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The incidence, outcome, and treatment of advanced organ failure and support after trauma: A review with implications for future large-scale combat operations

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ABSTRACT: Future large-scale combat operations could involve delayed patient evacuation because of contested theaters of operations where United States and allied forces are unlikely to have air superiority. Prolonged casualty care could be more prevalent with delays in evacuation, requiring personnel prepared to provide critical care for injured warfighters and innovation aimed at supporting patients for longer periods of time. We conduct a review on the incidence and mortality rates of organ failure, describe the potential benefits of organ support, and offer recommendations to improve the care of patients in future conflicts. We performed a review examining the incidence and mortality of organ failure and the documented use of advanced modalities in the care of patients with organ failure. The search was conducted from the database's inception to June 21, 2024. Primary literature from previous review articles was also incorporated into this review. Authors reviewed relevant abstracts and full manuscripts. Acute respiratory failure and the need for respiratory support are common in severely injured trauma patients. Acute renal failure and the need for advanced renal support were also found to be common after injury. Although less common, advanced extracorporeal support, when required, can improve patient outcomes. In order to prepare for future conflicts, investment in personnel training, sustainment, and innovative technology will be essential to saving lives. (*J Trauma Acute Care Surg.* 2025;00: 00–00.)

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KEY WORDS: Battlefield medicine; organ support; organ failure; battlefield surgery.

Trauma remains a leading cause of death in the United States and globally.[1] Civilian and military trauma care has evolved to include advances at point of injury including hemorrhage control with tourniquets and blood administration, as well as damage-control resuscitation (DCR) and damage-control surgery (DCS) focusing on restoring an injured patient's physiology before definitive repair.[2,3] During more than 20 years of war, rapid stabilization and aeromedical evacuation have been readily available to transport critically ill combat casualties along the care continuum to advanced and definitive care at Role 3 and Role 4 military medical treatment facilities.[4] Early evacuation and the reintroduction of blood-based resuscitation, versus crystalloid, have decreased the rate of organ failure in severely injured patients in austere settings.[5]

During potential future large-scale combat operations (LSCO), theaters of operations and evacuation will be contested, and US and allied forces will unlikely have air superiority. Prolonged holding of causalities at Roles 1, 2, and 3 will thereby be required.[6] The impact of this substantial change in evacuation times on clinical outcomes is not well understood and has generated large interest. While the Joint Trauma System (JTS) Committee on Tactical Combat Casualty Care has developed prolonged casualty care guidelines to support Role 1 caregivers in preparing for this contingency, other deployed medical capabilities are less prepared. Deployed medical capabilities have limited (Roles 2 and 3) or no ability (austere resuscitative surgical care [ARSC]) to provide ongoing critical care of combat casualties for prolonged time periods beyond initial resuscitation, DCS, and stabilization.[7] Future doctrine will be necessary for contingency planning in prolong care environments when there is a paucity of timely evacuation; prolonged care, critical care, advanced interventions, and initiation as well as sustainment of

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organ support will be required.[4,8–10] These scenarios are occurring in Ukraine, where dialysis is being performed at far-forward surgical care to mitigate the hyperkalemia induced from prolonged tourniquets. All roles of medical care have also been routinely targeted (attempted and completed destruction) during the Ukraine war, which complicates evacuation and the positioning of medical capabilities. Anticipating the evolving need for ongoing critical care capability in the future operating environment, the JTS Committee on Surgical Combat Casualty Care is assessing the current military medical expeditionary capabilities. Critical care training, medical materiel, and organ support capabilities have been identified as gaps in forward surgical care in all the Military Departments (Army, Navy, Air Force, and Marine Corps).[11]

Respiratory failure alone and multi-organ failure (liver and kidney being the most common) have previously been identified as the most common intensive care unit admissions in trauma patients.[12–14] Mechanical and organ support, including invasive mechanical ventilation, continuous renal replacement therapy (CRRT), extracorporeal membrane oxygenation (ECMO), and less common but emerging filtrations strategies such as albumin-based molecular adsorbent recirculating systems (MARS), are used to aide in performing the function of the failing organ in the most critically injured patients.[15]

Understanding the incidence of the most severe forms of organ failure and the role organ support plays in the care of trauma patients could impact future medical planning and provide guidance in addressing identified critical care gaps in austere environments where patients cannot be quickly evacuated, or Role 3 facilities are either nonexistent or targeted by a peer competitor. The purpose of this Committee on Surgical Combat Casualty Care sponsored narrative review is to (1) summarize the available evidence on the incidence of severe organ failure and organ support in trauma; (2) describe morbidity and mortality rates to inform future study, which will aide military forward deployed caregivers, medical planners, and capability developers in understanding the implications of prolonged holding of critically ill combat casualties at forward (ARSC, Role 2, Role 3) medical capabilities; and (3) identify research and development gaps for future study.

MATERIALS AND METHODS

We performed a narrative review examining the incidence and mortality of organ failure and the documented use of advanced modalities in the care of patients with organ failure. This work analyzes previous published data and is institutional review board exempt. PubMed and Google Scholar were searched for articles using the combination of the keywords listed in Box 1. The Defense Technical Information Center was also searched with no additional articles that met the criteria for inclusion in this review. The Preferred Reporting Items for Systematic reviews and Meta-Analyses checklist was used to guide the structure and content of this narrative summary (Supplemental Digital Content, Supplementary Table 1, http://links.lww.com/TA/E578).

The search was conducted from the database's inception to June 21, 2024. Primary literature from previous review articles was also incorporated into this review. Authors reviewed relevant abstracts and full manuscripts. Articles were included in this review that contained (1) critically injured patients requiring intensive care unit level care, (2) reported incidence/prevalence of interest, (3) and included the study of a trauma population, whether military or civilian. Articles without incidence/prevalence data were excluded as were articles that were conducted in nontrauma populations. Three authors independently collected data from each database. No automation tools were used for data collection. Authors also reviewed guidelines and supporting citations of included articles. The literature search was restricted to studies published in English, with focus on the trauma, and critical care literature. This article is a review and not a systemic review or meta-analysis. Thus, authors did not pool data or assess bias or risk. Given that this was a narrative summary, no independent statistical analysis was performed. All results were presented in narrative and table format. This was a narrative review so was not registered, and no additional protocol was prepared for data extraction bedsides what is described previously.

Box 1: Keywords Used for Review

- Intubation OR Mechanical Ventilation AND Incidence AND Trauma OR Battlefield OR Combat 14 results
- ARDS OR Acute Respiratory Failure AND Incidence AND Trauma OR Battlefield OR Combat 19 results
- ECMO AND Incidence AND Trauma OR Battlefield OR Combat 2 results
- Hyperkalemia AND Trauma OR Trauma OR Battlefield OR Combat AND Transfusion 36 results
- CRRT OR Renal Replacement AND Trauma OR Trauma OR Battlefield OR Combat AND Incidence 45 results
- Dialysis AND Trauma OR Trauma OR Battlefield OR Combat AND Incidence 14 results
- Trauma OR Trauma OR Battlefield OR Combat AND Acute Kidney Injury AND Incidence 17 results
- Liver Injury AND Trauma OR Battlefield OR Combat AND Incidence 9 results
- MARS AND Trauma OR Battlefield OR Combat 0 results

Roles of care were defined based on US military doctrine.[16] Role 1 provides immediate lifesaving measures, noninjury presentation and care, triage, resuscitation, and stabilization. Role 2 provides advanced trauma management and emergency medical treatment including continuation of resuscitation started at role 1. Role 2 can provide emergency surgical support and has a limited hold capacity. Role 2 can also have light capability requiring early evacuation or enhanced capability with greater ability to stabilize postoperative patients. Role 3 capabilities include enhanced surgical and postoperative care. Role 4 medical care is found in US base hospitals and robust overseas facilities.

RESULTS

Using the criteria and search parameters mentioned previously, relevant articles were separated by organ system for further analysis and discussion.

Acute Respiratory Failure and Respiratory Support

Civilian and military population articles demonstrated frequent rates of acute respiratory distress syndrome (ARDS) and

TABLE 1. Occurrences and Complications of Organ Failure Diagnoses

Citation and Population	Incidence/ Prevalence	Morbidity	Mortality	Conclusions
Acute respiratory failure				
Edens et al., 2010[17]*, US combat casualties	33%	N/A	N/A	Pulmonary injury leads to ALI
Chan et al., 2012[18]*, US combat casualties	11.2%	N/A	N/A	Warm fresh whole blood may increase the risk of ALI
Starkey et al., 2013[19], UK military casualties	9.5–23.3%	N/A	N/A	No increase in the incidence of ARDS with transfusions of varying ratios of plasma/red cells
Park et al., 2013[20]*, US combat casualties	5.3–8.4%	N/A	16.3–17.4%	Plasma/crystalloid are risk factors for ARDS
Belenkiy et al., 2014[21]*, Burned military casualties	32.6%	N/A	43.8%	Of patients who required mechanical ventilation, 1/3 developed ARDS
Waters et al., 2015[22]*, Military/civilian burn ICU	33–35%	N/A	33–48%	Burned military patients had a significantly lower overall and ARDS mortality
Park et al., 2016[23]*, US combat casualties	3.3%	N/A	12.8%	ARDS risk factors included female sex, higher injury severity, hypotension, and tachycardia
Schmitt et al., 2020[24], Combat casualties admitted to French ICUs	42%	Prolonged ICU stay Prolonged mechanical ventilation days	14–21%	ARDS was frequent and severe among French patients evacuated from war theaters Incidence of ARDS after trauma appears to be declining, mortality is on the rise
Kasotakis et al., 2021[25], US civilian TQIP data set	1.1–3%	Prolonged hospitalization Prolonged ICU stay Prolonged mechanical ventilation days	18–21%	
Hyperkalemia				
Perkins et al., 2007[26], Noncrush civilian injuries	29%	N/A	N/A	Caution is necessary with trauma patients who present with potassium levels >4.0 mmol/L massive transfusions
Aboudara et al., 2008[27]*, Noncrush military casualties	38.5%	N/A	N/A	Hyperkalemia is common after red cell transfusion
Au et al., 2009[28], Civilian operative trauma	4.8%	N/A	N/A	Patients were at no higher risk of hyperkalemia than those who received no blood products
AKI				
Podoll et al., 2013[29], Civilian trauma admitted ICU	8%	N/A	29.6%	Development of early AKI was independently associated with higher 30-d mortality
Heegard et al., 2015[30]*, US military casualties	34.3%	N/A	21.7%	AKI is common in combat casualties and is associated with crude mortality
Elterman et al., 2015[31]*, US military casualties	17.6%	N/A	N/A	Elevated CK levels are associated with AKI but not predictive
Stewart et al., 2016[32]*, US military casualties	12.5%	N/A	2.9%	AKI predicted mortality in combat veterans injured in war
Lai et al., 2016[33], Taiwan trauma registry system	0.54%	Greater ICU length of stay Greater length of hospital stay Higher rates of mortality	OR, 39.0; 95% CI, 24.69–61.8; $p < 0.001$	Patients with AKI presented with different injury characteristics and worse outcome
Stewart et al., 2016[34]*, US military casualties	10–23.5%	Higher incidence of AKI with rhabdomyolysis (23.5% vs 10%, $p < 0.001$)	3–7.2%	Rhabdomyolysis is associated with the development of AKI in combat casualties
Haines et al., 2018[35], Civilian trauma admitted ICU	19.6%	N/A	32.5%	First serum creatinine, transfusion, age discriminated need for RRT and AKI early after trauma
Harrois et al., 2018[36], Civilian French trauma registry	13%	N/A	OR, 1.943; 95% CI, 1.300–2.890; $p = 0.001$	AKI has an early onset and is independently associated with mortality in trauma patients
Don Bosco et al., 2019[37], Civilian trauma injuries	40%	N/A	6.3%	No association of AKI and mortality; AKI was associated with age, hypotension, and GCS
Hatton et al., 2021[13], Civilian trauma admitted ICU	45%	N/A	N/A	Posttraumatic AKI was common on arrival and frequently short lasting

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TABLE 1. *(Continued)*

Citation and Population	Incidence/ Prevalence	Morbidity	Mortality	Conclusions
Traumatic liver injury				
David Richardson et al., 2000[38], Civilian hepatic injury database	12–15%	N/A	9–19%	Nonsurgical therapy is used in more than 80% of blunt injuries. The death rates from both blunt and penetrating trauma have improved significantly.
Stankovic, 2005[39], Military injuries	16.6–83. 3%	Reoperation	18.1%	Complex liver injuries cause very high mortality rates
Badger et al., 2009[40], Civilian trauma injuries	5%	N/A	10–15%	In the absence of other abdominal injuries, operative management of the liver can usually be avoided
Buci et al., 2017[41]	17%	N/A	N/A	Success in conservative treatment correlated with grade of injury
Afifi et al., 2018[42]	38%	Delayed bleeding Biloma Pseudoaneurysm Necrosis	7.8%	All conservatively treated patients with high-grade liver injuries should be closely monitored for signs of failure

*US military patient population.

ALI, acute lung injury; CK, creatinine kinase; GCS, Glasgow Coma Scale; ICU, intensive care unit; N/A, not applicable; RRT, renal replacement therapy; TQIP, Trauma Quality Improvement Program.

acute respiratory failure (total, 1.1–35%; US military, 3.3–35%; Table 1). The populations were heterogenous between studies. Several articles identified risk factors for higher rates of ARDS/acute respiratory failure including older age;[25] female sex;[20] higher Injury Severity Score;[17,20,24] transfusion of fresh frozen plasma,[17] platelets,[17] and whole blood;[18] increased crystalloid administration;[20] and burns.[21,22] Rates of intubation in the military, prehospital, and in-hospital settings ranged broadly from 3.5% to 48.7% with limited recent data (Table 2).

Advanced pulmonary support in the form of venovenous extracorporeal membrane oxygenation (VV ECMO or lung bypass) was also examined. The use of ECMO for all indications is reported as increasing in the overall population;[53] however, only one study reported the incidence in the use of ECMO in all admitted trauma patients.[49] There were several studies on the use of ECMO in military trauma patients. From 2005 to 2011, The ECMO team was dispatched for 40 transports, 28 of whom were for traumatic indications.[10] Twenty-four patients were evacuated from combat zones to Germany on ECMO.[10] As of 2019, the US military cared for 184 inpatient ECMO patients, which included patients accepted from 110 ECMO transports.[50] There was a noted yearly increase in transports from 2013 to 2018. Of all 97 transported patients, 7.1% received ECMO for traumatic indications. Seventy-nine patients (81%) received VV ECMO.

Acute Kidney Injury and Renal Replacement Therapy

Like patients requiring respiratory support, trauma patients with acute kidney injuries and electrolyte disturbances are a heterogenous population (Table 1). Patients with acute kidney injury (AKI) after trauma are more likely to be older, have a higher Injury Severity Score, lower Glasgow Coma Scale scores, elevated lactate values, have rhabdomyolysis, and more likely to have hemorrhagic shock.[30,33,35] Acute kidney injury was observed in burn and blast patients as well as in crush injuries,[31,54–56] with rhabdomyolysis associated with AKI in nonburn combat-injured patients.[31] Electrolyte and acid/base disorders are commonly encountered in trauma patients and are indications for initiation of CRRT. Hyperkalemia is observed after massive transfusions in the civilian and military population with an incidence of 4.8% to 38.5% (US military, 12.5–34.3%).[26–28] The overall incidence of AKI after trauma was 0.54% to 45% (Table 1). The initiation of dialysis was observed in 0.2% to 19% of trauma patients (Table 2).

Liver Injury and Liver Support

The liver is the most commonly injured organ in blunt trauma.[14] Between 5% and 83.3% of traumatically injured patients have some degree of liver injury (US military specific data not available, Table 1). There is little military literature regarding battlefield liver injury incidence and treatments. One study reported a 16.6% to 83.3% incidence depending on the grade of injury.[39] Additionally, 35.3% of these injured patients had post-operative complications. In civilians, the incidence of liver injury is 5% to 38%. The patient populations studied were heterogenous, and the management of various degrees of liver injury was variable. No studies examined the incidence of MARS in the treatment of liver failure after trauma. However, MARS has been used in patients with acute liver failure after trauma with a 60% survival rate; no difference in mortality was observed between causes of acute liver failure requiring MARS.[57]

DISCUSSION

Military and civilian patients with traumatic mechanisms of injury can develop varying degrees of organ dysfunction. Depending on injury severity and mechanism, high rates of organ failure requiring support have been demonstrated in the literature, with some requiring organ support to prevent death. Multi-organ dysfunction is also commonly observed in severely

TABLE 2. Organ Support Modalities Used in Trauma Patients

Citation and Population	Incidence	Reported Morbidity	Reported Mortality	Conclusions
Mechanical ventilation				
O'Brien et al., 1988[43], Prehospital civilian trauma	39.5%	4.6%	N/A	With differing acuity, no difference in scene or transport times between those patients emergently intubated and those who were not
Talucci et al., 1988[44], Civilian trauma injuries	18.6%	N/A	0.9%	RSI with endotracheal intubation is an alternative to nasotracheal intubation in the spontaneously breathing patient
Katz and Falk, 2001[45], Prehospital civilian trauma	25.1%	NA	NA	Incidence of out-of-hospital, unrecognized, misplaced endotracheal tubes in this community is high
Katzenell et al., 2013[46]*, IDF military registry	7.3%	N/A	N/A	After the first intubation attempt, success with subsequent attempts tended to fall
Hardy et al., 2013[47]*, US military casualties	48.7%	N/A	N/A	Supports prehospital BVM ventilation as an alternative to cricothyrotomy with no difference in outcomes between groups
Broms et al., 2023[48], Prehospital civilian trauma	3.5%	N/A	0.7%	Prehospital tracheal intubation by anesthetists was performed with a high success rate
ECMO				
Powell et al., 2023[49], Civilian trauma injuries	0.1%	N/A	30%	Early ECMO resulted in ventilatory stabilization that allowed subsequent procedural treatment of injuries
Read et al., 2020[50]*, US military casualties	N/A	N/A	73.3%	The ability to cannulate patients in remote locations and provide transport has allowed the US military to maintain readiness of a critical medical asset
Hemodialysis				
Podoll et al., 2013[29], Civilian trauma admitted ICU	19%	N/A	29.6%	Development of early AKI was independently associated with higher 30-d mortality
Beitland et al., 2014[51], Civilian trauma injuries	8%	No dialysis needs >3 mo after CRRT	36%	Trauma patients with AKI undergoing CRRT often had severe primary injuries due to blunt trauma. Most of them suffered from secondary multiple organ failure concomitant to AKI.
Haines et al., 2018[35], Civilian trauma admitted ICU	5.1%	N/A	32.5%	First serum creatinine, transfusion, age discriminated need for RRT and AKI early after trauma
Farhat et al., 2020[52], Civilian trauma injuries	0.2–0.6%	N/A	N/A	Obesity was associated with an increased risk for dialysis after trauma
Civilian trauma injuries				

*Military patient population.
BVM, bag valve mask; IDF, Israeli Defense Force; RRT, renal replacement therapy; RSI, rapid sequence intubation.

injured patients requiring rapid recognition and intervention to improve patient outcomes.[58] In those patients who have such severe organ failure requiring mechanical or extracorporeal support, our review demonstrates reasonable rates of survival can be expected with timely critical care support and treatments.

Expected Organ Failure in LCSO

Compared with the recent global war on terror, previous wars involving LSCO have demonstrated independently higher rates of organ failure. Anecdotally, during World War II, prior to the development of dialysis capabilities, US Army surgeon consultant E.D. Churchill noted that "replacement of lost blood reached an extraordinarily high level of effectiveness… An appreciable number of the wounded survived, however, only to die about the tenth day with complete anuria…The obvious weak link in the severely wounded in this war was the kidney." In the Korean War, AKI was found to be associated with increased evacuation time, longer duration of hypotension, and decreased transfusions.[59] As opposed to global war on terror, all these factors can be expected during LSCO.

During the last 20 years of war, 93% of critically injured combat casualties were transported out of the Iraq and Afghanistan theaters to the Role 4 Landstuhl Regional Medical Center by Critical Care Air Transport Teams within 72 hours of initial injury (98.5% within 96 hours).[4] These times to evacuation out of theater were short because the medical footprint in theater was relatively small, which required rapid evacuation out of theater to ensure that there was always bed capacity. Additionally, rapid evacuation supported the civilian trauma centers timelines and contemporary experiences in managing postinjury organ failure. These times to evacuation out of theater were specifically targeted based on civilian trauma centers contemporary experiences in managing postinjury organ failure. In the future, such timely evacuation may not be possible. The deployed trauma system during CENTCOM operations was a built-in rescue strategy for casualties who would require organ support—the rapid timelines allowed a shift of critical care resources to be mostly maintained outside the combat zone. As such, the large numbers of severely injured and burned casualties expected in LSCO during multidomain operations (air, land, and sea) will require prolonged austere critical care in-theater (e.g., Roles 1, 2, and 3), well beyond traditional timelines of care.[6] In this future operating environment, organ failure resulting from the subsequent complications of injury and/or delayed surgical management from processes such as hemorrhagic shock, sepsis, prolonged tourniquet application syndrome, rhabdomyolysis, burn resuscitation, and massive transfusions should be anticipated,[6,60,61] and the ability to provide critical care and organ support will be necessary to save lives on the future battlefield.

ARDS/Acute Lung Injury in LSCO

Delays in organ support during future LSCO could worsen outcomes in combat casualties who survive initial DCR/DCS. Increased time to intubation in patients requiring mechanical ventilation after trauma increases mortality rates.[62] Timely reversal of inability to oxygenate and ventilate improves respiratory acidosis and aerobic metabolism and stabilizes the patient with respiratory failure.[63,64] The most common indication for VV ECMO in trauma patients is refractory respiratory failure.[65] In trauma patients who have severe acute lung injury refractory to stabilization with advanced techniques and strategies (e.g., heavy sedation, paralytics, proning, or Airway Pressure Release Ventilation), early VV ECMO is required, usually within hours from injury and may have a mortality benefit.[49,66] For patients with acute lung injury and traumatic brain injury requiring VV ECMO, delays of even a few hours lead to increased mortality.[67] For patients with burns and ARDS, the use of VV ECMO en route can provide needed stabilization for transport.[68] Regardless of the respiratory support required, early intervention is imperative to decreasing morbidity and mortality.

US ARSC and Role 2 capabilities routinely deploy with the ability to provide mechanical ventilation, although the number of expeditionary ventilators they deploy with is variable and often have limited settings. Forward deployed caregivers on these teams also have limited training and clinical experience providing prolonged mechanical ventilation and managing conditions such as ARDS in austere environments. Reassessing the number of ventilators, consumables, and medications and ensuring that the team has relevant protocols and is appropriately trained to perform complex ventilator management in the context of LSCO would be relatively easy, as these capabilities exist for these teams but are limited. At the time of this writing, the JTS was updating the mechanical ventilation and respiratory care clinical practice guidelines to assist forward deployed team in initial and advanced ventilator management.

Very few team members are adequately trained to provide respiratory support for severe lung injury such as ARDS. Far forward expeditionary VV ECMO is not a widespread US military capability. Currently, only specialized Department of Defense Tri-Service ECMO teams provide this capability in an expeditionary environment when deployed forward. During the early phases of LSCO patients requiring ECMO in far-forward austere environments may be too resource intensive to manage and provided expectant care only. However, as a potential future LSCO theater of war matures, specialized teams analogous to ARSC teams equipped with field expedient equipment designed to provide advanced critical care including VV ECMO may be a needed capability and is certainly worthy of future research and development.

AKI and Renal Replacement Therapy in LSCO

As demonstrated in the clinical vignette and in this review, early initiation of renal support is also important to improving patient outcomes in traumatic injury, shock, and sepsis.[69–72] Continuous renal replacement therapy corrects electrolyte abnormalities, assists in the clearance of myoglobin from rhabdomyolysis, and aides in the correction of acidosis.[73,74] In patients with CRRT indications, delays in initiation can worsen outcomes.[75] Preforming in theater renal replacement therapy was first used within a combat theater during the Korean War. US Army field hospitals and US Navy hospital ships routinely provided renal replacement therapy during the Vietnam War. In the Korean War, the mortality rate seen in AKI decreased from 80% to 90% to 53% with a renal replacement therapy capability.[59] Early in Operation Iraqi Freedom, the USNS Comfort provided renal replacement therapy for three patients, but this capability was not maintained in theater until 2010 when the Role 3 hospital in Bagram, Afghanistan, routinely initiated renal replacement therapy to reverse AKI-related acid-base disorders, severe hyperkalemia, and metabolic disorders. While critical care teams with advanced capabilities were available in previous conflicts to initiate and transport patients with organ support needs to specialty centers, this capability may be limited because of a lack of trained personnel and a compromised logistical resupply in contested environments.[8,76] Additionally, renal replacement is not a standard Role 3 capability. For example, the Kandahar Role 3 did not routinely have this capability, particularly during the last 5 years of war in Afghanistan. Anecdotally, when managing local nationals requiring renal replacement, peritoneal dialysis (PD) was used at the Kandahar Role 3 with the guidance of the JTS "Hyperkalemia and Dialysis in the Deployed Setting," clinical practice guideline. The ability to provide rapid, renal replacement therapy that is simplified in use and more readily available (in the form of electrolyte filtration, intermittent hemodialysis, PD, sustained low-efficiency dialysis, or CRRT) far forward during future LSCO will be required, and a ruggedized version of available technology should be developed for Role 2 use.

Liver Injury in LSCO

Liver injury requiring procedural intervention is common in severely injured patients, especially after blunt injury. Mortality rates in austere settings are high with increased grades of liver injury and subsequent failure.[39] In LSCO, liver toxin filtration adjuncts may be beneficial to stabilize patients with liver injury during prolonged holding. Molecular adsorbent recirculating system is one such approach that uses albumin-based dialysis to remove toxins that build up during acute liver failure due to impaired hepatic function.[77–79] Early studies demonstrated possible efficacy, but results were mixed.[80–84] While there is literature in other acute liver failure populations demonstrating improved outcomes with timely initiation of MARS,[85] it is not routinely used in trauma patients. Further study is needed to determine benefit and feasibility in injured patients in non–resource-limited settings. In addition, trained providers with the portable capability to perform MARS or other hepatic toxin filtration techniques would be required if future benefit is shown.

Potential Gaps in the Care of Patients With Organ Failure in LSCO

Perhaps, the largest critical care and organ support gap exists within Role 2 surgical teams (including ARSC teams). By military doctrine, Role 2 care provides enhanced ability to provide DCR and DCS to bridge the gap between wounding and definitive care.[16] Depending on the Role 2, this can include advanced monitoring, blood resuscitation, vasopressor support, and mechanical ventilation. However, current Role 2 care implies a surgical capability to perform DCR/DCS with limited holding capability and capacity. Current, Role 2 care in the current battlefield trauma system has evolved to have limited or no hold capacity or capability for even 24 hours. In the LSCO environment where patients cannot be immediately evacuated to other roles of care, there could be a gap in the ability to provide treatments for severe organ failure of all types. As demonstrated, timely initiation of treatment is essential to improving patient outcomes. Lack of trained critical care personnel and limited equipment and resource resupply at the Role 2 level have a high likelihood of resulting in increased mortality rates among injured warfighters who arrive alive to this level of care.

Telemedicine and Automation for Future Medical Care

The study and implementation of automation for the recognition of injury/illness, diagnosis, and treatment of patients are increasing in civilian and military medical care. From clinical decision support algorithms to automated hemorrhage control, the integration of artificial intelligence (AI) will be more prevalent in future conflicts.[86,87] Developing such technology that can risk stratify, assist with monitoring of critically ill patients, and perhaps even provide treatment for patients in environments with limited resources could further enhance survival even in the most austere environments. Paired with telemedicine support of specialists who can provide enhanced expertise to geographically dispersed teams, improved survival of injured warfighters may be possible.

Innovation for the Next Conflict

To prepare for LSCO and the medical care needs for injured warfighters, greater Role 2 critical care resources will be required.[7,88] First, investment in critical care trained personnel who can perform basic organ support is required. Critical care specialists improve patient outcomes through specific expertise, training, and clinical experience.[89,90] They have advanced skills in performing intubation, mechanical ventilation, and extracorporeal techniques and could provide advanced patient care during patient holding and evacuation. However, the current numbers of forward deployable critical care specialists on active duty or in the reserve component are not enough to manage the estimated number of critically ill patients in theater and in the United States during LSCO. Like other military caregivers, retention of these critical wartime specialists is poor, and attrition is high. Furthermore, current military health system patient volume and acuity do not adequately support maintenance of their specialized critical care skillset. An emphasis on recruitment, retention, training, and sustainment of military critical care providers is required to prepare for future conflicts.

In addition to personnel, critical care capabilities suitable for the austere environment are needed. Equipment used in the resourced hospital setting to provide organ support is typically not portable, rugged, or tested at environmental extremes, and these capabilities require ample disposable medical supplies and reliable power and potable or sterile water to function. Critical care personnel in Role 2 settings may require mechanical and organ support equipment capable of functioning in variable climates, using limited medical supplies, and with prolonged ability to operate on battery power. In addition, the ability to sterilize and use local water sources would expand the ability to perform various types of renal replacement therapy in austere environments and expand capabilities in LSCO. Investments into mechanical and organ support innovation now could improve forward and austere care of the injured and save warfighter lives.[91] We believe that doctrinal ARSC, Role 2, and Role 3 capabilities need to be reevaluated in terms of doctrine, personnel, materiel, team training, and protocols to provide critical care and organ support during LSCO. Mitigating the risks for a future LSCO environment requires the Military Health System to focus on recapturing high acuity and high complexity care instead of the current focus on limiting critical care and moving Military Health System to a digital outpatient environment. Box 2 describes specific recommendations and research priorities that need to be implemented as the US military prepares for future LSCO, and box 3 lists key take aways.

Box 2: Near and Long-Term Critical Care and Organ Support Recommendations to Save Lives on the Future Battlefield

Near Term

- Determine the number of critical care equipment (e.g., mechanical ventilators) needed during LSCO at each capability/role of care
- Development and promulgation of mechanical ventilation protocols
- Rapid development clinical evaluation and regulatory approval of ruggedized forward renal replacement (in such forms as intermittent hemodialysis, sustained low-efficiency dialysis, CRRT/CVVH, or PD) capabilities tailored to each role of care (e.g., Role 2, 3) and platform
- Increase the number of trained personnel capable of providing critical care and organ support
- Identification of training and augmentation paradigms to optimize those already trained to off load tasks and strategies to increase skills and abilities of members without formal critical care training including technology augmentation (e.g., AI) and curriculum and clinical practice guideline development
- Ensure that the current and future active-duty critical care trained workforce maintains this unique clinical skillset.

Long Term

- Develop far-forward VV ECMO capabilities

• Develop critical care augmentation teams capable of rapidly augmenting and providing organ support to in theater ARSC, Role 2, and Role 3 capabilities
• Identification of novel applications of mechanical and organ support capabilities
• Rapid development, clinical evaluation and regulatory approval of AI-enabled forward closed-loop control, and monitoring technologies for critically ill patients requiring ongoing resuscitation, pressor, and respiratory support.

Research Priorities

• Identification of risk factors for early initiation of organ support
• Define the ideal timing of initiation of organ support in austere environments
• Development of advanced organ support technologies in traumatically injured patients

Box 3: Key Takeaways

• Organ failure and needed advanced organ support is common for traumatically injured patients
• Optimizing current mechanical ventilation capabilities and developing far-forward and austere organ support capabilities is needed for anticipated future conflicts
• Renal replacement therapy strategies designed for austere utilization could be an important capability for improved patient survival
• Defining current and needed future numbers of military personnel with advanced critical care training and experience is required
• Defining training requirements and assessment metrics of forward deployed caregivers that may perform prolonged holding of critically ill patients is needed
• Innovation of personnel and therapeutic capabilities will save lives in future, large-scale, contested environments

Limitations

We present the available evidence for the need for organ failure support in trauma with additional focus on incidence in combat casualties. This review has several limitations. The presented literature is heterogenous in nature—civilian versus military and potential care differences between institutions; in the combat populations, sample sizes are typically small, and the risk of bias is not included in this review.

The authors also acknowledge the potential realities of a future contested LSCO environment. First, critically ill and injured casualties may not survive initial Role 1 prolonged casualty care to arrive at an ARSC/Role 2 capability. Second, the equipment and personnel capable of providing austere organ support and critical care (and DCR/DCS) are a limited resource. As such, the provision of organ support capabilities with expert personnel to provide critical care in the contested space must be coupled with appropriate logistical support (resupply, patient movement). Without such coupling, there is a significant risk of the medical team/equipment becoming a liability to the overall mission without intended benefit. That said, the only certainty in war is that it will be unpredictable. Therefore, any future critical care and organ support innovation will help forward deployed caregivers be flexible and rapidly adapt to the uncertainty of war.

CONCLUSION

Organ failure and organ support are commonly encountered in the care of the critically injured trauma patient. In future conflicts, prolonged holding of causalities will be required. Investment in advanced critical care capabilities and supporting them with doctrine, policy, training, personnel, materiel/technology, and leadership support are required to save lives, decrease morbidity, and decrease force attrition on the future battlefield.

AUTHORSHIP

E.K.P. created the concept and wrote the first draft of the manuscript. R.B., R.D.H., J.B., and E.H. participated in the manuscript revision and literature review. participated in the experimental design, data collection, and manuscript revision. M.S.T., V.G.S., and J.B.H. provided the manuscript revision. J.M.G. and M.D.T. provided the concept design and manuscript revision.

DISCLOSURE

Conflict of Interest: Author Disclosure forms have been supplied and are provided as Supplemental Digital Content (http://links.lww.com/TA/E579).

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