RESEARCH ARTICLE

Critical Care Anywhere: Principles for High-Functioning Management in Low-Resource Environments

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Abstract

Critically ill patients can present at any time and location, and they demand high quality care. Historical experiences from military, wilderness, and disaster medicine settings have helped shape the modern concept of caring for the most severely ill with limited available resources. We introduce a method to help design a successful critical care medical support endeavor, which includes properly defining components of Navigation, Environment, Resupply, Energy, Unconventional problems, and Support (NEREUS). Additionally, we provide recommendations for optimal team personnel composition, including utilization of paramedics, critical care providers, nurses, and respiratory therapists across the spectrum of care provided at point of injury, en route to definitive care, and definitive care. A review of critical care principles relevant to the austere setting proceeds with a systematic organization according to airway, breathing, circulation, and neurologic management. Lastly, we employ our proposed method of organizing a critical care medical support endeavor to a post-hurricane scenario. In summary, this review provides the historical background, modern definition, and practical framework for successfully administering critical care in scenarios with limited available resources. We emphasize the need to appropriately adapt critical care concepts to meet the unique demands of a specific scenario.

1. Introduction:

1.1 Introduction

The American College of Chest Physicians (ACCP) defines critical care in a resource-poor or resource-constrained setting as, "the provision of care for life-threatening illness without regard to the location, including pre-hospital, emergency, hospital wards, and intensive care setting."[1] Critically ill patients may present in any context without regard to resource availability, yet all demand high quality care.

1.2 Historical considerations

Military, wilderness, and disaster environments have helped define critical care medicine in the resource-limited setting. A brief review of specific historic events within these fields highlight the benefit of early, aggressive critical care, and the necessity of specialized personnel tasked with clearly defined roles in the modern austere setting.[2] Some of the earliest austere medical practitioners were naval surgeons, as evidenced in Homer's Iliad (c. 1200 B.C.) in which Machaon, the son of Asclepius and a naval surgeon, treated the arrow wound of Melenaus.[2,3] Further advances in critical care include efforts during the mid-19th century Crimean War by Florence Nightingale, who pioneered the concept of designating a core group of providers to care for cohorted severely ill patients.[4]

Care delivery model changes and technological advances over the 20th century further shaped modern critical care. During World War I (WWI), the British-operated Casualty Clearing Stations exemplified how to adapt critical care to the scenario. These transportable units were outfitted with staff and equipment necessary for medical and surgical emergencies, including wound care, antiseptic administration, anesthetic administration, and monitoring. Positioned near battlefields to receive ambulances, these stations stabilized casualties prior to prolonged transport to definitive care.[4,5] The first reported medical casualty evacuation was completed during this conflict.[6] The reduction in mortality from 8% to 3% during World War II was largely attributed to improved understanding of hemorrhagic shock, availability of skilled surgeons at the point of presentation, antimicrobial agents, and greater focus on blood product resuscitation.[7] Continued advances in therapeutic modalities during the latter portion of the Korean War and the Vietnam War further improved outcomes. For example, renal replacement therapy decreased mortality for crush injury victims from 80% to 50%.[8] Additionally, the adoption of helicopter evacuation during the Vietnam War corresponded with aircraft technologies, and this delivery model enabled advanced patient care while en route to definitive care locations.[6]

Although endotracheal intubation was available in the 1800s, the polio epidemic prompted Ibsen to advance tracheostomy and positive-pressure ventilation (PPV) in the 1950s, which improved polio mortality from 87% to 40%, and the process of cohorting these patients into distinct regions of the hospital helped to define the modern respiratory critical care unit.[9] Although the initial concept of acute respiratory distress syndrome (ARDS) was described as early as WWI, Ashbaugh and colleagues' description of ARDS in 1967 during the Vietnam War advanced understanding and management of the importance of invasive PPV and positive end-expiratory pressure (PEEP).[10] These principles laid the foundation of ventilatory support in the critical care setting.

The military made considerable strides in extending high-quality critical care from the field to the point of definitive care. Developed in the 1990s, Tactical Combat Casualty Care (TCCC) provides evidence-based guidance for prehospital military conflict care, emphasizing training, appropriate tourniquet application, pneumothorax management, damage control resuscitation, along with many other important principles. After adopting these guidelines, mortality related to extremity hemorrhage dropped by 67%.[11] Additionally, the Critical Care Aeromedical Transport Team (CCATT) focused on discrete delegation of duties during medical transport and it consisted of three-person teams that include a physician, critical care nurse, and respiratory therapist.[12] The military established an advanced network to improve patient evacuation that included casualty evacuation, medical evacuation, aeromedical evacuation, and medical attendants.[12] Utilizing a flight paramedic in lieu of an EMT-B for medical evacuation yielded further improvements during the conflicts in Iraq and Afghanistan in the 2000s. Historically low mortality rates were associated with wounds, an improvement attributed to adopting the above developments, damage control resuscitation, and rapid patient evacuation to definitive care.[13] These examples highlight the importance of an organized system that includes deploying nonphysician personnel in resource-limited settings with advanced practitioners to achieve optimal outcomes.

Understanding anticipated longer-term capabilities (e.g., rehabilitation services, ventilator support, chronic therapies) is crucial before initiating critical care services.[14] In 2010, a 7.0 magnitude earthquake struck Haiti, resulting in devastating infrastructural destruction and over 200,000 dead. The University of Miami Global Institute/Project Medishare field hospital cared for patients in the immediate aftermath for injuries directly related to the earthquake, but patient care resulting from these injuries remained for several months afterward.[15] Sometimes, however, environments with limited critical care capabilities at baseline require delivering the best care possible and optimizing thereafter.[16]

1.3 Objectives

Extensive and iterative developments in technology and organizational factors continue to evolve to optimize critical care in any setting. This review presents an organizational framework to implement such support in resource-limited settings.

Notably, we define critical care as the medical support provided to the most severely ill or injured individuals suffering from one or more acute pathophysiologic processes that pose(s) immediate risk to life or organ. Clearly defining critical care as *what type* of care rendered and not specifically *where* such care is administered (e.g., intensive care unit) provides a more accurate and complete understanding of the discipline and its necessary diagnostic and management priorities. We strive to elevate the quality of critical care to that which maximizes the resources available within a given scenario. Additionally, this review will focus on organization and management principals for brief, limited-scale, critical care medical support endeavors. We would direct readers interested in critical care administration focusing on large-scale, population-based, and comprehensive efforts of delivering critical care in resource-limited settings, to previous publications.[17]

2. Organization and planning:

The myriad possible scenarios and problems encountered in resource-limited settings demand thorough preparation prior to embarking on a critical care medical support endeavor. For example, the planning implications required to execute critical care support to a cadre of elite athlete mountaineers stranded in a high-altitude environment vastly differs from the initial medical response for a medically underserved and densely populated city following a devastating tropical storm. Only by defining the essential components of an upcoming endeavor can success be measured and achieved. Crafted from years of experience in the field, our group utilizes the standardized pre-deployment preparation acronym “**NEREUS**,” the name of the early Greek god of the sea, to ensure that all essential unique aspects of a critical care support endeavor are addressed. Using the following principles, a medical support endeavor can be customized for success in any setting.

1) *Navigation*: understand the geography, topography, modes of transportation, duration of intervention

2) *Environment*: climate, weather, urban versus rural, culture, language, population (number of casualties, comorbidities), health and industrial infrastructure, team safety
3) *Resupply*: equipment, personnel, consumables
4) *Energy*: energy needs (both en route and during intervention, equipment compatibility), power sources (e.g., solar, fossil fuel-powered generator, backup options), duration of needs, limitations
5) *Unconventional problems*: areas warranting special attention (e.g., conflict, political climate, infectious diseases, pandemic, nuclear exposure, collapsed infrastructure); this factor serves as an opportunity for team members to brainstorm and role-play scenarios
6) *Support*: required resources beyond immediate team members (e.g., logistics support, communication experts, maritime or air assets, security)

3. Personnel and team organization:

Multidisciplinary critical care improves patient outcomes.[18] Clearly defined yet synergistic roles and responsibilities of all team members are inherent to its success. According to a 2014 consensus statement from the ACCP, only those providers with experience in critical care, and ideally with disaster relief, should care for patients in a resource-limited setting such as a disaster. Additionally, the ACCP recommended training providers beyond general critical care to ensure competency in managing specific disease processes and within cultural contexts found in a given scenario.[14] Successfully administering critical care, especially in resource-limited settings, warrants team-based training and leaner-than-usual but well-defined roles for the team. The overall schema for team organization and responsibilities in this setting can be conceptualized into (1) care provided at immediate point of injury, (2) care provided en route to definitive care, and (3) definitive care. Within this system, gradations in levels of care exist and the ability for medical evacuation at any point exist within this continuum.[19]

The personnel responsible for care at the immediate point of injury should include one to two paramedics, a proposal informed by US military and civilian prehospital medical services (EMS). These team members should be able to provide advanced life support (ALS), endotracheal intubation, percutaneous cricothyrotomy, pleural space decompression, gastric decompression, intraosseous/intravenous access, medication infusions and blood administration, defibrillation, transcutaneous pacing, medical evacuation, and online consultative care to guide advanced therapies.[19,20] The requisite medical equipment and combat medic portable supply for an ALS ambulance unit has been described.[21,22] A medical command center should provide forward-care medical teams remote guidance regarding optimal medical care and triage. Prehospital EMS protocols provide the foundation for such care.

Personnel responsible for care provided en route to definitive care should include a critical care physician, critical care nurse, and respiratory therapist, mirroring the composition of the US Air Force (USAF) CCATT.[12,23] These team members should be able to manage ventilators, physiological monitors, multi-channel infusion pumps, point-of-care (POC) laboratory devices and other devices, such as a bronchoscope, ultrasound, medical supplies, medical formulary, IV fluids, and wound dressings.[24]

Although transporting a patient to definitive care may offer the best outcomes in resource-limited settings, a balance exists between providing prolonged field care at the point of contact and managing a patient while en route.[25] While the definition of “definitive care” may vary, it is generally considered to be a medical intervention that corrects a patient’s underlying medical problem, regardless of that patient’s physical location. For example, the definitive therapy for an intraabdominal hemorrhage usually is surgery (often accomplished in the hospital setting), definitive therapy for an ST-elevation myocardial infarction (STEMI) or ischemic stroke would be reperfusion (which ideally, though not necessarily, would occur in the hospital setting), or definitive care for a simple spontaneous pneumothorax would be a tube thoracostomy (which could potentially occur on the scene with later clinic follow up). Each instance of providing definitive care must adapt to the ever-changing supply and demand of resources within an environment.

4. Principles of critical care in the austere setting

The following section aims to provide principles for critical care management relevant to the resource-limited setting. For a more exhaustive discussion of general critical care principles, we refer the reader to a number of currently available texts.[26–28]

4.1 Airway management:

4.1.1 Basic considerations

Several modern critical care treatment strategies, including Adult Traumatic Life Support (ATLS) and Advanced Cardiac Life Support (ACLS), prioritize airway management during resuscitative efforts. However, hemodynamic management, including hemorrhage control and vascular access either simultaneously or even before airway efforts, may be warranted.[29,30] Most indications for advanced airway management include hypoventilation, hypoxia, airway protection, and shock. Unique to the austere setting is the need to secure requisite equipment available prior to performing a procedure, as well as the need for resources for ongoing management of that illness or injury.

4.1.2 Airway techniques

Airway repositioning (e.g., jaw thrust), adjunctive airway placement (i.e., oro- or nasopharyngeal airway), supraglottic airway placement, surgical cricothyrotomy, and endotracheal tube (ETT) placement comprise the major airway interventions. Effective airway training program provide longitudinal expert-led didactics and hands-on training.[31] Additionally, procedural checklists enhance efficiency, completeness, and patient safety. As an example, the prehospital rapid sequence intubation checklist using the “SPEEDBOMB” mnemonic includes suction, positioning, equipment, end-tidal carbon dioxide ($ETCO_2$), drugs, back-up, oxygen (O_2), monitoring, and briefing.[32]

Providers can intubate via video or standard laryngoscopy. Both novice and experienced users have adeptly used several video laryngoscope models in the austere setting.[33] Some preliminary studies have introduced advanced technologies (e.g., Google Glass, GoPro) to help guide the novice proceduralist in endotracheal intubation.[34] Nonetheless, the anatomically challenging airway may manifest as a “Can’t intubate, can’t oxygenate” scenario, described as the inability to secure an ETT and failure to maintain oxygenation via a bag-valve mask (BVM) or supraglottic device. Providers should use the scalpel-bougie cricothyroidotomy approach in this scenario, given its streamlined equipment and procedure sequence (i.e., number 10 scalpel, finger, bougie, size 6.0 mm ETT).[35,36] While cricothyrotomy is possible with many commonplace items,[37] advanced airway planning ensures that the optimal equipment is readily available. After securing the airway, proper tube placement should be confirmed using auscultation, $ETCO_2$ monitoring, ultrasonography, or x-ray if available.[38]

4.1.3 Airway equipment

Analgo-sedation, airway securing ties, bougie, BVM, cardiac monitor, $ETCO_2$ monitor, naso-/orogastric tube, neuromuscular blocking agents, ETT, laryngoscope, O_2 supply, PEEP valve, pulse oximetry, scalpel, suction device, supraglottic device, ultrasound, ventilator

4.2 Breathing management:

4.2.1 Basic considerations

Practical measures to assess the adequacy of a patient’s oxygenation and ventilation include mental status, spontaneous work of breathing, auscultatory findings, quantitative $ETCO_2$ monitoring, and POC blood gas analysis.

4.2.2 Ventilation

Noninvasive airway maneuvers (e.g., jaw thrust, adjunctive airway placement), inhaled bronchodilators for bronchospasm, BVM ventilation, and invasive mechanical ventilation can all improve patient ventilation. BVM ventilation with or without an advanced airway, and, if available, mechanical ventilation can treat respiratory failure requiring PPV. Without mechanical ventilators, manual BVM ventilation can provide stable tidal volumes for up to six hours in a simulated environment.[39] Modern emergency/transport ventilators (ETVs) can deliver reliable tidal volumes and PEEP and allow manipulation of inspiratory flow and ventilation modes. With ≥4 hours of battery life, ETVs meet the demands of the most severe respiratory failure patient.[40,41] Selecting the most appropriate ETV depends on several features, including battery lifespan, mechanism of technology (i.e., pneumatic, turbine, or compressor), ability to deliver noninvasive modes of ventilation, rate of O_2 consumption, weight, and cost.

4.2.3 Oxygenation

Team members can practically assess oxygenation by cyanosis, work of breathing, heart rate, auscultatory findings, pulse oximetry, and POC blood gas analysis. Generally, the goal of supplemental O_2 should be normoxia, correlating to pulse oximetry of 92-96% or 88-92% in those with chronic respiratory failure. Measures to improve oxygenation include supplemental O_2, application of PEEP, and invasive mechanical ventilation. The team supplying critical care in the remote setting must secure an O_2 supply in cylinder, liquid, or concentrator form.[42] While cylinder or portable O_2 concentrators can supply low flow rates (<3 liters per minute),[43] non-portable O_2 concentrators or cylinder O_2 can supply high flow, like that used by ETVs. Ambulances typically carry 1-2 M-tanks (3,000 liters per tank) for en route care and 2-3 D-tanks (350 liters per tank) for off-ambulance care.[44] Calculating O_2 needs must account for patient illness, duration of O_2 requirement, and, if applicable, bias flow (i.e., background O_2 consumption by the ventilator).[45,46]

4.2.4 Diagnostics

Handheld POC ultrasound (POCUS) is readily available in lightweight, portable, and durable devices with prolonged battery lifespan. Absent chest x-ray and CT imaging, POCUS can clarify the diagnosis in otherwise undifferentiated respiratory failure.[47] Several ultrasound protocols (e.g., RADiUS),[48] including one successfully used by medical students, can identify key pathologic processes, such as pleural effusion, pulmonary edema, pneumothorax, pneumonia, pulmonary fibrosis pattern, chronic obstructive pulmonary disease, pericardial effusion, systolic heart failure, and pulmonary embolism. Expeditious identification of these disease processes enhances management and triage.

4.2.5 Pleural space decompression

Providers should especially consider early pleural space decompression for pneumothorax and pleural effusion (e.g., hemothorax) in the hypoxemic patient, given the potential for marked improvement with intervention. While clinical signs and symptoms may raise suspicion of pleural pathology, POCUS is feasible, practical, and more sensitive and specific than chest radiography for pneumothorax.[49] If a tension pneumothorax is suspected or confirmed, current guidelines advise needle decompression with a 10-16-gauge, 3.25-inch catheter-over-the-needle placement in the 5th intercostal space in the anterior to mid-axillary line. The subsequent finger or chest tube thoracostomy permits more definitive pleural drainage and the ability to monitor tube output.[50] Prioritizing this procedure prior to air transport will help avoid altitude-induced air expansion and subsequent hemodynamic decompensation.

4.2.6 Acute Respiratory Distress Syndrome

After identifying ARDS, standard evidence-based supportive care should be delivered. These standards include lung-protective ventilation with tidal volumes 6-8 mL/kg ideal body weight, applied PEEP ≥ 5 cmH_2O, monitored plateau pressure <30 cmH_2O, restrictive fluid goals, and neuromuscular blockade and prone positioning for select cases. Non-physician transport team members can effectively conduct prone positioning with advanced planning.[51] Additionally, a dedicated transport team of respiratory failure providers (e.g., Acute Lung Rescue team [ALeRT]) can provide even further advanced mechanical ventilation and extracorporeal membrane oxygenation (ECMO) support to severe ARDS patients.[52,53] Adoption of these techniques can bring high quality critical care to the point of contact with patient suffering from ARDS.

4.2.7 Post-intubation sedation, analgesia, and neuromuscular blockade

The patient with ventilator dependence requires adequate analgesia, sedation, and potentially neuromuscular blockade. Current critical care guidelines recommend optimized analgesia, followed by sedation with non-benzodiazepine agents targeted to a goal level of sedation (e.g., Richmond Agitation and Sedation Scale [RASS]).[54] Post-intubation care in the austere setting may require deeper levels of sedation for patient and provider safety during transport, which can be achieved with either intermittent or continuous analgo-sedative agents, such as ketamine 0.5-1 mg/kg q10-20 minutes, fentanyl 1 mcg/kg q30-60 minutes, propofol 10-50 mcg/kg/min. When needed, neuromuscular blockade options include vecuronium 0.1 mg/g q30-60 minutes and rocuronium 1 mg/kg q30-45 minutes.[55,56] In some scenarios, such as transporting a patient in the prone positioning and/or receiving neuromuscular blockade, bispectral (BIS) monitoring may provide the most practical means of assessing depth of sedation.[57] Once the scenario and resources allow, however, sedation goals should shift towards one of limiting continuous analgesia-sedation infusions, avoiding benzodiazepines, and frequently reassessing the neurologic status by objective means (e.g., RASS goal) to achieve the target sedation level.

4.2.8 Breathing equipment

Analgo-sedation, BIS monitor, chest tube thoracostomy tray, $ETCO_2$ monitor, needle decompression, neuromuscular blockade, O_2 delivery systems (e.g., BVM, face-mask, nasal cannula, non-rebreather), O_2 supply, PEEP valve, percutaneous ECMO, suction device, ultrasound, ventilator

4.3 Circulation management:

4.3.1 Basic considerations

A conceptual framework to guide shock management includes three major principles: (i) source control, (ii) resuscitation, and (iii) supportive care. Providers should begin by assessing the degree of end-organ perfusion (e.g., mentation, capillary refill, skin mottling, urine output), vital signs (e.g., heart rate, mean arterial pressure), and echocardiography. Prompt vascular access and basic wound care comprise the initial emergent tasks for the patient with inadequate circulation.

4.3.2 Vascular Access

While vascular access includes a diversity of methods, the provider should utilize the intraosseous (IO) approach for truly emergent access. The IO technique provides multiple possible access sites, non-collapsible tissue target, speed in obtaining access, and overall higher success rates compared with other methods.[58] With adequate resuscitation and time, providers can thereafter obtain more definitive access with large bore (≥ 18 gauge) intravenous (IV) with potential flow rate of around 200 mL per minute. Additionally, peripheral IV catheters can upsize to large-bore (8.5-Fr diameter) catheters (e.g., Rapid Infusion Catheter) via Seldinger technique with an estimated flow rate of around 600 mL per minute.[59] POCUS can improve venous visualization and access in select cases. In most cases, large-bore peripheral access can deliver most medications safely, including vasopressors.[60] However, prolonged field and transport care may necessitate central venous catheter (CVC) placement, and prehospital physicians can successfully perform this skill.[61]

4.3.3 Diagnostics

Categories of shock include hypovolemic, obstructive, cardiogenic, and distributive shock. Various POCUS protocols (e.g., Rapid Ultrasound for Shock and Hypotension [RUSH], Extended Focused Assessment with Sonography for Trauma [E-FAST]) have aimed to categorize these states.[62] With its ability to identify hemorrhage (sensitivity 83.3%, specificity 99.7%), the FAST exam can risk-stratify patients in need of more rapid evacuation.[49]

4.3.4 Hypovolemic and Hemorrhagic Shock

For hemorrhage control, the foundations of care include direct pressure, pressure dressings, hemostatic agents, tourniquet application, and pelvic binders. While an individual can easily provide direct manual pressure, the process occupies personnel quickly. Applied pressure dressings can be limited by continued surreptitious bleeding. Providers should use the extremity tourniquet as the first method of hemorrhage control in major extremity trauma. Because significant medical complications can occur with prolonged placement (i.e., >2 hours), teams must prioritize training for proper tourniquet placement and duration of use. Currently available tourniquets include: Combat Application Tourniquet (C-A-T), Special Operations Forces Tactical Tourniquet, and Emergency and Military Tourniquet. Junctional tourniquets include: SAM junctional tourniquet, Combat-Ready Clamp, Junctional Emergency Treatment Tool.[63] Additionally, pelvic binders applied to pelvic fractures associated with shock can help stabilize those fractures. Commercially available Pelvic Binder, SAM Pelvic Sling, T-POD, and even easily obtained sheets or clothes arranged circumferentially can effectively bind the pelvis.[63,64]

Adjunctive agents for hemorrhage control include hemostatic wound dressings, which promote local clotting and/or wound sealing. The composition of these agents can include granules, mucoadhesives, and procoagulants.[65] Based on efficacy and safety reports, TCCC guidelines recommend Combat Gauze dressing for this role. Another agent, tranexamic acid, administered intravenously may correct traumatic coagulopathy related to fibrinolysis. In resource-limited settings, the CRASH-2 trial supports the use of tranexamic acid (1 g in 100 mL normal saline over 10 minutes within 8 hours of injury, then 1 g infused over 8 hours) for patients with significant trauma-related hemorrhage.[65,66]

In light of these options, blood product administration remains the optimal treatment for continued bleeding in hemorrhagic shock and unsuccessful attempts to limit blood loss. While awaiting medical transport to a location where definitive source control can be achieved, damage control resuscitation (DCR) should be instituted to limit crystalloid resuscitation, prevent hypothermia, prevent acidosis, and allow the systolic blood pressure (SBP) goal to be 80-90 mmHg.[67,68] Evidence suggests blood product administration in a 1:1:1 red blood cell:plasma:platelets fashion approximates whole blood composition and improves outcomes.[69,70] However, practically adhering to DCR principles in the austere setting remains challenging. In the extreme forward-care setting, hypotensive resuscitation may offer one of the few available methods to attenuate further blood loss while temporarily maintaining sufficient tissue perfusion. When blood administration is immediately needed, warm fresh whole blood (WFWB) administration may offer a solution to an otherwise fatal scenario. An emergency protocol designed for Norwegian Naval Special Operation Command for WFWB describes practical considerations, including blood type compatibility, infectious diseases screening, and necessary equipment. Planned endeavors may permit a work up to include blood typing, infectious diseases screening, and obtaining relevant history about blood thinning medications.[67,68] Storing and administering blood products while en route care may be more logistically feasible.

Excessive renal or gastrointestinal losses or inadequate hydration, particularly from heat exposure, can lead to non-hemorrhagic hypovolemic shock. Oral rehydration strategies may improve mild dehydration when IV fluids are not easily accessible. One regimen consists of an electrolyte solution, water, or diluted juice self-administered in 30 mL aliquots every 3-5 minutes for 500-1000 mL total.[71] Intravenous hydration, which should be reserved for moderate-to-severe cases and for those unable to tolerate oral intake, should be administered at 500 mL aliquots according to serial reassessments. When administered in large volumes, IV fluid composition should consist of balanced solutions (e.g., Plasma-lyte, lactated Ringer's).[72]

4.3.5 Obstructive Shock

Obstructive shock diagnoses include pneumothorax, pulmonary embolism (PE), and cardiac tamponade. Diagnosing PE in the austere setting relies primarily on clinical decision tools (e.g., Wells Score) and POCUS to exclude the diagnosis. POCUS can identify indirect and direct evidence of venous thromboembolic disease.[73] After diagnosis, proper risk stratification of patients with PE can designate them with high-risk versus moderate-low risk features to determine management plans. Medical evacuation may be prudent, but treatment at the POC, or en route can proceed with low molecular weight heparin (1 mg/kg, q12 hours, SQ). High risk PE may require thrombolytic therapy, and its prehospital administration is feasible.[74] POCUS findings including right ventricular dysfunction may assist identifying a patient with a hemodynamically significant PE. Additionally, POC ultrasonographers can diagnose cardiac tamponade.[75] For traumatic and atraumatic causes of developing cardiac tamponade, initial resuscitative measures in a resource-limited setting can include ultrasound-guided pericardiocentesis utilizing Seldinger technique with CVC from the subxiphoid approach.[76]

4.3.6 Anaphylactic Shock

The austere setting may expose an individual to several foods, medications, flora, and fauna, all with potential for distributive shock with anaphylaxis. Once anaphylaxis is diagnosed, providers should immediately remove the offending agent and administer epinephrine. Epinephrine (1:1,000, 1 mg/mL) (0.5 mg) should be administered intramuscularly (IM) in the antero-lateral thigh, followed by repeat dosing every 5-15 minutes. Subsequent epinephrine infusion (1:1,000,000; 1 mg in 1000 mL normal saline, 0.5 mg in 500 mL, or 0.25 mg in 250 mL) should be initiated if refractory to IM dosing at 1-2 mL/min with titration upwards to clinical effect.[77] Along with epinephrine, providers should concomitantly resuscitate with IV fluids. Though less effective, antihistamines, systemic steroids, and glucagon (for those taking beta-blockers) may attenuate symptoms from anaphylaxis.[78]

4.3.7 Septic Shock

Sepsis is defined as a "dysregulated host response to an infection leading to end organ damage," and may be operationalized to include the quick Sequential Organ Function Assessment score.[79,80] Two fundamental principles underpin appropriate and timely sepsis management: (1) source control (i.e., appropriate antimicrobial therapy and/or an intervention for pathogen removal [e.g., surgery]); and (2) adequate resuscitation to support end-organ function (e.g., IV fluids and/or vasoactive medications to maintain organ perfusion pressure). Although a rare occurrence in expedition-based settings, providers should treat sepsis at the point of contact in all settings by securing adequate IV access, administering targeted antibiotics, and IV fluids.

Rapid (<1 hour) antibiotic administration, thoughtfully targeting likely infecting pathogens, relies on researching local organisms and resistance patterns.[79] IV fluid resuscitation initially should treat hypovolemia, and, in many cases, requires 20-30 mL/kg of crystalloid with frequent reassessment (e.g., POC lactate, echocardiographic assessments, skin mottling, capillary refill) to evaluate ongoing benefit. In refractory shock (e.g., mean arterial pressure ≤65 mmHg or other signs of malperfusion), vasopressor agents may be needed, with norepinephrine considered first-line therapy at present.[79] Vasopressor titration en route to definitive care should utilize an intravenous pump, although "push-dose" vasopressor administration at the point of medical contact may allow for temporary blood pressure stabilization in the interim.[81]

4.3.8 Cardiogenic Shock

Cardiogenic shock results from cardiac pump failure, valvular dysfunction, or dysrhythmias. Emergency care should aim to treat any rapidly reversible causes. Immediate vasoactive support with norepinephrine is the first-line agent of support for these patients to ensure adequate coronary perfusion pressure.[82] Recognizing acute coronary syndrome (ACS) requires appropriate clinical history and diagnostics such as electrocardiography. While an electrocardiogram tracing can be obtained from advanced portable monitors (e.g., Lifepak 15, Zoll X Series), newer devices may allow for smartphone-based diagnostics (e.g., AliveCor).[83] Standard prehospital management of ACS includes telemetry monitoring, when available, chewable aspirin administration, normoxia, and medical evacuation to a facility capable of coronary reperfusion, such as percutaneous coronary intervention (PCI).[84,85] According to AHA/ACC guidelines for STEMI management, "in the absence of contraindications, fibrinolytic therapy should be administered to patients with STEMI at non-PCI-capable hospitals when the anticipated first medical contact-to-device time at a PCI-capable hospital exceeds 120 minutes because of unavoidable delays" (Class I, Level of evidence B). Several studies have established safety and feasibility in prehospital fibrinolytic therapy.[84,85]

4.3.9 Advanced Cardiac Life Support

Critical care in the austere setting should meet the needs of patients with conditions covered by ACLS (e.g., cardiac arrest, bradycardia, tachycardia), especially high-quality cardiopulmonary resuscitation (CPR) and early defibrillation.[86] Additional important principles consist of pharmacologic agents, medical evacuation for ongoing critical care needs, reperfusion, and post-arrest care. Furthermore, providers should concentrate on reversible causes of cardiac arrest, including MI, PE, ventricular fibrillation, cardiac tamponade, pneumothorax, electrolyte disturbances, and hypothermia. In resource-limited settings, mechanical CPR devices (e.g., LUCAS, Life-Stat, Thumper, Zoll AutoPulse) can assist during patient transport, and unique scenarios that may favor prolonged resuscitation attempts, such as hypothermia, and post-lytic PE.[87]

4.3.10 Circulation equipment

ACLS medications (epinephrine, calcium chloride, magnesium chloride, norepinephrine, amiodarone, lidocaine, sodium bicarbonate), blood collection bag with citrate-phosphate-dextrose (CPD)/CPD-adenine (CPDA-1), blood infusion set with filter, blood products, blood typing kit (e.g., EldonCard) cards, cardiac monitor, cardioverter/defibrillator, electrocardiogram, gauze rolls, hemostatic gauze rolls, intravenous/intraosseous access, IV fluids, marker pen, pressure dressing, sterilization swabs, tape, tranexamic acid, ultrasound, vasoactive agents, venous tourniquet

4.4 Neurological management:

4.4.1 Basic considerations

Neurological assessment should include a focused neurologic examination, with consideration for Glasgow coma scale, National Institutes of Health Stroke Scale, rapid blood glucose check, monitoring including pulse oximetry, electrocardiogram, and POCUS optic nerve sheath diameter. For individuals with a neurologic deficit, providers should initially assess standard vital sign monitoring, blood glucose concentration, and attend to airway, breathing, and circulation. Because many head injuries have concomitant spinal cord trauma, providers should also consider spinal column immobilization in these cases.

4.4.2 Head injury

Generally, teams should evacuate all patients with head injury for assessment in a definitive care setting capable of neuro-imaging, with particular attention paid to moderate to severe traumatic brain injury (TBI) (i.e., GCS ≤12, and loss of consciousness ≥30 minutes to >24 hours).[88] Patients with mild TBI should receive ongoing serial monitoring to help identify those requiring more expedient medical evacuation. Physical examination in the austere setting (e.g., pupillary changes, level of consciousness) may identify signs of increased intracranial pressure, and POCUS optic nerve sheath diameter may recognize this process as well.[89] Regardless of the setting, basic and essential management includes the avoidance of secondary injury, including hypoxemia, hypotension, hypothermia, and hypo-/hyper-ventilation, all of which can worsen expected outcomes such as mortality. With special attention for those with evidence of herniation (i.e., asymmetric pupils, non-reactive pupils, extensor posturing, no motor response), providers should elevate the head-of-bed to 30 degrees in neutral alignment, employ temporary hyperventilation (i.e., goal $PaCO_2$ 30-35 mmHg), and administer hypertonic saline (e.g., 3% saline 250 mL).[90] Pneumocephalus can develop or progress mid-flight transport, and may require descent if permissible. Broad-spectrum antibiotics, including ertapenem which does not require refrigeration, should cover penetrating injuries. The management of seizures, an expected complication after TBI, should proceed as below.[90]

4.4.3 Acute stroke

Suspicion of acute stroke, after eliminating other possible causes (e.g., hypoglycemia), mandates referral to medical evacuation capable of workup and neuro-imaging to further classify stroke (e.g., ischemia, hemorrhage, mass effect) and guide interventions. Although described, CT in the mobile stroke unit prehospital setting (e.g., CereTom CT) may prove an exceedingly limited resource and not often practical.[91] While certain clinical features may favor the diagnosis of a hemorrhagic from an ischemic stroke, neuroimaging remains the confirmatory diagnostic modality.[92] Without the ability to medically evacuate a patient with a devastating stroke syndrome, providers face a particularly trying scenario.

General acute stroke care at presentation and en route should focus on optimizing supportive care with focus on normoxia, hemodynamics, head/body positioning (e.g., head of bed at 30 degrees, neutral alignment), and metabolic components (e.g., blood glucose 140-180 mg/dL). Without CT imaging and the ability to characterize the stroke (i.e., ischemic or hemorrhagic), establishing the optimal blood pressure goal is challenging. It is generally advisable in these cases to avoid excessive hypotension (goal SBP >90 mmHg) or hypertension (permissible up to SBP 220 mmHg, diastolic blood pressure 120 mmHg for ischemic stroke) within the 24-hour period.[93]

4.4.4 Spinal injury

Spinal cord injury has potential for devastating injury, and requires ongoing need for spinal motion restriction (SMR) to prevent further injury. Trained personnel using the NEXUS criteria (i.e., no midline cervical tenderness, no focal neurologic deficit, normal alertness, no intoxication, no painful distracting injury–any single one warrants immobilization) and Canadian C-spine rule criteria should decide when to restrict spinal motion. These tools allow for C-spine clearance without the need for CT imaging. The Wilderness Medical Society Guidelines favor the vacuum splint (e.g., Fasplint Fullbody) over the rigid backboards and cervical collar for optimized spinal cord protection.[94] When facing suspected or confirmed spinal cord injury, the team should plan medical evacuation to definitive care for imaging and potential early neurosurgery intervention. No high-quality evidence to administer systemic steroids for traumatic spinal cord injuries currently exists.[95]

4.4.5 Seizure

Seizure activity in the austere setting should prompt consideration of typical causes (e.g., TBI, metabolic derangements, drug toxicity or withdrawal, underlying epilepsy) as well as those unique to the austere setting (e.g., exercise-associated hyponatremia (EAH), high-altitude cerebral edema). Initial maneuvers should include stabilization of the head and neck to avoid secondary traumatic injury and placement in the lateral decubitus position to avoid airway compromise for short-term seizure activity.

Benzodiazepines should act as the first-line agents for seizure treatment, including IM midazolam (initial dose 0.2 mg/kg, maximum 10 mg, once) in those without IV access, and IV lorazepam (initial dose 0.1 mg/kg/dose, maximum 4 mg, repeat once) in those with IV access. Continued seizure activity should prompt administration of other agents, including valproic acid, levetiracetam, fosphenytoin, or practically speaking, propofol infusion. The provider should consider other agents, including hypertonic saline (100 mL, 3% saline) for EAH, and dextrose (50 mL D50W IV) for hypoglycemia. Continued close airway monitoring should continue including relevant intervention to maintain patency.[96–98]

4.4.6 Neurologic equipment

Antiepileptics, antihypertensives (e.g., nicardipine, labetalol), bleeding reversal agents (e.g., vitamin K), dextrose, flashlight, hypertonic saline (no mannitol due to potential to freeze and its fragile glass bottle), ophthalmoscope, otoscope, thrombolytics, ultrasound

5. Case example:

The following example illustrates the proposed systematic organization of a critical care medical support endeavor:

A Category 4 hurricane struck a ~10,000 square mile Caribbean island with a total population of 11 million people scattered throughout multiple city centers and villages. Your team is tasked with disaster response in the immediate aftermath, specifically to reach more remote areas of the island to address critical medical problems, provide site survey information, and transport appropriate patients to an established field hospital.

Further analysis with the "NEREUS" assessment provides the organizational framework to organize a successful medical support endeavor with the targeted task. The "Navigation" component includes transportation to this Caribbean-based island in the immediate aftermath (i.e., within 48 hours) of a hurricane, with an expected duration of 3-5 days to complete the tasks. With this understanding, the team plans a support team size of eight individuals and necessary equipment. With two operational landing strips available, the team arranges air transport to and from the island's capital near the field hospital established by a disaster-relief organization. Expected interruptions in road transportation and infrastructure mandate the use of off-road capable trucks and transport helicopters for reaching disaster victims, administering critical care, and transporting appropriate casualties to field hospital care.

In the post-hurricane setting, the "Environment" includes a sea-level based region with expected average temperatures around 80-90ºF across a mix of urban and remote rural locations. The country of focus includes a government with growing instability, and in the aftermath setting, the team anticipates the potential need for increased security for providers and casualties. Before the disaster, the country faced several public health challenges, including safe transportation, water, sanitation, and major deaths related to HIV/AIDS and cardiovascular disease. In addition, preparation is needed for early disaster-specific traumatic injuries, personnel plan for heat-exposure illnesses, and safety support provided by security specialists.

The "Resupply" in this scenario is limited as noted above and the proposed personnel should include advanced provider roles (e.g., physician, physician assistant, nurse practitioner, registered nurse, paramedic) to supply at least two medical support roles for each available vehicle or aircraft. The above proposed essential equipment, utilized in standard ambulance or medic supplies, should additionally include equipment necessary for the most commonly anticipated injuries, notably, blunt traumatic injuries, puncture wounds, soft tissue injuries, and drowning. Specific equipment should include surgical airway equipment to relieve traumatic airway obstruction, BVM ventilation, pleural space decompression materials, tourniquet, hemostatic dressing, tranexamic acid, IV access kits, crystalloid fluids, antibiotic, splinting material, and analgesics. It should be noted that treatment rendered in the first 48-72 hours should focus on emergent/urgent problems, whereas post 72 hours will most likely focus on sequela of chronic/untreated problems (e.g., wound infections, untreated diabetes, hypertension). Recognizing this shift in treatment is critical to ensure medical supplies and equipment are appropriately allocated at the right time.

The "Energy" or power sources for the island, which were historically unreliable, have been further compromised after the disaster. In this setting, the field hospital procured generators capable of supporting medical equipment, including lighting, monitoring devices, and limited capacity for mechanical ventilation. Although providers plan to power medical devices via battery while en route and in the field, further rechargeable power from charging platforms (e.g., car batteries, portable solar panels) can supplement. Ensuring access to a single power source that has the capability to charge from the multiple sources we previously mentioned will greatly reduce additional gear requirements, thus increasing the mobility of the team and decreasing costs along with the resupply burden.

Within this scenario, several "Unconventional problem(s)" arise. In the immediate post-disaster setting, barriers to road transport require tools (e.g., chainsaw, hydraulic rescue tools) to clear debris, as well as air transport to provide extraction. The extreme temperatures require potable drinking water, fans for ventilation, tarpaulins for shade, and management of hyperthermia as a secondary insult to the initial traumatic injuries. The pre-disaster critical care limitations in the country require close monitoring of available resources (e.g., mechanical ventilators) in order to anticipate and adapt to these limitations (e.g., prolonged BVM ventilation by nonmedical providers).

Lastly, knowing how the immediate team will relate to the remaining "Support" provided is important. In this circumstance, personnel should have dedicated communication channels with medical command at the field hospital to inform and support as needed. This communication should include timely updates on available personnel resources, including capabilities for surgical interventions, mechanical ventilation, and ability for medical evacuations. As previously noted, planning should include a security perimeter. The team should outline the optimal transportation modes, frequencies, and durations of each expedition with driver(s) and/or pilot(s) in advance, based on the needs of casualties and available resources. Overall, this example illustrates the necessary steps to define a critical care support endeavor using the NEREUS system to achieve success.

6. Conclusion:

Historical events across a variety of austere settings have advanced the field of critical care and have simultaneously shaped critical care administration in resource-limited settings. While the standard of care within modern intensive care units continues to advance, severely ill and injured patients may present at any time and place, and they require high quality care. We propose a system to organize a medical support endeavor that focuses on the navigation, environment, resupply, energy, unconventional problems, and support (NEREUS) for a given scenario that can subsequently inform essential components in planning. The outlined current state of the art in critical care can be applied and customized to provide high quality care appropriate for any given scenario.

7. Author Declarations:

Authors Ward and McCurdy both work at Nereus Medical Solutions, LLC (https://nereusmedicalsolutions.com), dedicated to delivering emergency and critical care in resource-limited settings.

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