The *JSOM* Critical Care Supplement

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The past 20 years witnessed significant and critical improvements in trauma medicine, especially in the prehospital setting. The formation and development of the Committee on Tactical Combat Casualty Care provided a standardized, evidence-based guideline and training system for nonmedical personnel and clinicians of all levels. Rapid innovation with simple medical devices significantly decreased battlefield death, such as the use of limb tourniquets, which decreased limb hemorrhage mortality by 67%.[1] More advanced developments like the refinement of prehospital blood transfusions demonstrated significant survival benefit when started within minutes of wounding.[2] Despite many hospital-based improvements, effective prehospital medicine still offers the greatest opportunity for military clinicians to improve on rates of morbidity and mortality.

Delivery of critical care medicine in the prehospital setting is readily available in civilian emergency medical services (EMS). Medical evacuation (MEDEVAC) units saw the benefit of critical care paramedic level training compared to US Army combat medics (EMTs) assigned as flight medics.[3] Likewise, the critical care training and experiences afforded to Special Operations medics increase their knowledge and capabilities, undoubtedly contributing to Special Operations Forces (SOF) units demonstrating lower mortality rates than conventional units.[4–6]

To further improve critical care performance, education is key. Many choose specific areas of interest to become subject matter experts. Prehospital medicine is no different. This supplement was developed to help provide a review of topics that may be encountered in military and civilian prehospital settings. We deliberately sought Special Operations medics and paramedics to team with a physician assistant or physician to provide a review of these topics. The concept was to take critical care and hospital-based concepts and describe them in a manner that the SOF medic and critical care paramedics will not only understand but also find engaging and useful. Our hope is that these reviews will help build a foundation for further learning and improved patient care. As we have stated elsewhere, knowledge weighs nothing in a rucksack.

The initial topic list was incredibly broad. Throughout the process, the topics were narrowed based on the practicalities of author availability as well as time and space constraints. We sincerely hope that you enjoy this supplement and find it useful. We would like to thank Michelle Landers, Allison Esposito, and Rosanne Schloss for their hard work and patience during this process. Furthermore, we would like to thank all the reviewers who volunteered during their busy schedules to help improve the submissions. While many topics did not make it into this supplement, our hope is that this issue begins a process of continued development into the future with increasing community contributions and additional critical care supplements.

Thanks for reading!

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The authors have nothing to disclose and received no funding for this effort.

Disclaimer
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Management of Severe Crush Injuries in Austere Environments

A Special Operations Perspective

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ABSTRACT

Crush injuries present a challenging case for medical providers and require knowledge and skill to manage the subsequent damage to multiple organ systems. In an austere environment, in which resources are limited and evacuation time is extensive, a medic must be prepared to identify trends and predict outcomes based on the mechanism of injury and patient presentation. These injuries occur in a variety of environments from motor vehicle accidents (at home or abroad) to natural disasters and building collapses. Crush injury can lead to compartment syndrome, traumatic rhabdomyolysis, arrythmias, and metabolic acidosis, especially for patients with extended treatment and extrication times. While crush syndrome occurs due to the systemic effects of the injury, the onset can be as early as 1 hour postinjury. With a comprehensive understanding of the pathophysiology, diagnosis, management, and tactical considerations, a prehospital provider can optimize patient outcomes and be prepared with the tools they have on hand for the progression of crush injury into crush syndrome.

KEYWORDS: *crush injury; Special Operations medicine; tactical medicine; compartment syndrome; rhabdomyolysis*

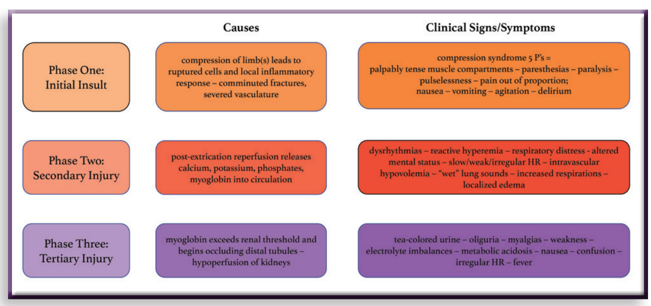
Introduction

An Army Special Operations Forces (SOF) team is deployed to Iraq on a Train, Advise and Assist (TAA) mission with Iraqi SOF. A sniper from this team takes up an observation post (OP) on top of a bombed-out building, which provides excellent overwatch of the local area. The building unexpectedly suffers structural collapse, and the sniper falls through multiple floors until reaching the ground floor. He is conscious, but he is complaining of clavicular pain and his left lower leg is pinned by debris. There is no significant hemorrhage. The SOF team secures the area and proceeds to extricate the sniper. The extrication is prolonged and requires the use of vehicle-mounted winches and improvised prybars. The sniper is then brought to the designated casualty collection point (CCP) for initial treatment. Due to tactical considerations, medevac to a forward surgical team (FST) will not be possible for several hours. On initial assessment of the sniper's injuries, he has a suspected fractured clavicle as well as a suspected fracture to the left tibia and fibula with associated crush injury of the soft tissues. This case is based on actual events, but details have been modified significantly for operational security.

Pathophysiology

As prehospital providers, medics are in the mindset of treating the injury that they come across at point of injury (POI). However, crush syndrome does not occur at the time of insult—it occurs during reperfusion. As the ischemic limb is being re-perfused, the cellular contents that are released from dying cells act as systemic toxins, disrupting cardiac, renal, and metabolic systems. Local tissue injury comes first, followed by organ system dysfunction and failure (Figure 1). By identifying the potential for crush syndrome, medics can be prepared to manage the complex series of systemic responses. Although typically crush syndrome results when reperfusion occurs 4–6 hours postinjury, it can occur as early as 1 hour depending on severity of trauma and degree of compression.[1]

FIGURE 1 *Progression of crush injury.*



Crush syndrome occurs when intracellular contents are circulated via the vasculature and disrupt systems throughout the body creating extensive electrolyte, chemical, and metabolic disturbances. These can lead to lethal arrythmias, renal failure, and potentially death in the most extreme cases. As muscle cells rupture due to damage inflicted by blunt trauma, they release a wide variety of chemicals, proteins, and enzymes into the interstitial fluid which is then removed by the vessels as the body attempts to achieve homeostasis and remove toxins. When in balance, potassium, sodium, calcium, magnesium, and phosphate facilitate electrical conduction and proper cellular function. Lysed (ruptured) muscle cells uncontrollably release these ions along with proteins, leading to arrhythmias, rhabdomyolysis, and compartment syndrome. All of these can be complicated to manage in the field on their own, and when combined create an even more challenging patient to manage.

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Myoglobin, a protein that carries oxygen within the muscle, damages the renal system by precipitating rhabdomyolysis when circulating at high levels. Crush injuries create an enormous amount of circulating myoglobin, which is not normally found in blood. Normally, the glomeruli in the kidneys filter myoglobin, but once renal threshold is surpassed, the convoluted distal tubules become obstructed, which leads to kidney dysfunction. Additionally, the increasing collection of myoglobin creates localized vasoconstriction, further exacerbating the problem of filtering out toxic metabolites.

Acute (traumatic) rhabdomyolysis caused by a rapid release of myoglobin may be more damaging than extended ischemia of soft tissue. During reperfusion, reactive hyperemia and increased capillary permeability causes intravascular hypovolemia and localized tissue edema, further increasing the potential for compartment syndrome as more fluid builds in the muscle contained by inflexible fascia.

The release of ions by damaged skeletal muscle cells affects the surrounding cells by changing the ratio of intracellular and extracellular components. Cells will third space intracellular fluid through osmosis in an effort to solve the problem. The result is damaged yet intact cells that initiate an inflammatory cascade, sending cytokines and proinflammatory markers to the injury site. Cytokines and inflammatory markers exacerbate local inflammation and the potential for compartment syndrome.

As the muscle cells increase in size due to the compression on the limb and inflammatory response, the muscle tissue becomes compressed within the fascia, creating a host of new problems. The fascia normally serves as a durable connective tissue enclosure for the muscle compartments, within which the muscle fibers can contract. As pressure rises within this enclosure, however, the perfusion of the capillaries, nerves, and cells can become compromised and can result in ischemic destruction to these tissues. Tissue edema and subsequent swelling maximizes in 1–2 days; however, postinjury reperfusion can appear anywhere between 2 and 5 days.[2] Compartment pressures above 30mmHg sustained for 6–8 hours can lead to irreversible tissue damage.[4]

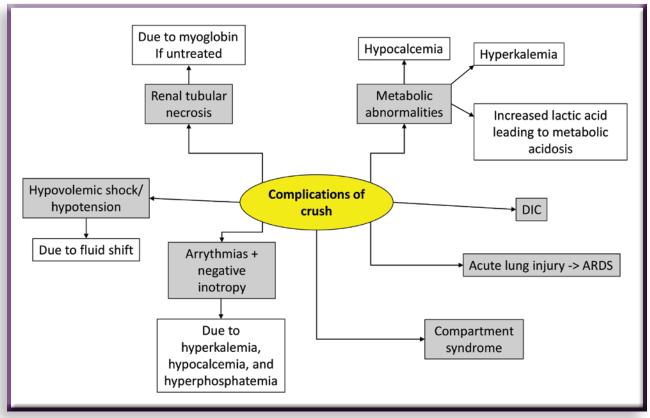
Additionally, occlusion of vessels by traumatic compression of soft tissue prevents oxygen from reaching the limb and the removal of toxins and damaged cells, leading to ischemia and localized edema. Cells not receiving oxygen must revert to anaerobic metabolism to conduct respiration, creating lactic acid as a byproduct. The buildup of lactic acid decreases tissue pH, causing metabolic acidosis. Each of these changes lead to systemic complications, detailed in Figure 2.

Diagnosis

Special Operations medics often work in resource-constrained environments, in which the mission may not allow the medic to have all the diagnostic equipment they would like to have. This section will discuss equipment or skill set required to assess the severity of patients at risk of developing crush syndrome. As popularized by the Joint Trauma System (JTS) Prolonged Field Care (PFC) Working Group, this will be discussed in a minimum, better, and best format.

With renal failure leading the list of concerns when it comes to crush syndrome, monitoring kidney function is a must. At a minimum, this means assessing the color, odor, consistency,

FIGURE 2 *Complications of crush injury.*



and amount (COCA) of the patient's urine. A patient experiencing rhabdomyolysis will have tea or cola-colored urine. As a mnemonic, the Special Operations medic can remember "COCA-cola equals rhabdomyolysis." This alone can indicate muscle cell breakdown or kidney dysfunction without the necessity of carrying an extra diagnostic tool. Utilizing a urine dipstick is better, as detecting and trending myoglobinuria is another means to identify the level of severity of muscle tissue breakdown. Urine dipsticks can detect myoglobin but will also present positive for hemoglobin, leading to a lack of specificity. However, in a resource-strained environment, this tool can still be useful, especially if there is an extended evacuation time. Best practice would be analyzing serum levels of myoglobin, requiring laboratory support. For a SOF team, this may be achievable in some environments due to the nature of partnerships built with governments and local civilian organizations.

Any means to measure the patient's urine output is necessary to gain a better picture of their clinical presentation. A medic needs to have a way to catch the patient's urine, utilizing a water bottle at a minimum and estimating urine output. A better solution is to catch urine in a water bottle and use a syringe to determine the patient's exact urine output. Best practice would be to place a transurethral indwelling "Foley" catheter, as it is the preferred way to monitor urine output. The goal of urine output is 100–200mL/hr.[5]

Cardiac monitoring is paramount postextrication due to the influx of intracellular potassium and calcium released systemically. At minimum, close monitoring of vital signs and circulation, examination for premature ventricular contractions (PVCs, palpated as skipped beats), bradycardia, decreased peripheral pulse strength, and hypotension is necessary.[5] A monitor with 3-lead capability is a better option so that a rhythm can be monitored. If resources allow, a 12-lead ECG and laboratory monitoring of potassium is ideal.[5] With hyperkalemia, sinus bradycardia is the primary sign. As hyperkalemia worsens, expect to see peaked T waves and a lengthening PR interval with possible loss of P waves as early signs. Further, the ECG will show prolonged QRS intervals, an eventual widening of the QRS that looks like a "sine wave," PVCs, runs of ventricular tachycardia, or conduction blocks. While likely not available at the POI in austere environments, a cardiac monitor should be utilized as soon as possible.

Clinical assessments are also necessary to determine the status of the patient and trend effectiveness of treatments. At minimum, monitor for increased work of breathing, productive cough with pink frothy sputum, and cyanosis, because pulmonary edema could be caused by the large volume of fluid required to treat fulminant rhabdomyolysis. A better practice would be lung auscultation with a stethoscope to assess for "wet" sounds and use of a pulse oximeter to monitor for impaired gas exchange. Post-extrication best practice is a chest radiograph to assess the extent of pulmonary edema present.

Medics should at a minimum be evaluating any extremities distal to the injury site for the "5 Ps" that can identify compartment syndrome: pain out of proportion to injury with passive movement, palpably tense muscle compartments, paresthesias or sensory deficits, pulselessness, and paralysis. It is important to note that paralysis and paresthesias could also be due to neural trauma.[2] It is also important to understand that many of these signs occur late. Special attention should be given to the finding of pain out of proportion on passive movement of the injured extremity and a high index of suspicion for compartment syndrome should be maintained when managing any crush injury, especially to the distal extremities. Compartment syndrome most often occurs in the lower legs, followed by the forearms. Compartment syndrome can occur in the proximal extremities but is much less common. While not all signs may be present, monitoring for compartment syndrome development is imperative. Best practice would be utilizing a compartment pressure monitor to determine the presence and severity of compartment syndrome, but this tool has significant limitations and is not recommended for use in theatre.[2]

Additional diagnostics for remote laboratory capability could be used to assess blood gases, electrolytes, metabolites, and coagulation factors if available. While an iSTAT™ (https://www.pointofcare.abbott/) or equivalent will unlikely be carried by a SOF medic on mission, in some countries the hospital system may have the same or a similar tool that can be borrowed or bartered for if necessary. Small lactate monitors are easy to carry and use, but only evaluate lactate, making it a hard bargain to add to an already full truck bag or prolonged field care (PFC) kit.

Management of Crush Patients

Management of patients who have experienced a prolonged crush injury focuses on preventing or readily addressing the associated complications discussed above. This patient management can be broken up into three phases: immediate, extrication, and evacuation.

The immediate phase begins when the medic arrives to the patient. Upon approaching a patient that has a crush injury, first conduct a standard MARCHE assessment and address any immediate, life-threatening injuries. Next, obtain intravenous (IV) access and begin an initial bolus of 1–2L of normal saline. Do not use lactated Ringer's due to the high potassium content in this crystalloid, which may exacerbate hyperkalemia the patient may experience during and after extrication.[5] The goal for the urine output should be equal to or greater than 1–2mL/kg/h during the extrication process, with an infusion rate of approximately 1.5L/h after the initial bolus.[5,6] During this time, the medic should be monitoring oxygenation (SpO_2) and administering supplemental oxygen, if available.[5,6] The medic should also auscultate the patient's lungs to ensure they are not getting "wet" due to excessive crystalloid infusion causing pulmonary edema. We acknowledge that monitoring urine output, administering oxygen and auscultating accurately in the immediate phase is technically difficult. These represent optimal management and are only recommended if they are also tactically sound.

Once the IV bolus is initiated, consider pain management, following established pain management protocols. Also, if time and tactical situation permit, 1g of ertapenem should be administered IV over 30 minutes as a prophylactic measure.[5-7]

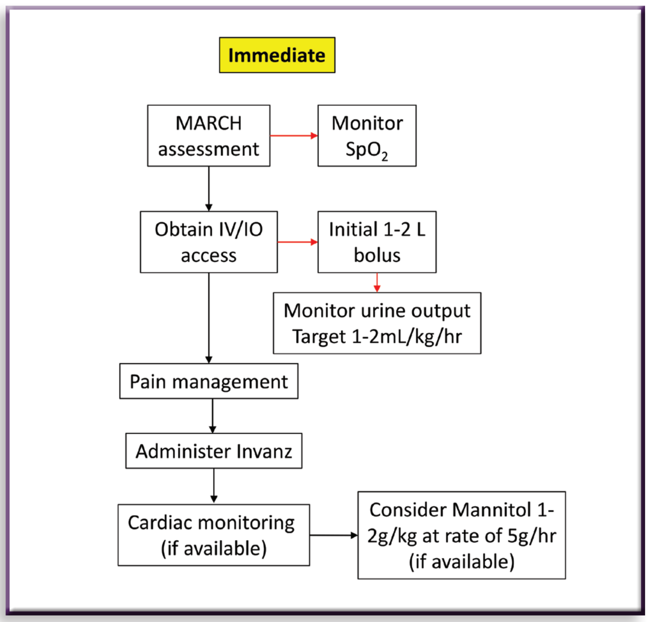
If available during the immediate phase, cardiac monitoring should be utilized to look for any signs of hyperkalemia. Sinus bradycardia will be the primary indicator of this, followed by peaked T waves or the presence of PVCs.[7] Also, administration of mannitol at 1–2g/kg at a rate of 5g/h can be considered if available and the patient's urine output has already been established.[6] It should be noted that mannitol causes large volume diuresis and can precipitate when stored in temperature extremes and requires a specific filter on the IV set. In addition, the use of mannitol in patients with possible ongoing internal hemorrhage or identified hemorrhage from other sources may exacerbate shock in a fashion that is difficult to recover from. As such, mannitol should be used thoughtfully, and this adjunct is not often carried by those providing POI or prehospital care in austere and resource-limited environments.

The extrication phase begins immediately before lifting the object that is crushing the patient. If an extremity is pinned, this is the time to apply and tighten tourniquets to prevent the potassium and myoglobin release into the blood stream. Sodium bicarbonate at a dose of 1mEq/kg should be given IV prior to extrication.[6] If a patient is going to experience a dysrhythmia or cardiac arrest, it may be immediately after extrication.[5] If there is any evidence of dysrhythmia or arrest, calcium should be administered to the patient. A medic can give either 10mL of 10% calcium gluconate or 5mL of calcium chloride 5% IV over 2 minutes, although in this case, calcium gluconate is preferred because it is less irritating to the vessel in a peripheral IV.[7] It is important to not administer either calcium product in a solution containing sodium bicarbonate due to the creation of calcium carbonate, a salt. A medic can also give albuterol to the patient showing signs of hyperkalemia, by either metered dose inhaler or nebulizer.[6] This will drive the free-floating potassium back into the cells and out of circulation.[7]

The final phase is evacuation. If the patient is still presenting with signs of hyperkalemia after administration of all medication above, one more ampule of sodium bicarbonate can be administered.[5,6] It is important to evacuate the patient to a higher echelon of care in the "urgent" MEDEVAC category, as this patient is going to require more advanced monitoring than a medic on the ground will be able to provide, including cardiac and laboratory monitoring.

The medic should pay close attention to the limb that was crushed, constantly assessing for evidence of a compartment syndrome. If compartment syndrome develops in a crushed extremity, a fasciotomy should be performed as soon as possible to reduce the risk of loss of limb in the patient.[5,6] Performing a fasciotomy outside of a forward surgical capability is controversial. On the one hand, it is undoubtedly the definitive treatment for compartment syndrome. However, the skin and fascial incisions required are necessarily long and the medic will have to manage bleeding using all available hemostatic options as well as managing relatively large wounds on both sides of the injured limb. In essence, there is a tradeoff between a compartment syndrome problem and a significant wound care problem. If not done properly, fasciotomies can be complicated by iatrogenic nerve and vascular injury. The procedure itself will require large amounts of local anesthetic or regional nerve block, followed by postprocedural analgesia. Therefore, a medic should perform a fasciotomy only if they have the teleconsultation available and the skillset or scope of practice allowing him or her to perform this procedure. If not, this information should be provided to the receiving facility and attempts should be made to cool the affected extremity to reduce swelling in that limb.[7] Continued pain management is important throughout treatment of this patient. Figure 3 outlines treatment options during the immediate, extrication, and evacuation phases of management of crush injuries.

FIGURE 3 *Immediate response to crush injury.*



Tactical Considerations

As with any scenario that a Special Operations medic may be faced with, there is more than just medicine to worry about. Medics can set themselves up for success by considering these conditions early and being prepared ahead of time.

Every medic—civilian or military—is taught that scene safety is the first part of their primary assessment; this is paramount in the scenario of a crushed service member. While a vehicle rollover causing a crush injury might seem to be the most likely case a medic may experience, the team may be responding to a structure collapse with trapped service members or local nationals, or a myriad of other situations within an inherently unstable environment. As a medic, one needs to ensure they do not become a casualty themselves. This is an easy concept when bullets are flying but is much more difficult in a setting such as what is likely to be experienced when responding to a crushed patient. Medics need to be aware of their surroundings when moving to a casualty and be certain they are minimizing the threat of being injured by the environment around them when providing care to the patient.

Getting the patient evacuated as quickly as feasible should be the focus in this situation. It is unlikely a team will have all the appropriate extrication equipment on hand or the training to extricate a trapped casualty properly and safely. While this is ultimately the decision of the tactical leader on the ground, the medic needs to be an advocate for their patient and request support for the extrication as soon as they realize it will be necessary. This may mean getting a rescue kit out of a vehicle or calling in a combat search and rescue capability such as pararescuemen (PJs) to provide the necessary expertise. Either way, extrication and evacuation need to be requested early and everything should be put in place to free the patient while the medic continues to work. The faster the patient is extricated and evacuated to a critical care capability, the better their chances of survival.[3]

Medics also need to consider the likelihood of a crush syndrome developing in a non-traditional setting. While it is easy to understand a patient stuck under a vehicle for hours may be at risk of developing crush syndrome, it is harder to conceptualize the Soldier who is stuck in a tree after a training parachute insertion and has been hanging from his harness with combat equipment for hours may be at equal risk. Understanding the physiology and knowing when to consider the possibility of this condition developing is essential.

Unless the team was alerted from their team house that they would be responding to a crush scenario, it is unlikely a medic will have all of the medications and fluid discussed above in their assault aid bag to be successful in treating their patient. Having premade "crush kits" with the medication and fluid necessary to manage a patient pre-staged can set the medic up for success. These can be left in a truck bag, set up in the medical treatment area of a team house, aid station, or coordinated to be left on a helicopter if the team has air assets, but there needs to be a plan to get this kit to the medic when they need it. If working in areas with greater risk of becoming crushed (e.g., dilapidated, multi-story buildings are common), it would benefit the medic to have crush kits closer to the POI, such as in a truck bag. As soon as the medic realizes they are dealing with a potential crush scenario, they need to request the crush kit to their location early.

Another consideration in this situation is pain management. Many medics simply are not carrying enough pain medication in their assault aid bags to control a patient's pain for hours with IV bumps. The time to start thinking about this is not when a medic has burned through all their ketamine with IV bumps and realizes the extrication can still take hours. A medic still needs to follow their organization's pain management protocols, but this might be the time to set up intravenous infusions for prolonged pain management. Another option is supplementing the standard ketamine bolus protocol—which seems to be most medics' go-to—with opioid administration, such as IV fentanyl. Hydromorphone, which has longer duration of action than ketamine, may also be considered.[6] Using a multimodal analgesia approach will likely provide better pain relief overall. Depending on what body part is crushed and the access to said body part, a medic can consider performing a regional block with an anesthetic such as lidocaine or bupivacaine as well, if appropriately trained. Last, if the medic on the ground is not comfortable with any of these options and wants to continually give IV boluses, they need to have a plan to get a pharmacological resupply before it becomes a need. Ultimately, having a plan for pain management early in the scenario is necessary.

Last, it is highly likely that a medic will be responding to a situation where more than one casualty may be crushed. Obtaining appropriate information as early as possible is important to ensure the proper amount of medical and rescue equipment is requested and made accessible during this process. This will impact performance and patient outcomes.

Conclusion

The initial case study places a Special Forces team in Iraq, where they were called on to respond and help an injured sniper who suffered crush injuries due to the structural collapse of a damaged building. This scenario illustrates the very real possibility for Special Operations medics of having to treat patients who are at risk of developing crush syndrome.

In response to the earthquake in Haiti in 2010, a four-person Air Force Pararescue team was attached to a search and rescue team out of Fairfax County, Virginia, and rescued at least 13 people from collapsed structures.[8] Additionally, 26 US Special Forces Soldiers assisted the Nepalese military with locating and rescuing survivors of the Nepal earthquake in April 2015.[9] It is not known if these service members treated any patients experiencing crush syndrome, but the likelihood of such casualties experiencing crush syndrome from this mechanism of injury is appreciated. Crush syndrome is a potentially lethal sequela of crush injuries. After the 1999 Marmara earthquake in Turkey, 18 patients who were transferred to the Istanbul University Hospital experienced crush syndrome. Seven of these patients did not survive the injuries caused by the manifestation of this syndrome.[3] This underscores the significance of crush injuries that can be encountered on the full spectrum of operations, both combat and non-combat in nature. To ensure mission success, understanding the physiology of crush injuries and crush syndrome and being prepared to treat these patients are paramount. Early coordination for supplies or capabilities needed to rescue and treat patients at risk of developing crush syndrome, and quick evacuation to a critical care facility, will ensure the greatest chance of survival for these patients.[3]

Disclosures

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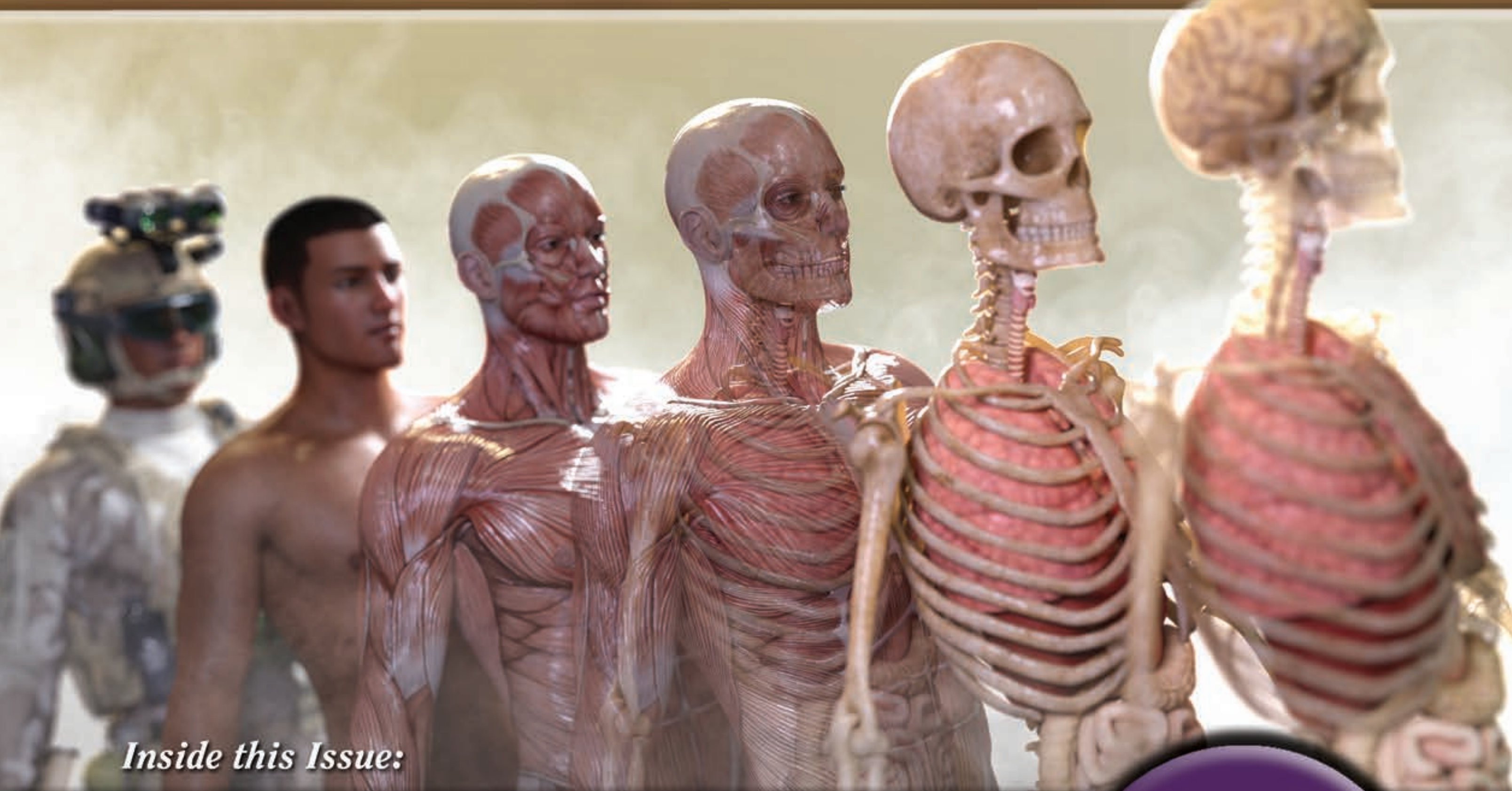

Inside this Issue:

Dedicated to the Indomitable Spirit, Lessons Learned & Sacrifices of the SOF Medic

A Peer Reviewed Journal That Brings Together The Global Interests of Special Operations' First Responders