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High-voltage electrical injury complicated by compartment syndrome and acute kidney injury with successful limb salvage: A case report and review of the literature

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ABSTRACT

INTRODUCTION: Although an uncommon form of admission to a burns centre, the deep, penetrating nature of noxious currents mean that electrical burns have the most catastrophic consequences of all burn injuries. Understanding the physics of electricity is crucial to explaining the mechanisms of tissue damage and organ failure in electrical injuries which necessitate special management above and beyond that of regular thermal burns.
PRESENTATION OF CASE: We present a young man who suffered significant occupation-related electrical burns that was complicated by compartment syndrome, rhabdomyolysis and acute kidney injury. He required multiple surgeries (including fasciotomy as well as soft tissue reconstruction), critical care and lengthy rehabilitation.
DISCUSSION: Rhabdomyolysis is common sequela of electrical burns and may result in severe and permanent metabolic and renal impairment. High cut-off dialysis membranes have shown great promise in myoglobin removal but further studies are required to determine whether this improves clinical outcomes. Debridement and decompression are the cornerstones of initial surgical intervention and are crucial to minimising infectious complications and preserving vital structures. Free tissue transfer has become increasingly popular, but the ideal timing of microsurgery is still uncertain. Nonetheless, pedicled flaps remain widely used and still have an important role in reconstruction of electrical burns.
CONCLUSION: Patients with electrical injuries have several unique acute manifestations that differ from other burns. Prognosticating outcomes is difficult, as the full scale of damage is seldom immediately evident. Multiple organ systems are often affected, which makes the treatment of such patients exceptionally challenging, multi-disciplinary and resource-intensive.

1. Introduction

Electrical injuries represent approximately 3% of admissions to burn units, however, the extent of injuries is often deeper and more severe compared with non-electrical burns [1]. The age distribution of patients is bimodal, with the first peak comprising young children (<6 years), and the second peak occurring in young adult males e.g. miners and construction workers (accounting for 6% of occupational fatalities) [2].

Electricity is defined as the flow of electrons from high to low concentration. This potential difference, or voltage (V), is the driving force, and the quantity of electrons flowing, measured in amperes (I), is the current. The impedance to flow is described as resistance (R). Ohm's law defines the relationship between these factors as $I = V/R$ [2].Thermal energy (E) generated is described by Joule's law, $E = I^2 \times R \times T$, demonstrating that damage is proportional to squared current, resistance and time [2]. Skin, bone and fat have a higher resistance and so tend to heat up and coagulate. Nerves and blood vessels have low resistance and conduct current readily. Dry skin has a high resistance, resulting in extensive superficial burns but limiting deeper conduction of harmful current. Moist skin has less resistance and therefore receives less injury, but allows current to pass through causing greater damage to internal organs [1].

Electrical shocks can be divided into high-voltage (≥1000 V) or low-voltage (<1000 V), with high-voltage shocks expected to cause more damage. Injury patterns depend on current, voltage, pathway, and duration of contact. A current parallel to the body's axis is more treacherous as it involves the heart, lungs and central ner-

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vous system, but determining this is at best a clinical guess. Direct currents cause a single muscular contraction, often throwing the person away from the source of electricity. Alternating currents are considered more dangerous as it can lead to tetanic contractions that cause the hand to grip onto the electrical source (forearm flexors are stronger than forearm extensors) and increase exposure time [2].

The noxious effects of electrocution can be categorized into four types: [1,2]

1 Burns from conversion of electrical to thermal (electrothermal) energy
2 Effects of current on the cardiac, musculoskeletal and neurological conducting systems (e.g. asystole, arrhythmias, apnoea)
3 Trauma from forceful tetanic contractures or from being thrown (e.g. fracture-dislocations)
4 Electroporation (formation of pores in lipid membranes leading to calcium influx and apoptosis)

We present a case of high-voltage electrical injury that was complicated by full-thickness burns, compartment syndrome, rhabdomyolysis and acute kidney injury (AKI). The pathogenesis of these conditions is examined and advances in management reviewed. This work has been reported in line with the SCARE criteria [3].

2. Case report

A 25 years-old previously healthy male shipyard technician was repairing a 1200 V alternating current electrical generator when it exploded. His right hand was touching the circuit box at the time of blast, but he denied prolonged contact or being flung. He sustained 16% total body surface area (TBSA) burns to his face as well as both arms and hands (Fig. 1).

Fluid resuscitation was commenced, and he underwent debridement of his upper limb burns (including escharotomy of his right forearm) and application of biosynthetic Biobrane® dressings (UDL Laboratories, Rockford, IL) to his face (Fig. 2A). Immediately after surgery, he complained of worsening, severe right hand pain, and an emergent fasciotomy was done for presumptive compartment syndrome (Fig. 2B). He also developed AKI with hyperkalaemia, a rising creatine kinase and myoglobinuria. Haemodialysis was initiated as his urine output failed to improve despite aggressive fluid boluses, mannitol diuresis and urinary alkalinisation. His AKI resolved after two weeks along with correction of his metabolic abnormalities and renal replacement therapy (RRT) was withdrawn.

Serial debridement was performed until his upper limb wounds were clean and the full demarcation of the depth and extent of his injuries had become apparent. Autologous split-thickness skin-grafting was performed; the dorsum of his right hand ultimately required coverage with a groin flap (Fig. 3). He was discharged after 4 months and returned to work after a year of intensive rehabilitation.

3. Discussion

It is estimated that 10% of survivors of high-voltage electrical injuries develop rhabdomyolysis, a consequence of massive skeletal muscle electrothermal conversion and electroporation [4].When such extensive destruction occurs, myoglobin, the primary oxygen-carrier in muscle cells, is released in large quantities along with other intracellular contents such as creatinine kinase (CK), lactate dehydrogenase and potassium. AKI is the most significant complication of rapid myoglobin release, and occurs due to myoglobin-induced renal vasoconstriction with resultant ischaemia, myoglobin cast formation in the distal convoluted tubule causing obstruction, and nephrotoxic effects of myoglobin on the epithelial cells of the proximal convoluted tubule [4].

Because definitions of rhabdomyolysis vary widely, the exact incidence of AKI in rhabdomyolysis is difficult to ascertain but is thought to range from 13 to 48% [5].Early identification of rhabdomyolysis is challenging as the classical triad of signs and symptoms (muscle pain, prostration and dark urine) may be masked when patients are sedated, or be confused with fluid under-resuscitation. Serum CK levels may be greater than 5 times the upper limit of normal and reach several 10,000s Units/Litre, peaking on day 3 and decreasing by half every 24–48 h. Serum and urinary myoglobin levels are also elevated, but serial assays have not been shown to be useful in predicting AKI or ongoing muscle damage [5].

Once diagnosed, prompt treatment should be commenced to avoid AKI. Management includes prompt fluid repletion with maintenance of a high urine output (2 ml/kg/hour) and correction of electrolyte derangements. Osmotic diuresis with mannitol (reduces myoglobin deposition, free radical scavenger, renal vasodilator) and urinary alkalinisation with sodium bicarbonate (minimises breakdown of myoglobin into nephrotoxic metabolites, reduces tubular crystallisation of uric acid) have been advocated as adjuncts, but are not supported by high-level evidence [5].

The use of RRT in rhabdomyolysis is controversial, but may be needed if conservative measures fail to improve metabolic abnormalities or renal impairment. Myoglobin (molecular weight 17.8 KDa) and other protein-bound toxins are poorly removed by conventional dialysis membranes, hence the use of RRT in treating rhabdomyolysis may be restricted beyond that of supportive therapy. The use of high-flux membranes improves blood and dialysate flow to increase clearance of larger solutes, but their molecular weight cut-off of 10–20 KDa remains a limiting factor [6].

High cut-off (HCO) membranes have also been developed with molecular weight cut-offs closer to that of the native kidney (65 KDa). Early studies have demonstrated their enormous potential in filtering myoglobin [7,8], with increases in clearance rates of up to five-times reported [8].However, using membranes with larger pore sizes is not without drawbacks, principally the unwanted loss of plasma proteins such as albumin (molecular weight 67 KDa) which may result in haemodynamic instability and necessitate albumin replacement [7,8].

Although high circulating levels of myoglobin may cause nephrotoxicity and delay renal function recovery, there is insufficient evidence to support any form of dialysis over conservative measures as first-line therapy. High-quality randomised-control trials are needed to determine whether use of these novel modes of RRT in rhabdomyolysis improves survival and prevents progression to chronic kidney disease [9].

Electrothermal damage also causes progressive muscle devitalisation from vascular thrombosis. Subsequently, oedema around necrotic muscles within their unyielding fascial sheath results in progressive obliteration of the microcirculation, giving rise to compartment syndrome. The principles of initial surgery involves: 1) early excision of unviable tissue to decrease the infective load, and 2) aggressive fasciotomy to prevent complete necrosis of affected compartments, thereby preserving vital structures and avoid development of ischaemic contractures [10].

The full extent of myonecrosis may not be apparent at first and may extend due to ongoing ischaemia, hence high-voltage injuries often require staged debridement after initial decompression. Unfortunately, amputation is often an inevitable consequence of electrical burns, with the ratio of extremity loss still unacceptably high compared to other forms of burns. This is particularly true in high-voltage injuries, with the correlation between voltage and fasciotomy, amputation as well as mortality well-established in numerous studies [11–13]. The decision to amputate may be


[redacted]

Fig. 1. (A) The patient sustained 3% TBSA superficial partial-thickness burns to his face with singed facial and nasal hair. (B) He also sustained 7% TBSA mixed deep partial thickness and full thickness burns to his right arm and hands. (C) There was 6% TBSA deep partial-thickness burns of his left forearm and hands.


[redacted]

Fig. 2. (A) After burns debridement, a sheet of Biobrane® (UDL Laboratories, Rockford, IL) was applied over the patient's face. (B) Decompressive fasciotomies of his right hand were performed due to worsening, severe pain and tenderness with marked swelling and impaired fingertip capillary refill. This provided immediate symptomatic relief.

very challenging, but to reduce morbidity and improve survival this should be performed early if the extremity is clearly necrotic or septic [11–13].

If digital or limb salvage is attempted, definitive soft tissue coverage should be delayed until it is clear all devitalised tissue has been excised. This assessment is difficult initially due to evolving compartment syndrome, superimposed infection and vessel thrombosis. The pre-operative use of magnetic resonance imaging (MRI) [14] and technetium-99 m-methylene di-phosphonate (99 T cm-MDP) scintigraphy [15] to aid identification of necrotic tissue have been reported to be helpful in guiding debridement of electrical injuries, but at present there is no imaging technique that has seen widespread clinical uptake for this purpose.

Skin grafting can give satisfactory outcomes, however in many cases the graft fails to take due to subclinical infection or exposure of bones and tendons. The introduction of well-vascularised soft tissue from outside the zone of injury is more resistant to infection, often yields better results, and frequently represents the only opportunity for limb salvage.

The optimal timing of reconstruction remains controversial, with Hsiao et al. reporting an 80% limb salvage rate with the use of a flow-through anterolateral thigh flap for soft tissue as well as vessel reconstruction, with the mean timing of microsurgery 5.8 days after electrical injury [16]. Likewise, Zhu et al. advocate emergency repair of vital structures at the time of primary excision with early wound resurfacing, resulting in 9% extremity loss compared with 41.5% in historical controls [10]. Saint-Cyr and Daigle found an 80% survival rate for free flaps performed a mean 19.1 days after electrical burns, with significantly fewer surgeries and reduced length of hospitalisation compared with conventional multi-stage pedicled flaps [17]. However, Ofer et al report an 85% success rate with microvascular reconstruction of electrical burns in 26 patients, with all cases of failure occurring within 21 days of injury [18].

Fig. 3. (A) Autologous skin grafting resulted in successful wound coverage of the patient's arms and left hand. (B) A pedicled flap from the groin was required to provide definitive coverage of the patient's right hand and fingers because successive debridements had led to exposure of extensor tendons and phalangeal bones, resulting in skin graft failure.

In the current era of microsurgery, many have questioned the need for traditional flaps from the abdomen and groin to reconstruct hand and forearms defects [19,20].Such pedicled flaps entail significant disadvantages such as longer hospitalisation, additional operations, increased discomfort and joint stiffness, leading to some groups to believe that it should only be reserved for when free or regional flaps cannot be used [19].Nonetheless, these flaps remain popular due to their dependability, relative technical simplicity and high resistance to infection. Indeed, Al-Qattan and Al-Qattan have defined high-voltage electrical injuries with the hand surviving on collateral circulation, and salvage of the thumb ray with concomitant radial artery thrombosis in high-voltage electrical injuries as two of the indications for pedicled flaps in hand and forearm reconstruction [20].

In spite of the tremendous increase in versatility and variability of reconstructive solutions in recent years, reconstruction of electrical burns remains challenging. Treatment must be individualised, based on the extent of injury, availability donor sites (which may have also been burnt), the patient's needs, surgeon experience and available resources.

4. Conclusion

Although uncommon, electrical burns cause wide-ranging and potentially devastating injuries. A basic knowledge of physics allows a holistic appreciation of such complications. Prompt recognition of rhabdomyolysis and acute kidney injury permits intervention to minimise further morbidity, and early prophylactic surgery with subsequent reconstruction if possible maximises functional outcomes. Multidisciplinary management is required to achieve optimal results for these patients.

Conflict of interest

The authors declare that they have no competing financial or personal interests.

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Ethical approval

Institutional review board/ethics committee does not require approval for case reports.

Consent

Written informed consent was obtained fro, the patient for publication of this case report and accompanying images. A copy of the written consent is available for review by the Editor-in-Chief of this journal on request.

Author contribution

C.W.H conceptualised the study, collected data, performed a literature review and drafted the manuscript. C.H.W performed a literature review and drafted the manuscript. S-H.Y and S.J.C critically revised the article. All authors approve submission of the final article.

Registration of research studies

Not applicable.

Guarantor

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