Published in final edited form as:

Ann Plast Surg. 2018 March ; 80(3 Suppl 2): S113–S118. doi:10.1097/SAP.0000000000001374.

Volume resuscitation in patients with high-voltage electrical injuries

Derek M. Culnan, M.D.¹, Kelley Farner, N.P.¹, Genevieve H. Bitz, B.S.¹, Karel D. Capek, M.D.², Yiji Tu, M.D.³, Carlos Jimenez, M.D., F.A.C.S.², and William C. Lineaweaver, M.D., F.A.C.S.¹

¹JMS Burn and Reconstructive Center, Merit Health Central, Jackson, MS, USA

²Department of Surgery, University of Texas – Medical Branch and Shriners Hospitals for Children – Galveston, Galveston, TX, USA

³Department of Orthopedic Surgery, Zhongshan Hospital, Fudan University, Shanghai, China

Abstract

Volume resuscitation of patients with high-voltage electrical injuries (>1,000 V) is a more complex challenge than standard burn resuscitation. High voltages penetrate deep tissues. These deep injuries are not accounted for in resuscitation formulae dependent on percentage of cutaneous burn. Myonecrosis occurring from direct electrical injury as well as secondary compartment syndromes can result in rhabdomyolysis, compromising renal function and urine output. Urine output is the primary endpoint, with a goal of 1 cc/kg/hr for adult patients with high-voltage electrical injuries. As such, secondary resuscitation endpoints of laboratory values, such as lactate, base deficit, hemoglobin, and creatinine, as well as hemodynamic monitoring, such as mean arterial pressure and thermodilution techniques, can become crucial in guiding optimum administration of resuscitation fluids. Mannitol and bicarbonates are available but have limited support in the literature. High-voltage electrical injury patients often develop acute kidney injury requiring dialysis and have increased risks of chronic kidney disease and mortality. Continuous venovenous hemofiltration is a well-supported adjunct to clear the myoglobin load that hemodialysis cannot from circulation.

Keywords

high-voltage electrical injury; acute kidney injury; burn resuscitation; fluid management; rhabdomyolysis; dialysis; myoglobinuria; urine output

Introduction

Electrical burns account for up to 5% of all burn injuries in developed countries and up to 27% in developing nations.^{1–3} Treatment protocols are contested amongst burn centers worldwide, including debates regarding resuscitation algorithms. High-voltage electrical

Correspondence: Derek M. Culnan, M.D., Burn, Plastic, and Critical Care Surgeon, Merit Health Central, 1850 Chadwick Dr., Suite 1427, Jackson, MS, USA, 39204.

Disclosure: The authors have no financial interest to disclose.

injury (HVEI) can involve tissues not included in resuscitation formulae based on total body surface area (TBSA). This review summarizes current and reported practice of fluid resuscitation in electrical injury patients.

Electrical Physics and Pathophysiology

The conversion of electrical energy to heat is primarily responsible for resultant tissue damage⁴. Voltage is a significant factor contributing to the degree of tissue damage in electrical burns⁵. Voltage pushes the electric current through the body, and the size of the current (or the quantity of electrons flowing per second) determines the severity and effects of an electric burn.⁶

High-voltage electrical burns can cause superficial and deep injury. Superficial injury results from direct thermal burns from arcs or resultant fire, whereas deep injury derives from one of three mechanisms: resistance generated heat according to Ohm's Law, electroporation, and electroconformational protein denaturation. Compartment syndromes and rhabdomyolysis are derivative injuries that increase the magnitude of deep injury. These multiple insults combine to create the distinct pathology of electrical burn injury.

Superficial cutaneous injury

HVEI patients often suffer flame burns. The arc created by electrical contact associates with a high temperature plasma that can be in excess of 35,000°F. This flash can rapidly cause large area, third-degree burns.⁷ This arc is additionally capable of igniting the patient's clothing. These cutaneous burn injuries are visible and able to be accounted for in the burn resuscitation.

Deep tissue injury

Joule heating is the elevation in temperature of tissues resulting from the passage of the electric current through body conductors, from contact point to contact point.^{8–10} Joule heating is governed by Ohm's Law, $V = IR$.¹⁰ The tissue damage resulting from an electrical injury is proportional to the electrical resistance of a specific tissue.^{11–13} The tissue damage seen in high-voltage electrical burns results from the heat generated along the tissues closest to the bones, as bone has the highest resistance to electric current.^{11–13} Injury severity is inversely proportional to the cross-sectional area through which the current transits, explaining why the greatest damage is usually found at the wrists and ankles.¹⁴ The pronator quadratus is a great marker of deep myonecrosis as it lies at the narrowest part of the distal wrist in close contact with the ulna and radius at the point where there is a gap between the two bones. The farther from the point of contact, the less noticeable the rise in dermal temperature, irrespective of the heated structures below the skin¹⁵. Thus, HVEIs can cause necrosis of deep structures, particularly muscle, from resistive heating to the skeleton that can create deep tissue injuries not reflected by the apparent cutaneous burn.¹⁶

Electroporation, or cell membrane permeabilization, degrades the integrity of cell membranes, producing pores in the cellular membranes allowing charged ions or large molecules passage through the membranes, a direct effect of the electric field of the current passing through the tissues.^{9,15,17,18} The resultant influx of calcium ions into the cytoplasm

results in cellular necrosis and apoptosis. Tissues with less resistance to current flow, such as blood vessels and nerves, may be more affected by electroporation than by heat. Electroporation can occur in the absence of thermal burn or significant Joule heating.¹⁹

Electroconformational protein denaturation is a more indirect effect of the electric current. It occurs in the presence of a strong electric field when membrane proteins change polarity by altering their conformation to increase their effective dipole strength.^{11,14} Following a strong electrical pulse, voltage-gated channel proteins, which are sensitive to transmembrane voltage differences, alter their ion specificities and conductances.^{20,21} Consequently, the membrane proteins lose regulation function.^{17,22} Animal studies have shown that myelinated axons are the most sensitive to electrical shock, and the number of myelinated axons irreversibly damaged is proportional to the applied electrical current.^{11,15}

These results illuminate how victims of electrical trauma can suffer extensive nonhomogeneous nerve and muscular damage through multiple pathways even if little thermal injury is superficially present.²³

Derivative complications

The deep intracompartamental injuries associated with electrical injuries can result in an elevated risk of compartment syndromes in electrical injury.¹² Due to increased pressures in an enclosed space, muscles fail to perfuse, eventually resulting in ischemia of the muscles.²⁴ This tissue ischemia exacerbates the damage caused by resistive heating, electroporation, protein denaturation, and burn shock to enhance myonecrosis.

Myonecrosis is a common complicating factor of the above pathologies as deep muscle bellies are often fixed to the skeleton and serve as heat sinks to the resistively heated skeleton. Simultaneously, their perfusion is compromised by compartment syndromes, burn shock, and electroporetically compromised vasculature. The resulting rhabdomyolysis and myoglobinuria is toxic to the kidneys. Renal perfusion may not be preserved with resuscitation based on TBSA. Surgical interventions of decompression and debridement are necessary to prevent ongoing systemic toxicities and progressive injury in deep tissues.

Electrical Injury Diagnosis and Evaluation

Knowledge of the events of the conduction, the source voltage, and current type are important considerations in management. As in all burn injuries, care must be taken to diagnose coincident trauma, such as falls and blast injuries. In most thermally burned patients, the cutaneous burn surface area is an initial surrogate for estimating the total volume of tissue injury burden as the heat wave progresses from the skin to the deeper structures. In HVEIs, deep tissue damage can be far more extensive than the visible cutaneous burn.²³ The patient's resuscitation must be comprehensively monitored. A low threshold ought to be maintained for decompression, exploration, and debridement.

Fluid Resuscitation

Fluid resuscitation is a critical component of care in HVEI patients. Burn shock results from the release of inflammatory mediators that increase the capillary permeability leading to fluid shifts from the intravascular space into the intracellular space and interstitium of the tissues.^{25–28} The resultant hypovolemia and hemoconcentration necessitates fluid administration to halt the chain of events otherwise leading to decreased cardiac output, cardiovascular collapse, end-organ hypoperfusion, vascular ischemia, and death.^{29–31} The goal of burn resuscitation is to maintain sufficient perfusion in tissues and organs to prevent ischemic injury during the acute phase of burn shock.^{32,33} Delays in resuscitation correlate directly with increased morbidity and mortality in burn patients.³⁴ Burn resuscitation applies to the fluid administered during the first 24 to 48 hours after injury. The Parkland formula is the standard starting point worldwide for adult burn resuscitation.^{35,36}

In this protocol, total resuscitation fluid $4 \text{ mL} \times \text{TBSA} (\%) \times \text{body weight (kg)}$, 50% of the total resuscitation fluid is administered over the first 8 hours and the remainder over the following 16 hours. The hours are based upon the time at which the injury occurred. For optimal results, fluid should be initiated within two hours of burn injury.³⁴ Burn patient populations requiring additional fluid include those with large burns, electrical injuries, inhalation injuries, secondary injuries, drug or alcohol addictions, and cases of delayed resuscitation.^{37–44}

The use of TBSA in the formula to calculate fluid requirements can lead to under-resuscitation of an HVEI patient. The cutaneous burn can misrepresent the scope of internal injuries from a high-voltage electrical burn. Children require proportionally greater fluids than adult burn patients due to their increased surface area to volume ratios; thus, the Galveston formula was developed.⁴⁵ This formula is again based on percent surface burn and so might also under-resuscitate a child with electrical injuries.

The Over/Under of Resuscitation

Patients with electrical injuries require greater volumes of fluid administration than patients with thermal burns.³⁸ HVEI patients can be under-resuscitated if fluid is administered solely based on amount of cutaneous burn as TBSA is a potentially inadequate determinant of fluid needs in electrical injuries.⁴⁶

While under-resuscitation of a patient can lead to potentially fatal AKI and end-organ damage, over-resuscitation can induce compartment syndromes of the abdomen, extremities, and orbit as well as pulmonary or cerebral edema, increased risks of infectious complications, acute respiratory distress syndrome, and anasarca.^{46–49} Improper resuscitation and fluid management may result in conversion of the burn injury to one of greater depth and size.^{50,51} Thus, care must be taken to not institute potentially dangerous fluid loading in an attempt to sufficiently resuscitate a patient.^{33,52}

End Points and Evaluation of Resuscitation

To ensure proper fluid administration, burn resuscitation should be guided by physiological parameters and end-points. The overall goal is to achieve euvoemia and maintain the patient at this euvoemic point. When resuscitation is insufficient, shock occurs, oxygen debt accrues, and end organ function suffers. Unfortunately, there is no good measures to indicate when euvoemia is achieved, so multiple end points of resuscitation must be monitored to guide euvoemic resuscitation.

The primary endpoint of resuscitation is urine output (cc/kg/hour).⁵³ Secondary endpoints are laboratory values such as lactic acid, base deficit, and hemoglobin.⁵³ These intermittent endpoints are supplemented by continuous hemodynamic monitors such as mean arterial pressure (MAP) and central venous pressure (CVP).⁵³

A myopic application of single endpoint goal-directed resuscitative therapy without use of secondary endpoint monitoring can be associated with serious overload complication such as abdominal compartment syndrome.⁵⁴

For a typical thermal burn, fluid should be given to maintain a urine output of 0.5 cc/kg/hr in adult patients.⁵⁵ For electrical injuries, the standard is to double the urine output goal in an effort to ensure clearance of the expected myoglobin load. Current American Burn Association (ABA) protocols recommend a treatment algorithm of titrating fluids to ensure a urine output ideally of 75–100 mL/hour or of 1 mL/kg/hour in adult electrical burn patients before reducing fluids.^{14,55–57} A child who suffered an HVEI should have an initial urine output end-point of 1–2 mL/kg/hr until the urine is no longer pigmented, at which time urine output can be titrated to 1 mL/kg/hr.⁵⁸ During resuscitation one must keep in mind the Ivy Index, which established that the risk of abdominal compartment syndrome increases markedly when the volume administered exceeds 250 mL/kg during the initial 24 hours of burn resuscitation.⁵⁹

Titration to a urine output goal tailors the resuscitation to each patient and achieves adequate end-organ perfusion, but bedside clinical titration can lead to human-derived calculation and input errors. Members of the burn team are unlikely to immediately decrease fluid administration once urine output meets targeted goal, potentially leading to fluid overload.⁶⁰ Computerized support systems such as Burn Navigator® (Arcos Medical; Houston, TX, USA) can assist the burn surgeon in administering appropriate fluid volume during burn resuscitation and fluid management.^{61,62}

Preexisting renal failure makes this endpoint useless, and the resuscitation of patients in end-stage renal disease is fraught with difficulties and carries a high mortality.⁶³ Patients developing an AKI as a result of burn shock or toxicological effects (e.g., rhabdomyolysis), can achieve a state of hypervolemia without a corresponding increase in urine output. Overly resuscitated patients developing abdominal compartment syndrome will become oliguric, and increased fluid administration will exacerbate their pathology.⁶⁴ There are many conditions in which urine output will be persistently elevated despite hypovolemia and even some degree of shock. Diuretic use compromises renal concentrating capacity and will result in excess urine output if there is sufficient blood pressure to drive glomerular filtration.⁶⁵ In

addition to the many patients who take diuretics as their home medications, burn patients may arrive to burn centers with the diuretic effects of other agents, notably alcohol. There are many incidences where diuretic compounds are administered to the burned patient during resuscitation. High dose vitamin C administered as an antioxidant,⁶⁶ hydroxocobalamin given as a cyanide antidote,⁶⁷ mannitol for rhabdomyolysis, and occasionally loop diuretics are all intermittently indicated during burn resuscitation. With any of these agents, urine output can become an unreliable indicator of resuscitation.^{68,69}

When urine output is compromised as an end point of resuscitation, other indicators must be repeatedly measured and used to guide fluid management.⁷⁰ Laboratory values monitored as secondary end-points of burn resuscitation include lactate⁷¹ and base deficit⁷² to monitor a building oxygen debt, hemoglobin to monitor hemoconcentration,⁷³ creatinine to monitor the occurrence of renal failure, and serum myoglobin and creatinine phosphokinase (CPK) to monitor rhabdomyolysis and myoglobinuria.^{7,74} Recent studies examining the predictive values of base deficit and lactate found that a burn patient's initial lactate level was a stronger predictor of outcomes than base deficit, and rapid clearance of lactate is associated with better outcomes.^{71,75,76} In the largest studying investigating lactate levels and outcomes of burn patients, when lactate levels normalized within 24 hours of injury, burn survival reached 68% while lactate levels above 2 mmol/L 24 hours after injury are associated with a survival rate of just 32%.⁷¹

Serum creatinine will not accurately depict the degree of kidney injury in burn patients with renal failure. Creatinine can overestimate glomerular filtration rate (GFR) by 10–20%. The rate of change and deviation of serum creatinine may better reflect the changes in the GFR as muscle injury can influence the production and clearance of creatinine as well as lead to increased baseline values of serum creatinine when taken at admission.^{77,78} Increases in hematocrit or hemoglobin indicate hemoconcentration from an increasing plasma deficit, though hematocrit levels during the latter stages of resuscitation can result lower from damaged erythrocytes.^{73,79}

Hemodynamic monitoring allows direct measures of intravascular filling and hemodynamic performance. many of these monitors are continuous, allowing ongoing assessment of resuscitation status. Monitors of intravascular volume such as central venous pressure, or stroke volume variation, combine with measures of cardiovascular performance such as pulse contour cardiac output, echocardiography, and thermodilution to allow continuous estimations of intravascular volume and cardiac performance. These data are critical to differentiating between pre-renal (e.g., inadequate perfusion) versus renal (e.g., tubular, glomerular, or tubule-interstitial damage) causes of oliguria.⁸⁰ Pre-renal AKI nearly always presents with oliguria (< 400 mL/day) whereas renal/post-renal AKI can develop regardless of the urine output rate.⁷⁷

In the HVEI patient population, developments of renal and cardiac dysfunction are common complications.⁸¹ This cardiac dysfunction and metabolic acidosis may require a minimum of 24–48 hours to resolve.⁸² Further, respiratory dysfunction negatively affects kidney function as does diminished cardiac output incited by mechanical ventilation.⁸³ Monitoring burn resuscitation and fluid management using just urine output and MAP has been demonstrated

to be insufficient.⁷⁰ Hypovolemia may not be reflected in MAP or urine output measurements but will be discerned by transpulmonary thermodilution (TPTD).^{53,84} HVEI patients are monitored for hemodynamic optimization using standard hemodynamic monitoring such as pulse, MAP > 65 mmHg⁷⁰ and CVP as well as advanced hemodynamic monitoring such as TPTD using the Pulse index Continuous Cardiac Output (PiCCO) monitor. Echocardiography, both transthoracic (TTE) and transesophageal (TEE), has been shown to underestimate the cardiac output and hemodynamic status of a burn patient.^{85,86} TTE has proven utility at estimating volume status.⁸⁵ TEE may indicate a patient is hypovolemic despite a lack of correlation with any other end-point of resuscitation, limiting its utility to monitor and guide resuscitation and fluid management.^{85,87} When renal function is compromised by AKI from myoglobinuria or iatrogenically, for instance by mannitol-induced diuresis, secondary means of measuring fluid management status and preloading other than urine output must be employed. Studies have shown that hemodynamic endpoints and monitoring assists in overcoming a poor or absent response to resuscitation.^{53,84,88} Therefore, the efficacy of various invasive monitoring techniques remains controversial in burned patients.⁸¹ They should be supplemented with regular monitoring of secondary endpoints such as base deficit or hemoglobin concentration.

Resuscitation is performed to a primary endpoint of urine output, with secondary endpoints of laboratory values (hemoglobin, base deficit, lactate), while hemodynamic factors are monitored to assure appropriate intravascular filling and cardiac performance. Each of these values has many flaws. Their interpretation by a skilled burn surgeon is the true practice of burn resuscitation.

Fluid management of known complications of HVEI

Rhabdomyolysis is characterized by the release of intracellular components of myocytes into circulation incited by the breakdown of striated muscle tissue.⁸⁹ This syndrome results from the cellular depletion of ATP in the sarcoplasm of injured skeletal muscles, leading to a high concentration of calcium in the sarcoplasm, activating cytolytic enzymes. Electroporation also causes direct cellular lysis. These injuries are compounded by compartment syndromes and eschar compressions causing ischemia. The injuries to the myocyte eventually cause the dispersal of intracellular contents (e.g., potassium, CPK, myoglobin, and phosphates) into the circulation.⁹⁰ The damage is compounded in trauma-induced rhabdomyolysis wherein neutrophils invade injured skeletal muscle, causing ischemia reperfusion and inflammation resulting in the volume depletion characteristic of burn patients with rhabdomyolysis.⁹¹ The dispersal of large amounts of myoglobin results in the circulation of reactive oxygen species, leading to cellular injury.⁹² The level of free myoglobin from the necrosis of at least 100 g of muscle tissue is greater than can be bound by the plasma. Unbound myoglobin can result in renal failure by intrarenal vasoconstriction, direct and ischemic renal tubular injury, or renal tubular obstruction, particularly in acidosis.^{92–94} Patients with rhabdomyolysis typically have reddish-brown or “tea”-colored urine⁹⁵, and a urine dipstick test has a sensitivity of 80% for detecting rhabdomyolysis.⁹⁶ Hyperkalemia (serum potassium > 5.5 mmol/L), hyperuricemia, and hypocalcemia are common complications of rhabdomyolysis.⁹² Management of CPK and myoglobin is critical in the prevention of the development of AKI, which occurs in up to 50% of all cases of rhabdomyolysis.^{93,97}

Myoglobinuria, which develops secondary to rhabdomyolysis,⁹² is characterized by serum myoglobin levels in excess of 1.5–3 µg/mL or 0.02 µg/mL in the urine.^{98,99} Blood in the urine absent of erythrocytes can be diagnostic of myoglobinuria.⁹⁰ Foncerrada et al. showed that electrically-injured patients had more days of myoglobinemia than other burn patient populations, reflecting the exaggerated ischemia and necrosis characterizing electrical burns.¹⁰⁰

Should the urine fail to clear within the initial hours of the burn resuscitation, administrations of mannitol, at 25 g every 6 hours for adults, and sodium bicarbonate, at 5% continuous infusion, to alkalinize the urine have both been advocated.^{45,56,95,101} In alkalinizing the urine, bicarbonate makes myoglobin more soluble and easier to clear by decreasing the precipitation of myoglobin in urine, inhibiting the redox reaction of myoglobin, and ameliorating renal vasoconstriction induced by the acidic environment.⁹² An osmotic diuretic, mannitol scavenges free radicals generated by iron in hemoglobin, increases urine output and thereby flushes leaked intracellular components injuring the kidneys, and generates a gradient to draw out fluid sequestered in damaged muscle tissues.^{91,97,102} Limited data exist to support the use of mannitol diuresis or the alkalinization of urine with sodium bicarbonate.^{57,95,103,104} Diuresis with mannitol comprises the ability of urine output to be used as an endpoint of resuscitation by decoupling urine output from intravascular volume and global perfusion. Alkalinization with sodium bicarbonate causes a hypercapnia in patients with compromised ventilator function as well as hypernatremia, each of which can compromise the patient's metabolic status. These adjuncts remain in common practice in the settings of HVEI burn patients complicated by myoglobinuria and rhabdomyolysis, particularly in those with compromised renal function.⁹⁵ Should mannitol or bicarbonate be administered, base deficit values can artificially elevate. Lactate levels more accurately reflect the patient's metabolic progress in such a setting. Serum calcium and potassium levels should be monitored to guard against hypocalcemia or hyperkalemia as well as urine pH to monitor for hyperuricemia while bicarbonate and mannitol are administered. Hyperkalemia should be managed with diuresis or dialysis.^{91,97,105} If urine pH fails to increase within 6 hours or other electrolyte complications develop, bicarbonate should be halted.⁹² Loop diuretics such as furosemide can be administered when a patient remains oliguric despite sufficient fluid management to increase urine output and decrease the risk of myoglobin precipitation.⁸⁰ They are not as effective at flushing myoglobin from the urine as osmotic diuretics.⁹⁵

Sokhal et al. found among their patients who developed AKI, 61% sustained HVEIs, accounting for approximately 37% of their HVEI patient population.¹⁰⁶ The combination of oliguria or anuria with hyaline casts in the urine is indicative of pre-renal AKI where epithelial casts suggests acute tubular necrosis and renal/post-renal failure.¹⁰⁷ Patients who are sufficiently fluid replete but have inadequate urine output should be evaluated for continuous renal replacement therapy (CRRT).

In patients with indications of AKI as well as metabolic acidosis or hyperkalemia despite fluid overload, CRRT is indicated.^{91,105} Burn patients requiring dialysis have an associated mortality risk of up to 80%; a minority will require long-term dialysis.^{81,108} The small incidence of dialysis dependence and development of chronic kidney disease may be due to

the fact that ICU patients who recover from AKI have a 65–75% 5-year mortality rate.^{109,110} Aggressive CRRT in severely burned patients with AKI has been shown to significantly decrease mortality risks.^{81,111} Due to the large size of myoglobin, hemodialysis is unable to efficiently clear myoglobin from circulation.⁹² Case reports have shown that continuous venovenous hemofiltration can clear myoglobin with the correct filter and high-flow rate.¹¹² Monitoring urine appearance, urine myoglobin, serum myoglobin, and CPK are critical components in monitoring for rhabdomyolysis and myoglobinuria for fluid management needs.

Early volume fluid administration and excision of necrotic tissues remain the foundation to treat HVEI victims with myoglobinuria and rhabdomyolysis. Removal of necrotic muscle tissues commonly generated in high-voltage electrical injuries eliminates one potential cause of AKI.⁸⁰ Sequestration of water in damaged muscle tissues caused by high-voltage electrical injuries can incite swelling in the fascia of an extremity, compromising perfusion from restricted venous outflow. For these limbs, loss of arterial pulses or compartments that have reached maximum distensibility (30 mmHg) indicate escharotomies and fasciotomies are necessary to relieve pressures.¹¹³ Initially, this edema may not be present but may develop as a consequence of burn resuscitation or fluid management.⁹⁵

CONCLUSION

The fluid resuscitations and managements of patients with HVEI do not conform to the established TBSA-based resuscitation formulae as TBSA can under-estimate the fluid requirements from damaged muscle tissues. Outcomes of morbidity and mortality are improved when resuscitation and fluid management are guided by end-points.¹¹⁴ The current consensus primary endpoint is urine output, titrated to 75–100 mL/hour or to 1 mL/kg/hour for a burn patient with HVEI. Secondary endpoints include lactate levels, base deficit, and are augmented by continuous hemodynamic monitoring of MAP and CVP through TTE and TPTD. Further clinical research is requisite to determine the ideal goals for resuscitation monitoring and titrating.

References

1. American Burn Association. [Accessed May 16, 2017] 2016 Annual Burn Repository. 2016. <http://www.ameriburn.org/MBR.php>
2. Shih JG, Shahrokhi S, Jeschke MG. Review of adult electrical burn injury outcomes worldwide: An analysis of low-voltage vs high-voltage electrical injury. *J Burn Care Res.* 2017; 38(1):e293–e298. [PubMed: 27359191]
3. Aggarwal S, Maitz P, Kennedy P. Electrical flash burns due to switchboard explosions in New South Wales--A 9-year experience. *Burns.* 2011; 37(6):1038–1043. [PubMed: 21621330]
4. Azzena B, Tocco-Tussardi I, Pontini A, et al. Late complications of high-voltage electrical injury might involve multiple systems and be related to current path. *Ann Burns Fire Disasters.* 2016; 29(3):192–194. [PubMed: 28149248]
5. Hettiaratchy S, Dziewulski P. ABC of burns: Pathophysiology and types of burns. *BMJ.* 2004; 328(7453):1427–1429. [PubMed: 15191982]
6. Fish RM, Geddes LA. Conduction of electrical current to and through the human body: A review. *Eplasty.* 2009; 9:e44. [PubMed: 19907637]

7. Teodoreanu R, Popescu SA, Lascar I. Electrical injuries. Biological values measurements as a prediction factor of local evolution in electrocutions lesions. *J Med Life*. 2014; 7(2):226–236. [PubMed: 25408731]
8. Muehlberger T, Krettek C, Vogt PM. Electric accident. New aspects regarding pathophysiology and treatment. *Unfallchirurg*. 2001; 104(12):1122–1128. [PubMed: 11803717]
9. Stecker MM, Patterson T, Netherton BL. Mechanisms of electrode induced injury. Part 1: Theory. *Am J Electroneurodiagnostic Technol*. 2006; 46(4):315–342. [PubMed: 17285816]
10. Tropea BI, Lee RC. Thermal injury kinetics in electrical trauma. *J Biomech Eng*. 1992; 114(2): 241–250. [PubMed: 1602768]
11. Jeng JC, Lee K, Jablonski K, et al. Serum lactate and base deficit suggest inadequate resuscitation of patients with burn injuries: Application of a point-of-care laboratory instrument. *J Burn Care Rehabil*. 1997; 18(5):402–405. [PubMed: 9313119]
12. Janis JE, Khansa I, Lehrman CR, et al. Reconstructive management of devastating electrical injuries to the face. *Plast Reconstr Surg*. 2015; 136(4):839–847. [PubMed: 26090762]
13. Arnoldo BD, Purdue GF. The diagnosis and management of electrical injuries. *Hand Clin*. 2009; 25(4):469–479. [PubMed: 19801121]
14. Arnoldo, BD., Hunt, JL., Sterling, JP., et al. Electrical injuries. In: Herndon, DN., editor. *Total Burn Care*. Edinburgh, United Kingdom: Saunders Elsevier; 2012. p. 433–439.
15. Lee RC, Zhang D, Hannig J. Biophysical injury mechanisms in electrical shock trauma. *Annu Rev Biomed Eng*. 2000; 2:477–509. [PubMed: 11701521]
16. Hussmann J, Kucan JO, Russell RC, et al. Electrical injuries--Morbidity, outcome and treatment rationale. *Burns*. 1995; 21(7):530–535. [PubMed: 8540982]
17. Marques EG, Junior GA, Neto BF, et al. Visceral injury in electrical shock trauma: Proposed guideline for the management of abdominal electrocution and literature review. *Int J Burns Trauma*. 2014; 4(1):1–6. [PubMed: 24624308]
18. Bhatt DL, Gaylor DC, Lee RC. Rhabdomyolysis due to pulsed electric fields. *Plast Reconstr Surg*. 1990; 86(1):1–11. [PubMed: 2359775]
19. Fish RM. Electric injury, part I: Treatment priorities, subtle diagnostic factors, and burns. *J Emerg Med*. 1999; 17(6):977–983. [PubMed: 10595883]
20. Chen W, Lee RC. Altered ion channel conductance and ionic selectivity induced by large imposed membrane potential pulse. *Biophys J*. 1994; 67(2):603–612. [PubMed: 7948676]
21. Chen W, Zhongsheng Z, Lee RC. Supramembrane potential-induced electroconformational changes in sodium channel proteins: A potential mechanism involved in electric injury. *Burns*. 2006; 32(1):52–59. [PubMed: 16384650]
22. Tsong TY, Gross CJ. Reversibility of thermally induced denaturation of cellular proteins. *Ann N Y Acad Sci*. 1994; 720(1):65–78. [PubMed: 8010654]
23. Cheema SA. Pattern and profile of electric burn injury cases at a burn centre. *J Ayub Med Coll Abbottabad*. 2016; 28(4):702–705. [PubMed: 28586577]
24. Genthon A, Wilcox SR. Crush syndrome: A case report and review of the literature. *J Emerg Med*. 2014; 46(2):313–319. [PubMed: 24199724]
25. Gibran NS, Heimbach DM. Current status of burn wound pathophysiology. *Clin Plast Surg*. 2000; 27(1):11–22. [PubMed: 10665353]
26. Heyland DK, Dhaliwal R, Day AG, et al. REDucing Deaths due to OXidative Stress (The REDOX Study): Rationale and study design for a randomized trial of glutamine and antioxidant supplementation in critically-ill patients. *Proc Nutr Soc*. 2006; 65(3):250–263. [PubMed: 16923310]
27. Scott JR, Muangman PR, Tamura RN, et al. Substance P levels and neutral endopeptidase activity in acute burn wounds and hypertrophic scar. *Plast Reconstr Surg*. 2005; 115(4):1095–1102. [PubMed: 15793451]
28. Cope O, Moore FD. The redistribution of body water and the fluid therapy of the burned patient. *Ann Surg*. 1947; 126(6):1010–1045. [PubMed: 17859039]
29. Moore FD. The body-weight burn budget. Basic fluid therapy for the early burn. *Surg Clin North Am*. 1970; 50(6):1249–1265. [PubMed: 4922821]

30. Tricklebank S. Modern trends in fluid therapy for burns. *Burns*. 2009; 35(6):757–767. [PubMed: 19482429]
31. Ipaktchi K, Arbabi S. Advances in burn critical care. *Crit Care Med*. 2006; 34(9 Suppl):S239–244. [PubMed: 16917429]
32. Schwartz SI. Supportive therapy in burn care. Consensus summary on fluid resuscitation. *J Trauma*. 1979; 19(11 Suppl):876–877. [PubMed: 490711]
33. Chung KK, Blackburn LH, Wolf SE, et al. Evolution of burn resuscitation in operation Iraqi freedom. *J Burn Care Res*. 2006; 27(5):606–611. [PubMed: 16998392]
34. Barrow RE, Jeschke MG, Herndon DN. Early fluid resuscitation improves outcomes in severely burned children. *Resuscitation*. 2000; 45(2):91–96. [PubMed: 10950316]
35. Baker RH, Akhavan MA, Jallali N. Resuscitation of thermal injuries in the United Kingdom and Ireland. *J Plast Reconstr Aesthet Surg*. 2007; 60(6):682–685. [PubMed: 17485059]
36. Fakhry SM, Alexander J, Smith D, Meyer AA, Peterson HD. Regional and institutional variation in burn care. *J Burn Care Rehabil*. 1995; 16(1):86–90. discussion 85. [PubMed: 7721916]
37. Baxter CR. Fluid volume and electrolyte changes of the early postburn period. *Clin Plast Surg*. 1974; 1(4):693–703. [PubMed: 4609676]
38. Pruitt BA Jr. Fluid and electrolyte replacement in the burned patient. *Surg Clin North Am*. 1978; 58(6):1291–1312. [PubMed: 734610]
39. Pruitt BA. Fluid resuscitation of the extensively burned patients. *Ann Chir Plast*. 1979; 24(3):268–272. [PubMed: 543691]
40. Wolf SE, Rose JK, Desai MH, et al. Mortality determinants in massive pediatric burns. An analysis of 103 children with $\geq 80\%$ TBSA burns ($\geq 70\%$ full-thickness). *Ann Surg*. 1997; 225(5):554–565. discussion 565–559. [PubMed: 9193183]
41. Yowler CJ, Fratianne RB. Current status of burn resuscitation. *Clin Plast Surg*. 2000; 27(1):1–10. [PubMed: 10665352]
42. Cancio LC, Chavez S, Alvarado-Ortega M, et al. Predicting increased fluid requirements during the resuscitation of thermally injured patients. *J Trauma*. 2004; 56(2):404–413. discussion 413–404. [PubMed: 14960986]
43. Cancio LC, Reifenberg L, Barillo DJ, et al. Standard variables fail to identify patients who will not respond to fluid resuscitation following thermal injury: Brief report. *Burns*. 2005; 31(3):358–365. [PubMed: 15774295]
44. Baxter CR. Guidelines for fluid resuscitation. *J Trauma*. 1981; 21:687–692.
45. Barret, JP. Initial management and resuscitation. In: Barret, JP., Herndon, DN., editors. *Principles and practice of burn surgery*. New York: Marcel Dekker; 2005. p. 1–32.
46. Mustonen KM, Vuola J. Acute renal failure in intensive care burn patients (ARF in burn patients). *J Burn Care Res*. 2008; 29(1):227–237. [PubMed: 18182927]
47. Bacomo FK, Chung KK. A primer on burn resuscitation. *J Emerg Trauma Shock*. 2011; 4(1):109–113. [PubMed: 21633578]
48. Kumar P. Fluid resuscitation for burns: A double edge weapon. *Burns*. 2002; 28(6):613–614. [PubMed: 12220924]
49. Cartotto R, Zhou A. Fluid creep: The pendulum hasn't swung back yet! *J Burn Care Res*. 2010; 31(4):551–558. [PubMed: 20616649]
50. Jackson DM. The diagnosis of the depth of burning. *Br J Surg*. 1953; 40(164):588–596. [PubMed: 13059343]
51. Edgar DW, Fish JS, Gomez M, et al. Local and systemic treatments for acute edema after burn injury: A systematic review of the literature. *J Burn Care Res*. 2011; 32(2):334–347. [PubMed: 21252688]
52. Pruitt BA Jr. Protection from excessive resuscitation: "Pushing the pendulum back". *J Trauma*. 2000; 49(3):567–568. [PubMed: 11003341]
53. Sanchez M, Garcia-de-Lorenzo A, Herrero E, et al. A protocol for resuscitation of severe burn patients guided by transpulmonary thermodilution and lactate levels: A 3-year prospective cohort study. *Crit Care*. 2013; 17(4):R176. [PubMed: 23947945]

54. Bracco D. Burn fluid resuscitation: Let the autopilot do it! *Crit Care Med.* 2011; 39(9):2178–2180. [PubMed: 21849825]
55. Pham TN, Cancio LC, Gibran NS, et al. American Burn Association practice guidelines burn shock resuscitation. *J Burn Care Res.* 2008; 29(1):257–266. [PubMed: 18182930]
56. Cancio LC, Jimenez-Reyna JF, Barillo DJ, et al. One hundred ninety-five cases of high-voltage electric injury. *J Burn Care Rehabil.* 2005; 26(4):331–340. [PubMed: 16006840]
57. White CE, Renz EM. Advances in surgical care: Management of severe burn injury. *Crit Care Med.* 2008; 36(7 Suppl):S318–324. [PubMed: 18594259]
58. Sharma RK, Parashar A. Special considerations in paediatric burn patients. *Indian J Plast Surg.* 2010; 43:S43–50. [PubMed: 21321657]
59. Ivy ME, Atweh NA, Palmer J, et al. Intra-abdominal hypertension and abdominal compartment syndrome in burn patients. *J Trauma.* 2000; 49(3):387–391. [PubMed: 11003313]
60. Endorf FW, Dries DJ. Burn resuscitation. *Scand J Trauma Resusc Emerg Med.* 2011; 19:69. [PubMed: 22078326]
61. Cartotto R, Greenhalgh DG, Cancio C. Burn state of the science: Fluid resuscitation. *J Burn Care Res.* 2017; 38(3):e596–e604. [PubMed: 28328669]
62. Salinas J, Chung KK, Mann EA, et al. Computerized decision support system improves fluid resuscitation following severe burns: An original study. *Crit Care Med.* 2011; 39(9):2031–2038. [PubMed: 21532472]
63. Emara SS, Alzaylai AA. Renal failure in burn patients: A review. *Ann Burns Fire Disasters.* 2013; 26(1):12–15. [PubMed: 23966893]
64. Hartford CE. Fluid creep. *J Burn Care Res.* 2007; 28(5):770–772. [PubMed: 17762389]
65. Gretchen, J., Carrougher, SH., Blayney, CB. Burns. In: Baird, MS., Bethel, S., editors. *Manual of Critical Care Nursing.* 6. St. Louis, MO: Mosby; 2011. p. 295
66. Kremer T, Harenberg P, Hernekamp F, et al. High-dose vitamin C treatment reduces capillary leakage after burn plasma transfer in rats. *J Burn Care Res.* 2010; 31(3):470–479. [PubMed: 20354446]
67. Nguyen L, Afshari A, Kahn SA, et al. Utility and outcomes of hydroxocobalamin use in smoke inhalation patients. *Burns.* 2017; 43(1):107–113. [PubMed: 27554631]
68. McDougal, WS., Slade, CL., Pruitt, BA. *Manual of Burns.* Vol. 2. New York: Springer-Verlag; 1978. Initial care; p. 25
69. Abbasy MA. The diuretic action of vitamin C. *Biochem J.* 1937; 31(2):339–342. [PubMed: 16746344]
70. Dries DJ, Waxman K. Adequate resuscitation of burn patients may not be measured by urine output and vital signs. *Crit Care Med.* 1991; 19(3):327–329. [PubMed: 1999092]
71. Kamolz LP, Andel H, Schramm W, et al. Lactate: Early predictor of morbidity and mortality in patients with severe burns. *Burns.* 2005; 31(8):986–990. [PubMed: 16274931]
72. Kaups KL, Davis JW, Dominic WJ. Base deficit as an indicator or resuscitation needs in patients with burn injuries. *J Burn Care Rehabil.* 1998; 19(4):346–348. [PubMed: 9710734]
73. Pruitt BA Jr, Mason AD Jr, Moncrief JA. Hemodynamic changes in the early postburn patient: the influence of fluid administration and of a vasodilator (hydralazine). *J Trauma.* 1971; 11(1):36–46. [PubMed: 5099912]
74. Visweswaran P, Guntupalli J. Rhabdomyolysis. *Crit Care Clin.* 1999; 15(2):415–428. ix–x. [PubMed: 10331135]
75. Jeng JC, Jablonski K, Bridgeman A, et al. Serum lactate, not base deficit, rapidly predicts survival after major burns. *Burns.* 2002; 28(2):161–166. [PubMed: 11900940]
76. Mokline A, Abdenneji A, Rahmani I, et al. Lactate: Prognostic biomarker in severely burned patients. *Ann Burns Fire Disasters.* 2017; 30(1):35–38. [PubMed: 28592932]
77. Lameire N, Hoste E. Reflections on the definition, classification, and diagnostic evaluation of acute renal failure. *Curr Opin Crit Care.* 2004; 10(6):468–475. [PubMed: 15616388]
78. Doolan PD, Alpen EL, Theil GB. A clinical appraisal of the plasma concentration and endogenous clearance of creatinine. *Am J Med.* 1962; 32:65–79. [PubMed: 13887292]

79. Reiss E, Stirmann JA, Artz CP, et al. Fluid and electrolyte balance in burns. *J Am Med Assoc.* 1953; 152(14):1309–1313. [PubMed: 13061267]
80. Belba M, Belba G. Acute renal failure in severe burns. Conclusions after analyses of deaths during 1998. *Ann Burns Fire Disasters.* 2000; 13(2):124–129.
81. Ibrahim AE, Sarhane KA, Fagan SP, et al. Renal dysfunction in burns: A review. *Ann Burns Fire Disasters.* 2013; 26(1):16–25. [PubMed: 23966894]
82. Saffle JI. The phenomenon of "fluid creep" in acute burn resuscitation. *J Burn Care Res.* 2007; 28(3):382–395. [PubMed: 17438489]
83. Bulger EM, Jurkovich GJ, Gentilello LM, et al. Current clinical options for the treatment and management of acute respiratory distress syndrome. *J Trauma.* 2000; 48(3):562–572. [PubMed: 10744307]
84. Soussi S, Deniau B, Ferry A, et al. Low cardiac index and stroke volume on admission are associated with poor outcome in critically ill burn patients: A retrospective cohort study. *Ann Intensive Care.* 2016; 6(1):87. [PubMed: 27620877]
85. Maybauer MO, Asmussen S, Platts DG, et al. Transesophageal echocardiography in the management of burn patients. *Burns.* 2014; 40(4):630–635. [PubMed: 24035579]
86. Wurzer P, Branski LK, Jeschke MG, et al. Transpulmonary thermodilution versus transthoracic echocardiography for cardiac output measurements in severely burned children. *Shock.* 2016; 46(3):249–253. [PubMed: 27058051]
87. Wang GY, Ma B, Tang HT, et al. Esophageal echo-Doppler monitoring in burn shock resuscitation: Are hemodynamic variables the critical standard guiding fluid therapy? *J Trauma.* 2008; 65(6):1396–1401. [PubMed: 19077633]
88. Schiller WR, Bay RC, McLachlan JG, et al. Survival in major burn injuries is predicted by early response to Swan-Ganz-guided resuscitation. *Am J Surg.* 1995; 170(6):696–699. discussion 699–700. [PubMed: 7492029]
89. Keltz E, Khan FY, Mann G. Rhabdomyolysis. The role of diagnostic and prognostic factors. *Muscles Ligaments Tendons J.* 2013; 3(4):303–312. [PubMed: 24596694]
90. Petejova N, Martinek A. Acute kidney injury due to rhabdomyolysis and renal replacement therapy: a critical review. *Crit Care.* 2014; 18(3):224. [PubMed: 25043142]
91. Vanholder R, Sever MS, Ereke E, et al. Rhabdomyolysis. *J Am Soc Nephrol.* 2000; 11(8):1553–1561. [PubMed: 10906171]
92. Bosch X, Poch E, Grau JM. Rhabdomyolysis and acute kidney injury. *N Engl J Med.* 2009; 361(1):62–72. [PubMed: 19571284]
93. Zager RA. Studies of mechanisms and protective maneuvers in myoglobinuric acute renal injury. *Lab Invest.* 1989; 60(5):619–629. [PubMed: 2716281]
94. Zager RA, Gamelin LM. Pathogenetic mechanisms in experimental hemoglobinuric acute renal failure. *Am J Physiol.* 1989; 256(3 Pt 2):F446–455. [PubMed: 2923223]
95. Sanford A, Gamelli RL. Lightning and thermal injuries. *Handb Clin Neurol.* 2014; 120:981–986. [PubMed: 24365365]
96. Melli G, Chaudhry V, Cornblath DR. Rhabdomyolysis: An evaluation of 475 hospitalized patients. *Medicine (Baltimore).* 2005; 84(6):377–385. [PubMed: 16267412]
97. Bagley WH, Yang H, Shah KH. Rhabdomyolysis. *Intern Emerg Med.* 2007; 2(3):210–218. [PubMed: 17909702]
98. Rosen CL, Adler JN, Rabban JT, et al. Early predictors of myoglobinuria and acute renal failure following electrical injury. *J Emerg Med.* 1999; 17(5):783–789. [PubMed: 10499690]
99. David WS. Myoglobinuria. *Neurol Clin.* 2000; 18(1):215–243. [PubMed: 10658177]
100. Foncerrada G, Capek KD, Wurzer P, et al. Functional exercise capacity in children with electrical burns. *J Burn Care Res.* 2017; 38(3):e647–e652. [PubMed: 27654868]
101. Jeschke MG, Herndon DN. Burns. In: Townsend, CM, Beauchamp, RD, Evers, BM, Mattox, KL, editors. *Sabiston Textbook of Surgery: The Biological Basis of Modern Surgical Practice.* 20. Philadelphia: Elsevier; 2017. p. 525–526.
102. Holt S, Reeder B, Wilson M, et al. Increased lipid peroxidation in patients with rhabdomyolysis. *Lancet.* 1999; 353(9160):1241.

103. Brown CV, Rhee P, Chan L, et al. Preventing renal failure in patients with rhabdomyolysis: Do bicarbonate and mannitol make a difference? *J Trauma*. 2004; 56(6):1191–1196. [PubMed: 15211124]
104. Homs E, Barreiro MF, Orlando JM, et al. Prophylaxis of acute renal failure in patients with rhabdomyolysis. *Ren Fail*. 1997; 19(2):283–288. [PubMed: 9101605]
105. Holt SG, Moore KP. Pathogenesis and treatment of renal dysfunction in rhabdomyolysis. *Intensive Care Med*. 2001; 27(5):803–811. [PubMed: 11430535]
106. Sokhal AK, Lodha KG, Kumari M, et al. Clinical spectrum of electrical burns - A prospective study from the developing world. *Burns*. 2017; 43(1):182–189. [PubMed: 27567159]
107. Anderson RJ, Barry DW. Clinical and laboratory diagnosis of acute renal failure. *Best Pract Res Clin Anaesthesiol*. 2004; 18(1):1–20. [PubMed: 14760871]
108. Brusselaers N, Monstrey S, Colpaert K, et al. Outcome of acute kidney injury in severe burns: A systematic review and meta-analysis. *Intensive Care Med*. 2010; 36(6):915–925. [PubMed: 20333353]
109. Korkeila M, Ruokonen E, Takala J. Costs of care, long-term prognosis and quality of life in patients requiring renal replacement therapy during intensive care. *Intensive Care Med*. 2000; 26(12):1824–1831. [PubMed: 11271091]
110. Schiff H, Fischer R. Five-year outcomes of severe acute kidney injury requiring renal replacement therapy. *Nephrol Dial Transplant*. 2008; 23(7):2235–2241. [PubMed: 18408072]
111. Chung KK, Juncos LA, Wolf SE, et al. Continuous renal replacement therapy improves survival in severely burned military casualties with acute kidney injury. *J Trauma*. 2008; 64:S179–185. discussion S185–177. [PubMed: 18376163]
112. Ronco C. Extracorporeal therapies in acute rhabdomyolysis and myoglobin clearance. *Crit Care*. 2005; 9(2):141–142. [PubMed: 15774064]
113. Gomez-Cia, T., Ortega-Martinez, JI. The Hand. In: Barret, JP., Herndon, DN., editors. *Principles and Practice of Burn Surgery*. New York: Marcel Dekker; 2005. p. 260–261.
114. Greenhalgh DG. Burn resuscitation. *J Burn Care Res*. 2007; 28(4):555–565. [PubMed: 17665515]