements. Timing is clinically dictated but most commonly occurring every 24-48 hours in the more acute phases of illness and every 48-72 hours later in the course of hospital stay79, 80. These serial operations also occur within 24 hours of arrival at each subsequent facility to allow fresh evaluation of wounds by successive surgeons. At the onset of both conflicts, war wounds were treated with wet-to-dry gauze dressings changed twice daily. From 2003 onwards, utilization of negative pressure wound therapy (NPWT) increased dramatically to become the standard of care for wound dressings81, 82. NPWT provides the added benefit of improving patient comfort by allowing the interval between painful dressing changes to lengthen from twice daily to once every 48-72 hours. This proved important as DCBI patients required an average of 8.6 operative procedures until definitive wound closure9.

**Amputation revision**

Traumatic amputations follow many of the same tenets noted in the section regarding serial wound debridements; that is, debridement of all non-viable tissue and copious isotonic irrigation. Extremity vessels are ligated as distally as is possible while remaining proximal to the limit of preserved bone. Use of proximal external fixation and preservation of as much viable bone and soft tissue as possible maximizes residual limb length. Eccentric skin and tissue flaps may be present and their preservation is paramount for later reconstruction. All wounds should initially be treated with negative pressure wound therapy (NPWT). If unavailable, saline or Dakins-soaked gauze dressings can be used instead83. Delayed sequelae of blast wounds include the development of heterotopic ossification (HO), the ectopic deposition of bone in non-bone tissue, which results in pain, ulceration, or poor fitting of prostheses. The prevalence of HO in war-wounded patients is 63-65%84, 85. Symptomatic HO not amenable to prosthetic modification or medical therapy requires surgical excision84. In general, the results of HO excision are acceptable with low rates of recurrent, symptomatic HO84. Additional complications in amputated limbs included infection, dehiscence, neuroma formation, as well as poor cosmetic and functional outcomes86. As a result, over half of lower extremity amputations require a revision86.

**Non-critical fracture treatment**

Fractures that do not contribute significantly to bleeding or physiologic compromise (fractures other than spine, long bones, and pelvis) are not addressed at the index surgical procedure in an unstable patient. These fractures
are typically initially managed at a secondary surgery with external fixation or wire fixation. Definitive internal fixation is delayed until the patient is more physiologically stable which has not resulted in major orthopedic complications\textsuperscript{87, 88}.

**MAJOR COMPLICATIONS**

DCBI resolution is hampered by wound complications, localized and systemic infections, heterotopic ossification, venous thromboembolism, and death. Significant effort has been expended to better classify these complications and prevent or treat them.

**Invasive Fungal Infections**

Previously a rare complication of traumatic injury involving farms, industry, or natural disasters, invasive fungal infections (IFI) have become more common in the setting of blast trauma and massive blood product transfusion. The rates of IFI among trauma admissions in Afghanistan reached as high as 3.5\%\textsuperscript{83} and were associated with a high mortality rate of 11-38\%\textsuperscript{80}. It has been demonstrated that patients with IFI experienced a statistically significant increase in number of operative procedures, longer ICU stay, and increased rates of more proximal amputation revision and death\textsuperscript{91}. Definitions of invasive fungal infections had previously targeted the presence of IFI in primarily or secondarily immunosuppressed patients (typically cancer patients). Case definitions developed by the European Organization for Research and Treatment of Cancer/Invasive Fungal Infections Cooperative Group and the National Institute of Allergy and Infectious Diseases Mycoses Study Group (EORTC/MSG) Consensus Group classified IFI by level of evidence of clinical infection and includes proven IFI (the presence of fungal elements in diseased tissue), probable IFI, and possible IFI\textsuperscript{92}. IFI in the combat setting was adapted from the Mycosis Study Group classification. To meet criteria combat casualties must have traumatic wounds that have undergone greater than one debridement with tissue necrosis noted in the wound on two or greater subsequent debridements as well as evidence of IFI as follows: proven IFI confirmed with angioinvasion on histopathology, probable IFI suggested with tissue invasion without angioinvasion, and possible IFI suggested with a positive fungal culture in the absence of positive histopathology\textsuperscript{89}.

Treatment is centered on appropriate surgical debridement, initiation of topical and systemic antifungal therapy, and correcting predisposing factors\textsuperscript{93}. Appropriate surgical debridement is frequent (~every 24 hours initially) and aggressive\textsuperscript{84}. Devitalized tissue lacks blood flow to deliver systemic antifungal therapy and therefore must be thoroughly debrided\textsuperscript{89}. Topical antifungal therapy consists of irrigation with modified Dakin’s solution during operative debridement, instillation of modified Dakin’s solution via NPWT, or use of Dakin’s-soaked dressings. Topical antifungal therapy is instituted if three or greater risk factors exist for IFI, which include: dismounted blast injury; proximal lower extremity amputation; extensive perineal, genitourinary, or rectal injury; and transfusion of greater than 25 units of blood\textsuperscript{84}. Systemic antifungal therapy is started for histopathologic evidence of IFI or progressive tissue necrosis over 2 or more consecutive debridements and consists of Voriconazole and liposomal Amphotericin B\textsuperscript{95, 96}.

Invasive fungal infections carry significant increases in morbidity, mortality, and utilization of healthcare resources. In an attempt to provide predictive tools to better stratify those at high risk for IFI; case-control data from DoDTR was reviewed. Large volume blood product transfusions and dismounted IED injuries resulting in proximal lower extremity amputations were identified as risk factors for developing invasive fungal infections\textsuperscript{90}. [A retrospective review of data from Landstuhl Regional Medical Center (LRMC) was performed to assess if timing of diagnosis of IFI in both the pre- and post-CPG institution (before and after February of 2011) had an effect on outcomes. According to the study results, the institution of the CPG allowed earlier identification of IFI; however, earlier diagnosis and treatment did not decrease length of hospital stay or overall mortality\textsuperscript{97}. The authors believed that some implementation of earlier IFI screening prior to publication of the CPG might have decreased the power of their study.

Serum biomarkers may also be of use in predicting which trauma patients are at high risk for invasive fungal infections. A retrospective case-control study compared immune biomarkers from DCBI patients with and without IFI. Serum values of IFN-\(\alpha\), IL-10, IL-15, and RANTES were significantly higher in patients with IFI than in those without. Elevations of these biomarkers were shown to be excellent predictors of IFI\textsuperscript{98}. The authors suggest future use of these biomarkers as a blood test for the presence of IFI in order to guide earlier treatment.

Data-driven computer algorithms have been shown to be beneficial in guiding clinical diagnosis\textsuperscript{99-101}. The Surgical Critical Care Initiative (SC2I) was able to develop a tool to predict the likelihood of IFI based on presence of traumatic pelvic and/or genital injuries, rectal injury, above knee amputation, theatre base deficit, theatre colostomy placement, theatre shock index, and first 24 hour PRBC transfusion requirement. This tool provides a percent likelihood that an IFI is present. In concert with clinical judgment, decisions about instituting treatment can be made (http://sc2i.org/tools). It is probable that many similar tools will be developed to aid clinicians in diagnosis and management of complex patients.

**Measures of Quality Care**

The use of benchmarking in clinical practice to evaluate quality of care provided has expanded into military trauma care as well. Diagnosis and treatment of complications such as symptomatic heterotopic ossification and venous thromboembolic disease allow military physicians to assess the care that the combat wounded patient receives.

Heterotopic ossification occurs as a result of blunt or penetrating trauma, neurologic trauma, and burns\textsuperscript{102, 103}. HO complicates lifestyle and return to duty by causing pain, poorly fitting prostheses, as well as vascular, neurologic,
and skin injury\textsuperscript{103, 104}. The prevalence of HO in patients with traumatic combat amputations approaches 65%\textsuperscript{85}. Methods of HO prevention include NSAIDs and radiotherapy; however, once formed the definitive treatment for HO is surgical excision\textsuperscript{105-107}. Recent research has implicated increased bioburden as a contributor to increased likelihood of HO formation in an animal model\textsuperscript{108}. These experiments suggest that contaminated soft tissue wounds in blast trauma may also increase the likelihood of HO formation. Early and aggressive management of wounds (debridement, thorough irrigation, and appropriate antibiotics) may help decrease the burden of future HO development\textsuperscript{108}.

Venous thromboembolic (VTE) disease is characterized by deep venous thrombosis (DVT) and pulmonary embolism (PE). DVT and PE are a major cause of morbidity and mortality in the trauma population\textsuperscript{109}. Although precise incidences of VTE disease in DCBI patients has not been explored, in combat wounded patients with bilateral lower extremity amputations the rate of VTE is 17.9\%\textsuperscript{1, 110}. Patients that develop VTE disease remain at risk for the sequelae which include post-thrombotic syndrome, chronic thromboembolic pulmonary hypertension, and an elevated risk of recurrence\textsuperscript{111, 112}. Blast-wounded patients from OEF and OIF seem to have a rate of PE/DVT that exceeds that expected for the trauma population as a whole despite adherence to VTE prophylaxis\textsuperscript{8}. Independent risk factors for the rate of VTE is 17.9\%\textsuperscript{1, 110}. Patients that develop VTE wwere non-compressible, truncal hemorrhage (49-67\%), junctional hemorrhage (19-21\%), and compressible extremity hemorrhage (14-33\%)\textsuperscript{5, 12}. Additional major causes of PS death were airway (10-15\%), CNS injury (6-13\%), and sepsis or multi-system organ failure (2-6\%)\textsuperscript{12}. Interventions to prevent PS death therefore must target these causes in a methodical and thorough fashion\textsuperscript{123}.

Conceptualizing death from battlefield injuries requires some common nomenclature. Fatalities as a result of battle injuries were stratified into those that occurred prior to arrival at a military treatment facility (MTF) and were considered killed in action (KIA) versus those that occurred after MTF arrival and died of wounds (DOW)\textsuperscript{10}. 87\% of all combat deaths were KIA; of these 76\% were classified as potentially survivable (PS) vs. 24\% deemed non-survivable (NS)\textsuperscript{5}. Non-survivable injuries (NS) fall into the broad categories of total body disruption, catastrophic CNS or high cervical spinal cord injury, cardiac or intra-thoracic tracheal or vascular injury, solid organ avulsion, or traumatic hemipelvectomy\textsuperscript{5}. Of the PS injuries, hemorrhage accounted for 83-90\%. Sources of hemorrhage were noncompressible, truncal hemorrhage (49-67\%), junctional hemorrhage (19-21\%), and compressible extremity hemorrhage (14-33\%)\textsuperscript{12}. Of the PS injuries, hemorrhage accounted for 83-90\%. Sources of hemorrhage were noncompressible, truncal hemorrhage (49-67\%), junctional hemorrhage (19-21\%), and compressible extremity hemorrhage (14-33\%)\textsuperscript{5, 12}. Additional major causes of PS death were airway (10-15\%), CNS injury (6-13\%), and sepsis or multi-system organ failure (2-6\%)\textsuperscript{12}. Interventions to prevent PS death therefore must target these causes in a methodical and thorough fashion\textsuperscript{123}.

**ELEMENTS OF A SYSTEMATIC APPROACH TO IMPROVING DCBI CARE**

**Adaptation of TCCC**

The vast majority (75-87\%) of combat deaths occur prior to arrival at a Role III facility\textsuperscript{2}. TCCC, as mentioned above, was designed to decrease mortality from potentially survivable injuries in combat with a focus on prehospital interventions.

The 75\textsuperscript{th} Ranger Regiment is a US army light infantry special operations force\textsuperscript{124}. In 1998 the unit’s regimental commander shifted responsibility for casualty response from unit medics to the unit’s tactical leadership and instituted continuous training in TCCC\textsuperscript{10}. Kotwal and colleagues examined nine years of battlefield casualties in Afghanistan comparing case mortality rate of the 75\textsuperscript{th} Ranger Regiment to the remainder of DoD casualties and found a rate of 3\% versus 19-28\%, respectively\textsuperscript{10, 12}. Furthermore; the small percent of fatalities reported by Kotwal et al were not the result of extremity hemorrhage, tension pneumothorax, or airway obstruction which represented the three major causes of preventable death\textsuperscript{10}. Definitions of PS deaths did not differ between the studies. This significant decline in mortality was attributed to TCCC training and supported the continued effort to expand TCCC training and utilization throughout the entire DoD.

TCCC is divided into three phases; Care Under Fire,
Tactical Field Care, and Tactical Evacuation Care. The following is derived in brief from the Military Health System Guidelines on TCCC: Care Under Fire (CUF) refers to the period of time in which the first responder and casualty are still engaged by the enemy and under fire. The priorities of this phase of care are stopping life-threatening hemorrhage, attaining fire superiority and moving the casualty to relative safety. Only life-threatening hemorrhage control should be attempted during this phase to prevent exsanguination and death. Fire superiority must be attained by the first responder (and, if able, the casualty) prior to addressing any injury. Afterwards, casualties should be moved to areas of relative safety to avoid ongoing potential sources of injury (enemy fire, burning structures/vehicles, etc).

The second phase, Tactical Field Care, begins once enemy fire is suppressed and the casualty is in relative safety. The acronym MARCH (Massive Hemorrhage, Airway, Respiration, Circulation, Head Injury/Hypothermia) describes the priorities of this phase of care. Massive Hemorrhage refers to control of life-threatening bleeding with placement of extremity tourniquets, junctional tourniquets, or topical hemostatics. Tourniquets placed during Care Under Fire are reassessed and additional, or "side-by-side" tourniquets may be placed. Airway refers to placement of airway adjuncts or establishment of definitive airway (either supra- or infraglottic or surgical). Respiratory directs decompression of tension pneumothorax with needle thoracostomy, placement of a vented chest seal on open chest wounds, and ventilatory support by bag-valve mask. Circulation refers to establishment of intravenous or intraosseous access and fluid administration guided by the principle of permissive hypotension (goal of palpable carotid pulse). Casualties with altered mental status or enemy combatants are disarmed to prevent ongoing threat to providers.

The third phase, Tactical Evacuation (TE), prepares stabilized patients for transport to advanced medical and surgical care. Planning for evacuation ideally occurs early to account for delays in arrival of the evacuation platform and prolonged transport. Adjuncts such as TXA and intravenous antibiotics are given during this phase. Patient packaging is performed with thermal blankets to prevent hypothermia. Providers must be diligent about assessing their patients for evidence of decompensation such as decreasing Glasgow Coma Scale (GCS), changes in respiratory status, or weakened pulses suggestive of ongoing hemorrhage.

**Aeromedical evacuation (2nd)**

Helicopters were first used to evacuate casualties during the Korean War. The U.S. military improved on this platform during the Vietnam War by adding trained flight medics to provide en route care. Evacuation improved even further during OIF/OEF with faster and more highly skilled battlefield transport.

Movement of combat casualties is divided into casualty evacuation (CASEVAC) and medical evacuation (MEDEVAC). CASEVAC refers to any non-medical vehicle tasked to bring casualties to medical care while MEDEVAC refers to any vehicle solely equipped and manned for casualty evacuation. MEDEVAC crew and vehicles are not armed with offensive weapons and explicitly marked with a red cross. Specifically for air transport rotary wing platforms were the most common means for casualty evacuation. During OEF/OIF these were the US Army MEDEVAC call sign “DUSTOFF” (due to the dust and dirt blown from the rotors), US Air Force Pararescue Expeditionary Rescue Squadron (ERS) call sign “PEDRO,” and UK Medical Emergency Response Teams (MERT) call sign “Tricky”.

Medical care on a DUSTOFF platform during OEF/OIF was primarily delivered by a flight medic trained to the level of an Emergency Medical Technician – Basic (EMT-B), which are currently being converted to paramedics. EMT-B skills include CPR, intravenous access, basic airway protection, and stabilization of musculoskeletal injuries. These basic skill sets are augmented to include additional training in hemorrhage control. DUSTOFF was augmented, in a scalable manner depending on mission and resource availability, by US Army En Route Care CCRNs and US Air Force Tactical Casualty Care Evacuation Teams “TCCET” after 2010. These included participation in point of injury and intra-theater transport missions. In addition, after 2013 the Vampire Program was developed primarily to place blood products on participating DUSTOFF units for en route transfusion. Although primarily a combat rescue and recovery platform, the PEDRO teams consist of two Emergency Medical Technician -Paramedic (EMT-P) trained pararescuemen (PJs). In addition to the EMT-B skills set, EMT-Ps can perform advanced airway maneuvers, needle decompression, cardiac monitoring, obtain IV with administration of fluids and medications. Medical crewmembers on a MERT include a physician (often an Emergency Room physician or an anesthesiologist), a critical care nurse, and two paramedics. United States Marine Corps (USMC) rotary evacuation platforms are all designated CASEVAC; no permanent MEDEVAC platform exists. Aircraft used for USMC CASEVAC are either diverted from a tactical mission or so designated as CASEVAC for specific missions. The designated CASEVAC aircraft are manned by Navy corpsmen who provide en route medical care.

Improvements in survival have been attributed specifically to altering the makeup of these teams from EMT-B-trained providers to critical-care trained mid-level providers and physicians. Deployments of Air National Guard MEDEVAC units staffed by flight medics trained to civilian critical care flight paramedic (CCFP) standards afforded a comparison with standard MEDEVAC. A retrospective review of severely injured patients in Afghanistan demonstrated that estimated risk of mortality decreased by 66% when aircrews evacuated patients with critical care flight paramedics (CCFPs) instead of EMT-Bs. A similar study demonstrated significantly improved survival as well as improved parameters of shock in patients evacuated by CCFPs vs. EMT-Bs. The demonstrable improved survival that CCFP-manned MEDEVAC is able to offer has caused the US Army to recruit and train CCFPs to man its evacuation platforms.
Current recommendations for process improvement are to update flight medic training to EMT-Paramedic standards. Furthering use of critical care-trained rotary wing evacuation staff can be expected to improve outcomes for critically ill war wounded patients.

Improved survival of battlefield casualties through the course of the U.S. military’s most recent conflicts has also been linked to shorter evacuation times mandated by then Secretary of Defense Robert Gates in 2009. His directive called for aeromedical transport times to be shorter than 60 minutes from point of injury to surgical care; these times were, on average, well over 60 minutes prior to his mandate. A report by Kotwal and associates demonstrated an increased survival when comparing casualty evacuation times before and after Mr. Gates’ mandate. Secretary Gates’ 60 minute mandate provides a clear example of directed policy and its ability to improve care.

**Military Trauma System**

Robust civilian trauma systems exist in the United States and worldwide. A well-designed regional trauma system will coordinate training and rescue capabilities for patients from the point of injury to definitive care and on to rehabilitation. The US military lacked a codified trauma system during the initial phase of OEF. In 2004, the Joint Theatre Trauma System (JTTS) was implemented in theater to establish a data registry and provide a performance improvement capability for combat casualties. The Joint Trauma System (JTS) at the US Army Institute of Surgical Research evolved from the JTTS to provide an permanent support system for all DoD trauma care. The system was tasked with improving the quality of care provided for combat wounded. Some of the JTS efforts included optimizing deployment of surgical resources, informing the curriculum for training of deploying trauma teams, establishing worldwide communication about cases, and developing clinical practice guidelines to ensure delivery of best practices. Among its most significant contributions, the JTS developed the Department of Defense Trauma Registry (DoDTR). Vast amounts of clinical data on injuries, treatments, and acute outcomes from nearly all combat casualties from OEF/OIF are collected in the database. This data is also available to support research. DoDTR data analysis helped develop and adapt CPGs that aided in improving mortality in the combat wounded patient. DoDTR data will continue to guide current and future combat casualty care.

**Prevention of Hypothermia**

Hypothermia is a component of the ‘lethal triad’ in trauma, which also includes coagulopathy and acidosis, and has been shown to correlate with severity of injury. Its consequences include the following: coagulopathic bleeding, increased oxygen demand, acidosis, cold diuresis, vasoconstriction, and cardiac arrhythmias. Hypothermia has been shown to independently increase mortality in major trauma patients with mortality being twice that of normothermic casualties. Prevention of hypothermia is therefore a necessity and has become a priority for the DoD combat casualty care.

The JTS released a CPG to decrease rates of hypothermia. This was assessed upon arrival of patients at Role 3 facilities. Recommendations for prevention of hypothermia are arranged by level of medical acuity. At point of injury or Role I, the Hypothermia Prevention Management Kit (HPMK) is applied to package a patient and actively rewarm them. En route medical caregivers also may have disposable oral/cutaneous thermometers, warmed blankets, and hypothermia caps. Role 2 and higher facilities are able to provide warm operating rooms, forced air warming devices, and rapid fluid warmer/infusers. After instituting this CPG, the rates of hypothermic patients arriving at Role 3 facilities decreased from seven-fold from 7% to 1%.

**Use of Tourniquets**

Analysis of battlefield deaths determined that compressible extremity hemorrhage was a significant cause of potentially survivable death. Tourniquets, when placed correctly, arrest arterial inflow to a hemorrhaging extremity and prevent exsanguination. Though the subject of renewed enthusiasm among the special operations community after their experience in Somalia, tourniquet use was not aggressively supported throughout the military at large in the first several years of OEF/OIF. This reluctance to use tourniquets early and aggressively owed to historic concerns about the effectiveness of tourniquets and the complications of failure, limb ischemia and nerve palsies. Data from the late 1990s and early 2000s demonstrated the life-saving potential of tourniquets (Helmholtz). 3% of deaths in the early years of OEF/OIF could have been prevented with extremity tourniquet placement. In 2003, the Advanced Technology Applications for Combat Casualty Care Conference was held in which subject matter experts discussed available evidence and recommended that all soldiers be issued tourniquets and trained in their use. The Surgeon General of the Army would recommend in 2005 that all service members had a tourniquet in their possession. Tourniquets were subsequently widely distributed to all deployed service members and standardized into the individual first aid kit (IFAK). This policy of wide distribution of tourniquets accounted for an 85% decrease in deaths from extremity hemorrhage when compared between 2001-2004 and after 2007.

Tourniquets are issued to all service members intended to be self-applied or applied by either medical or non-medical colleagues. Tourniquets are placed on bleeding extremities 2-3 inches proximal to injury. Tourniquets are tightened sufficiently to occlude significant hemorrhage though some oozing from non-compressible osseous medullary bleeding may continue. Frequent reassessment of tourniquets is paramount throughout the evacuation process to ensure that they have not become dislodged or otherwise ineffective.

Proximal extremity injuries can cause hemorrhage that...
is compressible but not amenable to tourniquet placement. Sites of potential junctional hemorrhage include the neck, axillae, pelvis and perineum, gluteal region, and proximal inguinal region\textsuperscript{158}. Commercial products have been developed which demonstrate the potential to prevent hemorrhage in groin injuries by occluding the common femoral artery; these include the Abdominal and Aortic Junctional Tourniquet (AAJT) (Compression Works, LLC), Combat Ready Clamp (CroC) (Combat Medical Systems, Charlotte NC), and Junctional Emergency Treatment Tool (JETT) (North American Rescue, Greer, SC)\textsuperscript{157, 158}. Data regarding effectiveness of these devices in the field remains limited. Animal trials have suggested that junctional tourniquets provide effective hemostasis for proximal hemorrhage. The CroC was evaluated in a swine model of common femoral artery hemorrhage in which placement of the device provided hemostasis; subsequent removal of the device permitted exsanguination\textsuperscript{159}. Junctional tourniquets have been able to cease simulated femoral artery bleeding in a perfused cadaver model\textsuperscript{157}. Similarly, trials in healthy human volunteers demonstrated cessation of lower extremity pulse after device application which suggests efficacy of these devices\textsuperscript{160}. Case reports from the field have demonstrated that the devices are effective at stopping hemorrhage in combat\textsuperscript{161, 162}.

Numerous prospective and retrospective studies attest to the performance of modern extremity tourniquets. A review of battlefield casualties among Israeli Defense Force (IDF) soldiers from 1997-2001 demonstrated no deaths from extremity hemorrhage in battlefield casualties treated with tourniquets\textsuperscript{152}. A prospective survey of combat casualties requiring tourniquet placement in Iraq in 2006 demonstrated a survival benefit as well as low rate of complications secondary to tourniquet use\textsuperscript{163}. Retrospective review of casualties with traumatic amputation, major extremity vascular injury, or pre-hospital placement of a tourniquet was performed at a U.S. Combat Support Hospital (CSH) in Iraq which demonstrated that 57% of deaths without tourniquet placement would likely have been prevented if an appropriate tourniquet had been placed\textsuperscript{164}.

Modern data about the benefits of tourniquet use has been widely adopted. In a U.S. series looking at tourniquet use in OEF/OIF, the rate of tourniquet placement from 2001-2010 increased from 4% to 40%\textsuperscript{165}. The UK experience in Iraq and Afghanistan from 2003-2007 noted a dramatic increase in tourniquet utilization after inclusion of tourniquet education in pre-deployment training and addition of tourniquets to individual first aid kits\textsuperscript{166}. Rates of complications from tourniquet placement (neuropathy, myonecrosis, extremity compartment syndrome, thrombosis) have been shown to be low and outweighed by the survival benefit of tourniquet placement\textsuperscript{167, 168}. Tourniquets have been widely distributed among service members in theatre and training in Combat Lifesaver and (CLS) and TCCC has been extensive. Use of tourniquets in civilian trauma patients has been recommended and has shown promising results\textsuperscript{169, 170}.

The American College of Surgeons Committee on Trauma (ACS-COT) recently held a meeting in Hartford, CT on the prevention of death from mass casualty and active shooter situations. At this meeting, the Hartford Consensus III was developed to define roles for responders and techniques of preventing death from hemorrhage\textsuperscript{171}. Outgrowths of the Hartford Consensus included the “Stop the Bleed” campaign and the “B-Con” course. “Stop the Bleed” aims to educate and empower laypeople to control life-threatening hemorrhage with direct compression and tourniquet\textsuperscript{172}. The “B-Con” course trains laypeople in hemorrhage control with tourniquets, packing, and topical hemostatics\textsuperscript{173}. Tragedies such as the bombing of the Boston Marathon in 2013 have shown that hemorrhage control lessons learned in combat have benefitted civilian victims\textsuperscript{174}.

**Prevention of Wound failure**

Dismounted IED blasts yield large soft tissue defects. In the acute phase, these wounds are treated with serial debridement and irrigation followed by application of negative pressure wound therapy\textsuperscript{175}. Definitive wound closure is achieved via delayed primary closure or use of tissue grafting. Traditionally the decision for wound closure was a clinical one based on the appearance of the wound in the operating room, the patient's clinical picture, and ultimately the surgeon’s judgment. Clean wounds in healthy patients typically heal; however, adiposity, poor nutrition, infection or colonization, tobacco use, and immunosuppressed states all decrease the likelihood of normal wound healing. Failed or ‘dehiscent’wounds do not undergo the normal coagulative, inflammatory, proliferative, and remodeling stages of wound healing\textsuperscript{176}. Dehiscent wounds will demonstrate separation of the wound edges and may suppurate. Without intervention, dehiscent wounds will go on to become at best chronic non-healing wounds and at worst grossly infected wounds that endanger the life of the patient. Even with ideal conditions, well-appearing wounds in stable patients were at risk of dehiscence and less-reassuring appearing wounds may be capable of being successfully closed\textsuperscript{177}. Rates of wound failure in OEF/OIF were reported to be 16-27%\textsuperscript{68}. Significant work has been expended attempting to better determine which factors will ultimately favor successful wound closure and decrease the likelihood of wound dehiscence.

The Surgical Critical Care Initiative (SC2I) has utilized wound effluent, blood samples, and tissue cultures to classify the wound microenvironment and systemic wound environment favoring successful wound closure\textsuperscript{7}. Wound effluent from wounds that went on to dehisce expressed higher IL-6, IL-1α, IL-2, IL-3, EGF, bFGF and lower IL-2, IL-4, MCP-1, MIG and IP-10\textsuperscript{7, 178}. Elevations of IL-1α, IL-1β, IL-8, MCP-1, MIP-1, GM-CSF and depressions of IL-4, IL-5, IL-13 in wound tissue biopsies were associated with an increased likelihood of dehiscence\textsuperscript{7, 179}. Forsberg and colleagues found that increased serum and wound effluent procalcinol as well as decreased wound effluent RANTES protein level and IL-13 level in extremity war wounds were shown separately to increase the likelihood of wound dehiscence\textsuperscript{177}. Conversely, no wound dehiscence was observed in the presence of normal wound effluent procalcinol, IL-13,
or RANTES. The ability to more accurately predict whether or not wounds are ready for definitive closure will likely decrease hospital stay and decrease the likelihood of wound dehiscence and/or amputation revision.

Predicting the Need for Massive Transfusion

Blood bank management is challenging in an austere environment, owing to the difficulties of supply chain, appropriate storage, and proper utilization. Buddy blood, or warm whole blood donated from friendly elements is often used for trauma resuscitation among NATO troops. Small forward operating bases with Role II medical facilities often experienced long periods of calm punctuated by mass casualty (MASCAL) incidents. Long-term storage of large quantities of blood products is logistically difficult at small facilities, resulting in the potential for significant waste.

Certain injury patterns increase the likelihood of the need for massive transfusion. Benfield and colleagues demonstrated that in dismounted IED blast casualties with multiple traumatic limb amputations the following injuries were all independent predictors for necessitating massive transfusion: open pelvic fractures, guile/perineal soft tissue injuries, and gastrointestinal injuries. In addition, the authors found that casualties with these injuries required 50-100% more blood products than those who did not sustain these injuries. As an adjunct to the surgeon’s clinical judgment, several tools are available to help predict the need for massive transfusion in trauma. These include the Trauma-Associated Severe Hemorrhage scoring tool which uses systolic blood pressure, hemoglobin, the presence of intra-abdominal fluid, complex long bone and/or pelvic fractures, tachycardia, acid/base status (base excess), and gender. In the case of the TASH tool, Hb is the most substantial contributor to prediction model.

Interestingly, Benfield found that admission hemoglobin (Hb) was not a significant predictor of the need for transfusion. In the past, time between injury and stabilization/resuscitation in trauma had been significant and aggressive crystalloid fluid resuscitation had been initiated en route to definitive care. This allowed the Hb to decrease in a manner consistent with the actually oxygen-carrying content of the blood. Now, modern combat casualties are rapidly transported to a forward surgical asset typically in a permissively hypotensive state in accordance with damage control resuscitation principles. This limits the utility of Hb as a predictor for transfusion by allowing it to remain falsely elevated; failing to reflect the reality of the physiologic derangements in a patient in hemorrhagic shock. Further research is needed to adequately guide steereage of blood product resources for optimal distribution in time of need.

Factors such as systolic blood pressure < 110mmHg, heart rate > 105 beats per minute, hematocrit < 32%, as well as pH < 7.25 were used to help guide decision-making about the need for MT. More recent findings have disputed admission hemoglobin and hematocrit as predictors of MT, finding instead that open pelvic fractures, gastrointestinal injuries, and/or extensive perineal or gluteal wounds suggested the need for MT. In that study, admission Hb and ISS were not found to affect the need for MT.

The difficulty in precisely determining indicators of massive transfusion from single variables led several trauma surgeons to develop a machine learning-clinical decision support tool. This tool takes into account several hemodynamic parameters (blood pressure, heart rate, and base deficit) as well as mechanism of injury and adjusts weight given to specific variables based on continued data input. The authors went on to develop a smartphone application to improve ease of use and speed of decision-making in a clinical setting. More work is needed to discover ideal indicators for trauma patients that should receive MT.

Balanced Resuscitation (DCR)

Data from OEF and OIF has had a significant impact on the practice of blood and fluid resuscitation in trauma. Massive transfusion (MT) refers to transfusion of 10 or greater units of packed red blood cells or whole blood in a 24 hour period. MT acts as a proxy for the most grievously injured patients. Traditional practice patterns called for aggressive crystalloid resuscitation to replete the intravascular space and blood-component based blood product resuscitation in major trauma. Blood product resuscitation ratios were not fixed; patients would receive significantly more packed red blood cells than FFP or platelets. It was hypothesized that outcomes in major trauma patients would be improved by increasing systemic oxygen delivery above normal with aggressive fluids; however, this was shown not to be the case. Early data in OEF/OIF suggested that hypotensive resuscitation and balanced use of blood components improved survival. After issuance of the DCR CPG, patients requiring MT received blood products in a ratio of 1: 1: 1 (packed red blood cells: plasma: platelets) or fresh whole blood (FWB) along with cryoprecipitate as indicated to reverse coagulopathy and acidosis. Banked blood is transfused during a massive transfusion in a “last-in-first-out” pattern to ensure that critically injured patient can derive the most benefit from transfusion. Rapid and frequent shipping of blood products to theater has decreased the average age products given during a massive transfusion from 33 days to 23 days. A goal of not transfusing blood products older than 14 days has been proposed but reaching this goal has been difficult to achieve. Review of the DoDTR suggests that mortality among massively transfused casualties decreased from 32% to 20% during the time course following adoption of the MT CPG. Studies assessing damage control resuscitation in civilian institutions have also demonstrated survival benefits. Consequently civilian trauma institutions have begun modifying massive transfusion practices to better approximate 1: 1: 1 resuscitation.

Biomarker Profile Analysis

The wound microenvironment and patient serum in blast trauma can yield practical data about the likelihood of
wound dehiscence, invasive fungal infection, and the interval development of heterotopic ossification. Analysis of wound effluent and serum markers in service members with traumatic bilateral lower extremity amputations from blast trauma was performed in a study by Lisboa et al. The findings were consistent with previous assessments that IL-8 was relatively increased in trauma patients; IL-13 and GM-CSF were relatively decreased. De novo findings from this study demonstrated increased IL-1 and decreased MCP-1 and MIG in patients with bilateral lower extremity amputations that went on to suffer a wound dehiscence as well as increased IL-1RA, IL-4, IL-8, IL-8, MIG, MIP-1a, and MIP-1b in patients with the same injury pattern that went on to develop heterotopic ossification. Of particular interest is the finding that patients that would subsequently develop wound dehiscence could be characterized by a local cytokine-predominant immune response in contrast to a predominantly systemic immune response seen in those that would go on to develop heterotopic ossification. In a recent paper by Forsberg and colleagues, serum and wound biomarkers from military blast trauma patients were compared with those of civilian blunt trauma patients. The researchers demonstrated that similar alterations of biomarker profiles and rates of wound dehiscence were noted between these two study populations. Data from this study permitted development of a clinical decision support tool using biomarker data to predict the likelihood of wound dehiscence. Research is ongoing utilizing wound microenvironment and serum biomarkers to further explore the immune response to trauma.

Lack of utility of ISS

The Injury Severity Score (ISS) may be a poor gauge of injuries in combat trauma patients. ISS has been demonstrated to underestimate injury severity as well as resource utilization including transfusion requirements, length of ICU stay, and length of hospital stay in patients with extremity amputations. The ISS and was developed through data from civilian motor vehicle injuries. The ISS is calculated first by computing a score on the Abbreviated Injury Scale (AIS). AIS scores are calculated by determining a numerical severity of injury from 0 (no injury) to 6 (nonsurvivable) for 6 body regions. These body regions are Head & Neck, Face, Chest, Abdomen, Extremity, and External. ISS is calculating by squaring the top three highest scored body regions and adding them together. The maximum score is 75; a score of 6 in any body region automatically scores 75. A patient with severe bilateral lower extremity injuries and a patient with a severe unilateral lower extremity injury would be scored the same in the Extremity body region. This represents a flaw in the ISS scoring system as several studies have demonstrated that these patients may have remarkably different courses of illness and resource requirements. However, the ISS may be of some utility in comparing and contrasting between severities of injury between patients with similar mechanisms of injury. To address the shortcomings of the ISS scale, new assessments of injury severity have been proposed. These scales often eschew civilian models based off motor vehicle trauma and utilizing models more consistent with combat trauma such as Military Combat Injury Scale (MCIS). New injury scales continue to be developed to better describe injury patterns and true physiologic insult in war wounds, but these scales need validation.

Novel Injury Scales

New nomenclature was developed to accurately describe lower extremity injuries caused by IEDs, where the use of previous systems such as the Gustillo and Mangled Extremity Severity Score failed to provide sufficient detail. The Bastion Classification was proposed as a way to grade the proximal extent of lower extremity IED injury in order to improve communication between physicians at various echelons of care and to help guide treatment especially in regards to vascular control. According to the Bastion Classification, Level 1 injuries extend no further proximally than the foot allowing for below-knee tourniquet placement. Level 2 injuries involve the lower leg but are be amenable to below-knee tourniquet placement. Level 3 injuries involve lower leg and/or thigh and can accommodate tourniquet placement above the knee. Level 4 injuries involve the proximal thigh where tourniquet placement would be ineffective or technically challenging to place. Level 5 injuries extend to the level of the buttock. While this classification system was internally validated and provides more information regarding the extent of injury, its widespread use was not implemented and operative management decisions still remain guided by the surgeon’s clinical judgment.

Pelvic and perineal injuries incurred by blasts were also categorized. The pelvi-perineal trauma score (PPTS) divided the pelvis and perineum into anterior (urogenital), middle (perineal), and posterior (anorectal) zones. Injuries to structures in these zones were then scored by severity to calculate a score from 1-36. Presence of a pelvic fracture and its subsequent classification increased the potential range from 1-42. Mortality was shown to increase with increasing PPTS and therefore PPTS may be useful for predicting mortality after pelvic and perineal blast wounds.

Evolving Practice with REBOA utilization

As mentioned previously, REBOA is emerging as a useful adjunct for temporary hemorrhage control prior to definitive management. Though previously shunned for high rates of complications and death, new techniques and equipment have renewed interest in its use. REBOA is intended as a less-invasive alternative to resuscitative thoracotomy (RT) or as an adjunct in RT. REBOA attenuates hemorrhage through occlusion of the aorta via endovascular balloon. Indications for REBOA include pulseless electrical activity or profound shock in the setting of blunt or penetrating trauma yielding intra-abdominal, pelvic, or hemorrhaging extremity injuries. The promising data from civilian centers utilizing aortic balloon occlusion in trauma has led to the addition of the REBOA to the military CPGs. The REBOA CPG recommends that REBOA only be performed at surgically capable facilities in patients with shock due to uncontrolled chest, abdomen, or
extremity hemorrhage\textsuperscript{213}. To date, there have been a few reports of U.S. military providers using this device in theaters of combat operations.

Current placement requires fluoroscopic guidance to confirm guidewire and balloon placement. This is a limitation in facilities where fluoroscopy may not be readily available. More recent iterations of REBOA devices have been developed that may allow safe balloon placement without imaging such as the ER-REBOA (Pryor Medical Devices, Boerne, TX) Non-fluoroscopic REBOA placement has been shown to be feasible in a swine model of hemorrhagic shock\textsuperscript{214}. The Federal Drug Administration (FDA) recently approved a non-fluoroscopic REBOA device for use in US civilian hospitals. In the UK, pre-hospital placement of a REBOA without fluoroscopy was successfully performed by a physician with London Air Ambulance\textsuperscript{215}. These newer devices may allow physicians or special operations medics and corpsmen to place REBOA in the pre-hospital environment. The CPG already recommends REBOA placement by anatomic landmarks if fluoroscopic support is not available. A measurement taken from the femoral head to a point halfway between the 12th rib and the medial heads of the clavicles should approximate the necessary depth for guidewire advancement to the distal aortic arch\textsuperscript{212}. Moving forward, military providers will need proper training on this device prior to deployment to ensure appropriate technical performance and maximal benefit to the casualty. Training in REBOA insertion technique is currently offered to surgeons through the Basic Endovascular Skills for Trauma (BEST) course.

**Use of Tranexamic Acid**

Tranexamic acid (TXA) is a synthetic analog of the amino acid lysine\textsuperscript{216}. TXA indirectly prevents fibrinolysis; leading to its initial applications in preventing obstetric and coagulopathic bleeding\textsuperscript{217}. TXA is an adjunctive therapy recommended to be given within 3 hours of injury in a patient thought likely to require massive transfusion. Patients in hemorrhagic shock, patients with 1 or more proximal amputations, or patients with penetrating torso injuries are more likely to require MT\textsuperscript{6, 125}. Providers can administer TXA as soon as intravenous or intraosseous access is obtained. The foundation for the use of TXA in trauma is based on two studies, the CRASH-2 and MATTERs trial. The CRASH-2 trial was a large civilian multi-center study that demonstrated a survival advantage in trauma patients receiving TXA versus those that did not. Post-hoc analysis revealed that administration of TXA should be given within three hours of injury and ideally within the first hour. The subsequent MATTERs study was a retrospective study of the military application of TXA which also demonstrated a mortality benefit in casualties receiving TXA without an increase in adverse events\textsuperscript{218, 219}. Interestingly, in both studies there was no difference in blood product transfusion requirements between treatment groups, which has raised questions into the mechanism of action of TXA outside of its anti-fibrinolytic properties. In cardiac patients administration of TXA has been shown to have an anti-inflammatory function that may attenuate the immune response after cardiac bypass\textsuperscript{220, 221}. Additional research is needed to better define the mechanism by which TXA improves survival.

**SUMMARY**

Comprehensive data regarding injury patterns, management, and outcomes of battlefield trauma was gathered throughout OIF and OEF. This data has been and continues to be analyzed to guide trauma practices for both military and civilian trauma care in the future. The promising results from the utilization of TCCC, DCR, and the other military CPGs will likely continue to be exploited in the next conflict.

Forward military medical assets are often resource-scarce in terms of space and supplies. Predicting resource utilization is of critical logistical importance in supplying materiel to environments such as Role II and Role III facilities. This is compounded by the potential for normal operating tempo to be stressed by the addition of a mass casualty (MASCAL) incident. Predictive models that allow for better planning for needed resources will be of benefit in future conflicts.

Ongoing basic science and translational research continues to answer questions about the topics raised above. Animal models of HO, VTE, polytrauma with the focus on the immune response, and invasive fungal infections provide novel strategies for intervention. Furthermore, advances in prosthetic devices and rehabilitation programs have led to better functional outcomes for these combat amputees.

Further investigation of data obtained in the DoDTR will continue to improve upon current practice while also providing innovative approaches to trauma care. As the utilization of IEDs by foreign militaries and other non-state actors increases, the knowledge and experience gained over the past fifteen years of conflict will assuredly save life and limb.

**ABSTRACT**

Improvised explosive devices (IEDs) have caused significant morbidity and mortality in Iraq and Afghanistan. High-yield IED injury patterns produced critically ill patients that have challenged military medical care. Studies of both original research and reviews from the US and British military experience during these two wars were explored.

Dismounted complex blast injury (DCBI) is a pattern of injuries sustained by dismounted service members. DCBI is a unilateral or bilateral proximal traumatic lower extremity amputation with accompanying soft tissue injuries to the pelvis, perineum, and gluteal region\textsuperscript{1}. More severe iterations include abdominal hollow viscus and solid organ injuries as well as complex upper extremity injuries\textsuperscript{2}. The DCBI pattern increased in frequency throughout Operation Enduring Freedom.
(OEF) and Operation Iraq Freedom (OIF), emphasizing the need for familiarity with treatment\(^1,3\).

The care of the wounded service member sustaining DCBI evolved with the application of Tactical Combat Casualty Care (TCCC), rapid evacuation to NATO Role II and III surgical facilities, and enhanced en route care capabilities\(^4,5\). Index surgical procedures were brief and focused; and non-life or limb-saving interventions were postponed until the critically ill patient condition was stabilized\(^6\).

The complex dismounted IED blast injury pattern has been found to be associated with major complications including wound dehiscence, invasive fungal infection, venous thromboembolism, heterotopic ossification, and death. Wound dehiscence has been demonstrated to be associated with a distinct local and systemic cytokine profile at the time of wound closure\(^7\). Predictive models including a clinical decision support tool for identifying risk of Invasive Fungal Infection (IFI) have been developed to assist the surgeon in wound management. The prevalence of venous thromboembolism among combat injured exceeds that seen in the civil trauma patient population despite VTE chemoprophylaxis\(^8\). Strict adherence to VTE prophylaxis has decreased VTE rates in the combat injured population\(^9\). The mortality of DCBI ranges from 8-10%\(^1,9\). Outcomes from this injury pattern have been improved by evidence- and experienced-based best practices, prevention, training, and advancements in rehabilitation\(^10,11\).

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