Electricity: The Enemy Invisible

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ABSTRACT

Electrical injuries, as such, are less prevalent in comparison to other forms of burn injuries. However, this type of injury is considered to be one of the most devastating injuries due to its high morbidity and mortality. It is also associated with high costs and long-term hospitalization as well as the need for multiple surgical procedures. It is more prevalent in developing countries. Most of the pediatric population suffers injuries at home from low voltage appliances.

The patient with electrical injury is usually a young, employed person who can potentially return to a productive working life. Successfully achieving this goal would save society a great loss of human potential. The plastic surgeon is actively involved in all phases of the pursuit of maximal recovery of the patient with electrical injuries. Reconstructive procedures are required both in high voltage injuries and low voltage injuries and have improved the quality of lives of these patients by timely intervention.

Precautionary measures are necessary to reduce the incidence of high voltage injuries and their devastating effects. The incidence of high voltage injuries would not have been so high had the electric workers been properly trained and hazards of high tension lines explained. Moreover emphasis must be laid on the use of safety measures.

Keywords: Electrical injury, voltage, current, reconstruction

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INTRODUCTION

Modern age is an age of electricity. It has become an inevitable, invisible companion of modern man. Since its inception in 1849, commercial use of electricity has been one of the most potentially dangerous commodities in our society. Although electrical burns occur less frequently than thermal/scald burns, accounting for 3-9% of all patients treated in burns centres. However, they give rise to a series of very complex problems. Electrical injuries are a common form of trauma with a unique pathophysiology, and are known for high morbidity and mortality. They encompass several types, such as lightning injury, high-voltage injury, and low-voltage injury. Clinical manifestations may range from transient unpleasant feeling without any apparent injury to massive tissue and/or organ system damage. Many a times, such injuries are instantly fatal. Familiarity with the mechanisms of injury and the principles of management improves the patient care. These injuries are associated with high costs and longer hospitalization as well as the need for multiple surgical procedures; so the need for specific management considerations are required. The burden of electrical burn injury is more among developing than developed countries, with prevalence rate higher among men. In developing countries, people are less acquainted to proper and safe use of electricity in contrast to developed countries.

Electricity is unavoidable in present day life. We cannot imagine a life without it. The uses of electricity in our daily life are too numerous to be counted. We are becoming more and more dependent on it, and so is the rising incidence of electrical injuries. Demographic data reveals that more number of electric injuries occur at work, involving the...
young population and work forces - the main human resources of countries. In contrast, most of the paediatric population suffer injuries at home from low voltage appliances.

**ELECTRICITY**

Electricity is generated by the flow of electrons across a potential gradient (difference) from high to low concentration through a conductive material. The voltage (V) is the term used for this potential difference. Amperage represents the rate of flow of electrons. Every time 6.242 x $10^{19}$ electrons pass a given point in 1 second, 1 ampere (A) of current is said to have passed.

Alternating current (AC) is three times more dangerous than direct current (DC) for the same voltage exposure, leading to more morbidity and mortality. Skin offers greater resistance to direct current than alternating current, thus 3-4 times more direct current is required to produce the same biologic effect elicited by alternating current. DC current causes cardiac rhythm disturbances, and throws the patient off, thus, limiting the exposure to the source but inflicting traumatic injuries. With increasing alternating current, sensations of tingling give way to contractions of muscles. The magnitude of the muscular contractions enhances as the current is increased. Finally, a level of alternating current is reached for which the subject cannot release the grasp of the conductor. The maximum current a person can tolerate when holding a conductor in one hand and still let go of the conductor using the muscles directly stimulated by the current is termed the "let-go" current. A narrow range exists between perceptible current and the "let go" current. The "let go" current for the average child is 3-5 mA; this is well below the 15-30 A of common household circuit breakers. For adults, the "let go" current is 6-9 mA, slightly higher for men than for women. Such strong muscular reactions may cause fractures and/or dislocations. Numerous cases of bilateral scapular fractures and shoulder dislocations and fractures in electric accidents have been reported.

Electrical injuries are typically divided into high-voltage and low-voltage injuries, using 1000V as the cut off. High morbidity and mortality has been described in 600V direct current injury associated with "third rail" contact. In India, standard household outlets (0.5mA, 60Hz, AC, 120V) produce startle response, cutaneous burns. >10mA alternating current produces tetany, “locked-on” phenomenon. >100mA produces loss of consciousness, asystole, and severe tissue injury. Low voltage current injuries are similar to thermal burns. High tension injuries (>1000 volts) result in massive necrosis of deeper structures, often necessitating fasciotomies and major limb amputations.

$V = IR$ (Ohm's law) where R is Resistance, I is current. Resistance varies depending on the electrolyte and water content of the body tissue through which electricity is being conducted. Blood vessels, muscles, and nerves have high electrolyte and water content, and, thus, low resistance, and are good conductors of electricity better than bone, fat, and skin. Resistance of the human body has been likened to that of a leather bag filled with an electrolyte fluid, with high resistance on the outside and lower inside. Skin resistance is encountered primarily in the stratum corneum. Resistance varies among different tissues and also with condition of skin. In vivo, however, conduction of current is related to the composite resistance of all body tissue components and to the cross-sectional diameter of the body part. Resistance values of hand to foot vary from 400 to 600 Ohms and ear to ear-100 Ohms. Again resistance is inversely proportional to cross-sectional area of joints, so small joints of body like joints of foot and hand suffer from maximum injury.

<table>
<thead>
<tr>
<th>Skin resistance</th>
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<tbody>
<tr>
<td>Mucous membranes</td>
<td>10 ohm/cm²</td>
<td></td>
</tr>
<tr>
<td>Wet skin</td>
<td>1,000 ohm/cm²</td>
<td></td>
</tr>
<tr>
<td>Dry skin</td>
<td>100,000 ohm/cm²</td>
<td></td>
</tr>
<tr>
<td>Calloused palm skin</td>
<td>1,000,000 ohm/cm²</td>
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**Pathophysiology:**

The 3 major mechanisms of electricity-induced injury are as follows:

1. Electrical energy causing direct tissue damage, altering cell membrane resting potential, and eliciting muscle tetany.
2. Conversion of electrical energy into thermal energy, causing massive tissue destruction and coagulative necrosis. (Joule effect)
3. Mechanical injury with direct trauma resulting from falls or violent muscle contraction.

Effects of electricity on the body are determined by 7 factors: (1) type of current, (2) amount of current, (3) pathway of current, (4) duration of contact, (5) area of contact, (6) resistance of the body, and (7) voltage.
HIGH VOLTAGE ACCIDENTS

Burns are often ultimately much worse than they appear initially. The national electric code defines high-voltage exposure as greater than 600 volts. In the medical literature, high-voltage exposure is judged as greater than 1,000 volts. In high-voltage accidents, the victim is often thrown away from the electric circuit, which leads to traumatic injuries (e.g., fracture, brain haemorrhage). Burns due to contact with high-voltage electric circuits conform to 4 general types:

1. **Burns from an electric arc**
   An electric arc is formed between two bodies of sufficiently different potential that are not in direct contact of each other. The arc (intense, pale-violet light) consists of ionized particles that are driven by the voltage pressure between the two bodies. Temperature of the ionized particles and immediately surrounding gases of the arc can reach as high as 2500-5000° C, resulting in deep thermal burns where it contacts the skin.

2. **Burns from an electric current**
   When electric current passes through body of a person between the entry and exit site the electric energy is converted into thermal energy which causes hidden deep tissue damage. High-voltage electric entry wounds are charred, centrally depressed, and leathery in appearance, while exit wounds are more likely to “explode” as the charge exits.

3. **Burn from a flame**
   Ignition of clothing causes direct burns from flames. Both electro-thermal and arcing currents can ignite clothing.

4. **Burn from flash**
   When heat from a nearby electrical arc causes thermal burns but current does not actually enter the body, the result is a flash burn. Flash burns may cover a large surface area of the body but are usually only partial thickness.

Mortality/Morbidity

Electrical injuries are the fourth most common cause of traumatic work-related deaths. It is estimated that 0.8-1% of accidental deaths are due to electrical injury, with approximately one quarter caused by natural lightning. Overall, mortality rate is 3-15%. Morbidity and mortality are largely affected by the particular type of electrical energy involved.
contact involved in each exposure. There are reports which record deaths after exposure to 46 volts or after therapeutic application of currents with tension as low as 30-50 volts. In the United States, about 1000 deaths are due to electric injuries each year.\(^1\,2\)

Flash burns have a better prognosis than arc or conductive burns\(^5\). Persons, who experience low-voltage injuries without immediate cardiac or respiratory arrest, have low mortality, but they may have significant morbidity from oral trauma in children who bite electrical cords\(^6\) or adults who suffer burns to the hand. High-voltage injuries often produce severe burns and blunt trauma with high risk of myoglobinuria and renal failure. (Photo1)

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### Neurologic Complications

2. Neurologic complications are the most common complications of electric injury. In high-voltage electric injuries, nearly 70% of patients are rendered unconscious. Delayed spinal cord injuries causing paraplegia or quadriplegia. Peripheral nerve injury may be involved by direct injury at the site of entrance or exit or in polyneuritic syndrome involving nerves far removed from the points of contact.

3. High-voltage electric current can produce a wide variety of different cardiac rhythm and conduction disturbances\(^7\). Cardiac arrest either from asystole or ventricular fibrillation often presents in electrical injuries. Hand to hand pathway (across heart) produces more mortality.

4. Acute pulmonary complications in the form of pleural damage resulting in effusions and lobular pneumonitis directly adjacent to the entrance and exit wounds.

5. A wide spectrum of abdominal visceral complications has been reported following high-voltage electrical injury\(^8\). Nonspecific adynamic ileus occurs in approximately 25% of patients. Stress ulceration (Curling ulcer) is probably one of the most serious complications (3%)\(^9\).

6. In high-voltage accidents in which the current enters near bony tissue, lesions of the bone are common\(^10\). High resistance of bone to the passage of electric current results in periosteal necrosis and melting of the calcium phosphate matrix.

7. Electric injuries to the eye occur chiefly when current enters the body through the patient's head. (Photo2) Cataract can occur in 6% of cases\(^11,12\).

### Complications of Electrical Injuries:

1. Traumatic injuries due to fall or throw away force.

### Age and Gender

Incidence of electrical injury is higher among boys than girls; rates of injury in adults are significantly higher in men than in women, likely because of occupational predisposition. Most series show more than 80% of electrical injuries occurring in men\(^13,14,15\). A bimodal distribution of electrical injuries exists among the very young (children < 6 y) and again among young adults/working age\(^16\). Patterns of electrical injury vary by age (for example, low voltage household exposures among toddlers and high-voltage exposures among risk-taking adolescents and via occupational exposure)\(^17,18\).

### Prehospital Care

First, rescuers should practice awareness of scene safety and be sure there is no imminent threat to bystanders or responders in attempting to remove the victim from the electrical source. A witness of the accident must turn off the power source as soon as possible. Wearing insulated gloves, the victim should be separated from the circuit by a specially insulated pole. Looping a polydacron rope around the injured patient is another method of pulling him or her from the electric power source. Patients may need basic or advanced cardiac life support. Spine should be immobilized prior to movement, indicated by the mechanism of injury.
Given that injuries may be limited to a ventricular arrhythmia or respiratory muscle paralysis, aggressive and prolonged cardiopulmonary resuscitation (CPR) should be initiated in the field for all electrical injury victims, as they are likely to be younger with fewer comorbid conditions and have better chances of survival after prolonged CPR.

Patients with high-voltage electrical injuries require the ongoing care of a burn specialist, which should be instituted as early as possible, as aggressive early intervention via fasciotomy can prevent subsequent limb amputation. Consider additional consultations with trauma/critical care, orthopaedics, plastic surgery, and general surgery, depending on the type and severity of traumatic injuries. Cutaneous burn size may be of lesser magnitude compared to the non-electric burn population. Increased rate of orthopedic injuries, head injuries and other organ injuries due to fall associated with high voltage injuries are observed. The threshold for suspicion of associated injuries in high voltage injuries should be kept low for prompt diagnosis and management.

A greater number of fasciotomies, escharotomies and amputations are seen in high voltage injuries in comparison to low voltage injuries where amputations, if any, are limited to digits only, most of the times. High tension injury produces gradual ischemia due to thrombus formation in the small arterioles, thus, constricting blood flow in vessels, subsequently resulting in amputation.

Most of the injuries are afflicted to the upper limbs. Hands are mostly first part of body to come in contact with electric circuit. So hand & forearm are most commonly & most severely affected. Small circumference also contributes to greater tissue injury. All of this illustrates the vulnerability of the extremities, particularly the upper limb to the injuries.

Injury may appear to be superficial at the first instance; however, deeper structures like bone, tendon & neurovascular bundles are affected requiring flap cover for future reconstruction of these structures to get functional and sensate hand. Involvement of the plastic surgeon in early management helps prevent the progression of nerve injury and preservation of muscle and tendon function. In the early phase, plastic surgeons are involved in

Photo 2: Post electric burn exposed nasal bones

EMERGENCY DEPARTMENT CARE

Stabilize patients and provide/secure airway and circulatory support as indicated by ACLS/ATLS protocols. Full spinal immobilization as needed based on mechanism of injury. Primary survey should assess for traumatic injuries such as pneumothorax, peritonitis, or pelvic fractures. Initiate cardiac monitoring for all patients with anything more than trivial low-voltage exposures.

Hydration is the key to reducing the morbidity of severe burns. There is no formula, however, to assist in management due to the unpredictable nature of the underlying tissue damage. In general, the fluid requirements per percent of burn are 1.5 to 2 times that of a skin burn alone given the nature of the added soft tissue injury. The rate of fluid administration is based on the amount necessary to maintain adequate perfusion using the same guidelines as for burn shock management. High voltage injuries have a greater incidence of muscle necrosis, myoglobinuria, raised creatine phosphokinase levels and renal failure. A urine flow of 1 cc/kg/hr or more is needed until pigment load has decreased. Mannitol (25g bolus followed by 12.5 g every 2 to 4 hours) is often required to maintain this level of output. In addition, sodium bicarbonate is often needed to maintain urine pH equal to or greater than 7 in order to minimize pigment precipitation. In refractory cases, dialysis should be considered.

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fasciotomies, nerve tunnel release, and possible options for immediate resurfacing. Many authors like Kamar et al., Zhu et al., Yunchuan et al., and Chai all reported reconstruction during this period with excellent results. They utilized multiple local and pedicled flaps for reconstruction. However, more study is needed to determine the best timing of major reconstruction and to evaluate whether progression of injury is prevented by doing so. Patients lacking sufficient tissue to perform successful reconstruction, dermal matrix or tissue transplant may be considered as future options for coverage of massive electrical wounds. Despite all these efforts complete return of function & sensation in hand and forearm is very difficult to achieve. Out of various options available for resurfacing of defects, we have to choose one option taking into consideration, the defect size, local tissue availability, availability of regional tissue, condition of neurovascular bundle at recipient site. Groin flap is a time tested, easily available work horse option with proper positioning of hand without much discomfort to patient. Next easily available option is random pattern abdominal flap or its various modifications. Reverse radial forearm flap can be used in cases with availability of local tissue in radial forearm territory. Cross finger flap and First dorsal metacarpal artery flap are used for covering small defects over fingers. For larger defects which cannot be covered by other options, free tissue transfer is to be considered.

Reconstructive procedures improve the quality of lives of these patients by timely intervention. Amputations, major or minor (as per the indication) are performed at this stage. The advocates of early surgery need further studies to reach some final protocol designing. Authors like Al-Qattan et al. and Barone et al. have described satisfactory results with splinting after primary healing. Physical and occupational therapy is started to minimize complications such as contracture, decreased range of motion and eventual joint fusion, pressure sores, and generalized deconditioning. The plastic surgeon revisits the patient after the primary healing period is over; trying to fully restore function. Particularly, tendon and nerve procedures may restore some lost function during the late reconstructive phase. Ultimately, all these interventions may decrease final impairment and facilitate them return to work and society as a useful member.

The operative procedures required and length of hospital stay are more in high voltage injuries. The patient is usually a young, employed person who can potentially return to a productive working life. Successfully achieving this goal would save society a great loss of human potential and benefit the patient greatly. The impact of amputation is grievous in the life of electric burn survivor both physically and economically. The psychosocial impact of such events leaves a stigma in the patient's life forever. Most of the patients are linemen or workers and are not able to resume their occupation. Rehabilitation of such patients is another issue.

Electric department workers (Photo 4) are at a greater risk of exposure to high voltage injuries. To reduce the incidence of high voltage injuries and their devastating effects, precautionary measures are indispensable. (One of the most effective precautions was expressed by Kennely in 1927 who recommended keeping one hand in the pocket while visiting an electric plant!) Main culprit is lack of proper knowledge and training of electrical workers. Standardization of electrical devices, continuous supervision of workers, proper use the devices, security precautions, using “danger” labels on highly dangerous electrical devices, restriction of access of unskilled individuals to dangerous electrical instruments, setting proper shifts, settlement of continuous educational programs for workers and electrician, informing them about...
the dangers of improper use of electrical devices and explaining preventive methods to them would be beneficial in reducing this type of injury. New rules and regulations should be designed and implemented for prevention of electrical burn injuries. Use of insulated devices, ground fault circuit interrupters (GFCI) may prove a boon. Departments should have a safety wing, laying emphasis on safety measures like helmets, electrician’s gloves, safety belts, insulated ladders and other insulated equipments. Upgradation of transmission system especially in rural areas can decrease such accidents. For general population mass media awareness programs on electrical safety are necessary. Proper and quick referral after initial resuscitation at peripheral centres can save many lives.

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Photo 4: Electric workers without any precautionary measures or safety gadgets
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