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Electrical Injuries

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There are about 2000 burn unit admissions and about 1000 deaths per year due to electrical injuries in adults and children.[1] Much of the literature about electrical injuries focuses on the serious complications associated with severe injuries due to high voltage or long-duration exposure. Fortunately, few of these serious injuries occur in children. Articles about low voltage injuries focus on the life-threatening complications of apnea and ventricular fibrillation. Less serious complications and injuries receive scant attention. This is unfortunate, since low-voltage electricity is the leading cause of electrical burn injury in children and adults.

With the emphasis in the literature clearly focused on major complications of high-voltage injuries, the recommendation for admission of the patient with a minor electrical injury for 24-48 hours is widespread.[2-7] Many emergency department (ED) practitioners clearly have noted that most injuries to children are minor and require no monitoring or invasive procedures.[3,4,8,9] Research needs to be conducted to determine the spectrum of electrical injuries and guidelines for care.

This paper puts these issues into proper perspective and gives the emergency physician counsel about both the common minor injuries and the much rarer life-threats.

— The Editor

Epidemiology

The people who are most commonly injured by electricity are, of course, those who work with it, such as electricians and construction workers. About 93% of electrical injury victims are male and the bulk of these are in their 20s.[10-11] Electrical injury is the fifth leading cause of occupational deaths.

Most electrical injuries in children are due to faulty electrical equipment or to children playing with extension cords and outlets.[12-13] Although we have created multiple safeguards for electrical outlets, most injuries occur with extension cords. The most common ages of injury are between 1 and 5 with the peak occurring in 2-year-olds. Most injuries occur between 10 a.m. and noon and between 4 and 6 p.m. Of the objects inserted into wall sockets, the most common are pins, keys, and fingers.

Pediatric emergency physicians also will see youths who are bent on exploration, often in dangerous places such as high-voltage transformer enclosures or near high tension lines. Other youths who are commonly involved in an electrical accident are hobbyists who are working with radios, computers, and similar electrical appliances and devices.

Physics of Electrical Injuries

The effect of the passage of electricity on various inorganic substances may be one of the most widely studied phenomenon in science. There is a huge body of literature that describes these studies and predicts effects of the passage of electricity through a substance. These effects are unchanged in the organic human model, but since humans are not uniform in composition, the descriptions become more complex.

In the inorganic model, the most important determinants of the extent of changes induced by electrical current are the intensity of the current and the duration of the contact.

Direct current (DC) is a constant current in a single direction. Sources of direct current include electronic power supplies, battery chargers, arc welders, and third rails for some transportation devices such as subways and trams. DC current injuries are not common, as few DC sources deliver much more than 30 volts. The exception to this is the subway third rail.

Alternating current (AC) is current that switches polarity on a regular basis. It is defined by the number of cycles per second as it switches from positive to negative. 60-cycle AC will have 60 negative half cycles and 60 positive half cycles per second.

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Common frequencies for AC include 60 cycles (U.S. household current), 50 cycles (European household current), and 400 cycles per second, used in some aircraft and military applications. When the frequency of alternating current is greater than 10,000 cycles per second, it is often referred to as high frequency current. Greater than about 30,000 cycles per second is considered radio frequency.

A transformer only works with AC, so most commercial high tension power lines are AC to allow for more efficient change of voltage. Some long distance, very high tension lines may be DC to increase the efficiency of transmission over long distance, but this is infrequent. Virtually all electrical injuries due to commercial current at any voltage are due to AC supplies.

A volt is the unit of electromotive force or "tension" on the line. Multiple descriptions from high school texts to college physics tomes use a familiar example of the water-filled pipe or hose to describe the passage of electrons through a conductor. Voltage is the pressure that forces the electrons through the line.

Voltage can be measured between the terminals on a battery or between the black wire and either the green ground or the white wire. Common voltages encountered in United States and Canadian households are 120 and 240 volts. Business users may encounter 440 volt lines, while the transformer on the street corner will be supplied by a 1200- or 2400-volt line. Europeans often will use 220 volts as household current.

High voltage is arbitrarily defined as a driving force of greater than 1000 volts.

An ampere is the unit of current flow. In the plumbing illustration mentioned previously, an ampere would represent the filling of a bucket at the end of the hose. If the bucket fills rapidly, then there is higher current flow. An ampere represents the passage of approximately 1023 electrons per second through a wire.

The resistance of a substance to the passage of electricity is measured in ohms. Dry skin has a resistance of about 100,000 ohms. In the plumbing simile, the size of the hose or pipe would represent the resistance to flow. A smaller hose would mean more resistance to the flow of current.

Intensity of current flow is governed by Ohm's law, which states that the electrical current is directly proportional to the voltage difference between two points and inversely proportional to the resistance between these two points.

Ohm's Law: $E_{(voltage)} = I_{(current)} \times R_{(resistance)}$

This equation is accurate and applicable for a copper wire of uniform composition. In the organic model, this law still is applicable, but the resistance may not be constant. Resistance in human skin is dependent on perspiration, contact area, variability of skin and underlying tissue, grounding, and the pathway of the current.

The production of heat by the passage of electrical current is significant. This heat is generated by the passage of electrical current through a resistance and is expressed by Joule's law. A watt is one ampere of current flow for one second. One watt of power for one second produces 0.24 calories of heat. One watt-second also is called a joule.

Joule's Law: $Heat_{(power)} = 0.24\ I^2 \times R \times T_{(time)}$

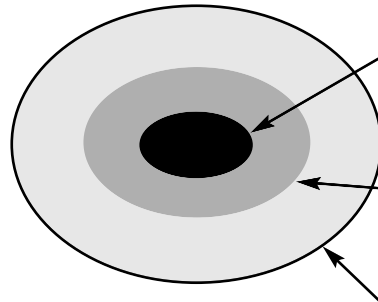
In this equation, the voltage can be substituted for $I \times R$ in the $I^2 \times R$ component, so heat produced is directly proportional

Table 1. Tissue Resistance to Electricity

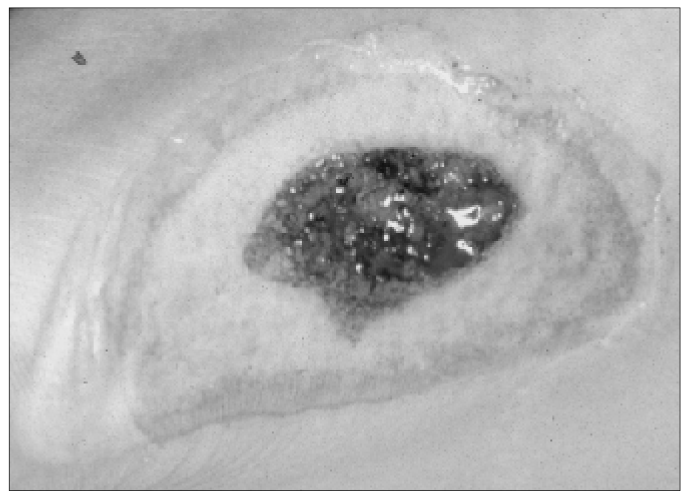
LISTED IN ORDER OF LEAST RESISTANT (MOST CONDUCTIVE) TO MOST RESISTANT (LEAST CONDUCTIVE)
• Nerves
• Blood vessels
• Muscles
• Wet skin
• Dry skin
• Tendon
• Fat
• Bone

Figure 1a and 1b. Electrical Entry/Exit Burn

1a. The entry/exit contact lesion has three areas:



1b. These three areas can be seen in this foot burn.



to the driving voltage:

$\text{Heat}_{(\text{power})} = 0.24\ I \times E \times T$

If all other factors are constant, dangerous current passage is more likely as the voltage increases and the time of exposure increases. Of these factors, time may be more important in human electrical burns than voltage.

The amount of current passing through a conductor also varies as the size of the conductor increases. When the current flows through a smaller area, the intensity of the current increases. This leads to the familiar contact burn on a finger touching the current source, while a foot immersed in water may have no burn at all.

An equal number of deaths from high- and low-voltage electrocutions occurred in a study of 220 fatalities.[14] This study did not discuss the duration of exposure.

Four separate tissue effects due to the passage of the current can be found in the electrical burn: 1) direct tissue heating (Joule heating); 2) contact burns (entry and exit point burns); 3) arc burns; and 4) thermal burns from ignition of clothing.

In addition to these tissue effects, distant effects on the body from the effects of the electrical passage are found in the cardiac and respiratory center effects, the nervous system effects, and the late effects. Additionally, mechanical trauma may result from the contractions induced by the current or from a fall caused by loss of consciousness.

Tissue Heating Effects

As noted, passage of current through the tissues will cause heating of the tissues. This heating can cause vascular spasm and thrombosis, peripheral and central neurologic injury, and muscle necrosis. As the current continues to heat the tissues, it literally cooks the tissues from within. This thermal injury is similar to a crush injury.

Different tissues have varying resistance to electric current. The least resistance is, of course, encountered in the nervous system, which is designed to carry electric current. Blood vessels and muscles carry electricity well because of their high electrolyte composition. Skin, tendon, fat, and bone are rather resistant to the flow of electricity. Unfortunately, if the voltage is high enough, the current will flow through all resistant structures, and the heating becomes greatest in the most resistant tissues. When the contact is prolonged, fat and tendons will melt. Bone heats, and this may cause periosteal damage.

Muscle necrosis, or rhabdomyolysis, second to electrical injury has potentially serious systemic consequences.

Classically, the diagnosis of rhabdomyolysis is made by the finding of dark urine that is strongly positive for hemoglobin but without red cells or red cell fragments. Such urine should be quantitatively assayed for myoglobin. The finding of creatinine phosphokinase (CPK) levels in excess of 5000 units clinches the diagnosis. In most cases, the CPK is greater than 20,000 units.

Contact Lesions

The contact lesions (entry and exit) consist of three characteristic areas: a charred, blackened center; a middle zone of grayish white coagulation necrosis; and a periphery of partial tissue damage. *(See Figures 1a and 1b.)*

As noted earlier, these contact lesions are due to the current density and local tissue heating at the points of entry and exit. If the patient has contact with the current source over a wide area, either an exit or entry point may be absent. Current traveling through a dry finger can create an impressive burn, whereas the patient sitting in a tub of water may have no exit or entrance burns. Extensive electrothermal damage at the entry and exit points indicates that there has been significant current flow and the child has an increased risk of deep tissue damage.

Lip Burns. Specific mention must be made of lip burns. These injuries occur most frequently in 1- and 2-year-olds, and generally (60%) in boys. These burns can damage the mouth and lips, leaving a permanent scar. They almost uniformly occur in toddlers who bite on an electric cord (29.9%) or suck on an extension cord socket (53.7%). *(See Figure 2.)* Sucking an electric outlet accounts for only 1.8% of these burns. Worn insulation on cords may contribute to the incidence of such injuries.

Lip burns most commonly occur when an arc is formed between two wires and the child's electrolytic saliva conducts the electricity. The saliva rapidly is heated by the current source and a burn occurs. These injuries are local in nature and have no systemic involvement. Such injuries are characterized by local tissue destruction and hemorrhage that may occur 5-10 days following the accident. They may be associated with lip contractures bony injury, dental injury, and delayed bleeding from the labial artery. An electric burn of the lip should be managed by a surgeon familiar with this injury. The family of any child who is discharged should be counseled about the possibility of and care for hemorrhage within 5-10 days of discharge. Discharged children should have a scheduled follow-up.

Flexor Crease. Flexor crease burns may occur across any joint whenever the current produces tetanic contractions of the adjacent muscles. The contractions put the joint in extreme flexion, and this forces the skin from either side of the joint into close proximity. The close apposition allows current to travel from one skin surface to the other, burning both. Flexor crease burns commonly are seen when the hand becomes stuck to an electrical source and tetanic muscle contractions cause the elbow to flex, forming electric current arcs from the forearm to the biceps.

Arc Burns

The second potential effect from an electrical injury is the arc burn, which results from the external passage of high voltage current. This spark consists of ionized, heated plasma with temperatures from 5000-20,000°C and arcs about one inch for each 10,000 volts. It is the arc burn that causes the charred, central portion of the electrical injury with high voltages. The severity of the surface burns will depend upon the proximity of the skin to the arc. Arc burns may be seen at both entry and exit points if very high voltage is involved.

Arc burns usually do not result from household voltage (even with 220 volts) because the arc formed is so small.[15] Arc burns are, therefore, not a significant component of household burns.

Faraday Effect. Very high-frequency, alternating current tends to flow on the outside of a conductor rather than through the conductor. This phenomenon was first described by Michael Faraday and is now called the Faraday effect. This effect means that little deep tissue effects are found with radio frequency electrical currents. Indeed, instructors demonstrate the Faraday effect using very high-frequency, high-voltage current in science museums and physics classes on a daily basis.

Thermal Burns

The exceedingly hot plasma arc also can ignite flammable materials such as clothing. This creates the third type of local burn effect, the thermal burn. Thermal burns should be treated in conjunction with the local burn unit or burn surgeon.

Figure 2. Lip Burn

An oral commissure burn may occur when a child chews on a live electrical cord.

Clinical Effects

Current Flow Sensation. Humans are very sensitive to the flow of electric current. The most sensitive organ is the tongue, where the first sensations are detected at only 45 microamperes. When 60-cycle current is passed through the body, an unpleasant tingling sensation is felt at about 1.1 milliamperes current flow. Direct current requires substantially more current to be detected and is felt as increasing warmth.

Muscular Contraction. With increasing flow of alternating current, the unpleasant tingling sensation soon is replaced by muscular contractions. As a sufficiently high level of alternating current is reached, the subject is no longer able to release a grasp on the conductor (the "let go current").

This tetanizing effect on muscles is most pronounced in frequencies from 15-150 cycles per second. The strong muscle contractions cause frequent and well-documented fractures and dislocations, particularly bilateral scapular fractures and shoulder dislocations. As the frequency increases above 150 cycles per second, the tetanizing effects fall off and are not noted above 500,000 cycles per second.[16]

Since direct current does not change polarity, there is no tetany. Direct current does not have a "let-go" threshold, it produces continuous muscle contractions and heat sensations. The abrupt exposure to direct current may cause a muscle contraction that may throw the victim back some distance.

Cardiovascular and Respiratory Effects. Most of the mortality involved in electrical injuries, whether from high- or low-tension lines, is due to cardiovascular and respiratory effects. When the current path crosses either the respiratory center or the heart, then either respiration or the heart may be affected. The path the current takes through the body is a major determinant of morbidity and mortality but it is very difficult to predict. When high voltages travel hand-to-hand, traversing the chest, mortality may be as high as 60%. The mortality associated with high voltages passing hand-to-foot and foot-to-foot is approximately 20% and 5%, respectively.

Many mechanisms have been proposed to account for the myocardial and conducting tissue damage seen in electrical injury. These include the induction of coronary artery spasm, direct thermal injury, ischemia secondary to arrhythmia-

Table 3. Effects of Various Current Densities

CURRENT DENSITY	EFFECTS
1 mA	Threshold of perception
5 mA	Accepted as maximum harmless current
10-20 mA	"Let go current"
50 mA	Pain, fainting, exhaustion, and mechanical injury. Heart and respiratory function are normal.
100-300 mA	Ventricular fibrillation threshold
300 mA-4 A	Sustained myocardial contraction followed by a normal cardiac rhythm or ventricular fibrillation. Ventricular fibrillation is common. Respiratory paralysis occurs and is temporary. Burns may result if current density is high.

induced hypotension, chemoreceptor stimulation producing acute hypertension, catecholamine-mediated injuries, and coronary artery ischemia as part of a generalized vascular injury.[17]

As many as one-third of patients with significant electrical injury may have some significant cardiac component. The shock produces ventricular fibrillation with alternating current and asystole with direct current. If the respiratory center is involved, a respiratory arrest may be produced. Indeed, early research on cardiopulmonary resuscitation was motivated by the effects of electrical current on the heart and respiratory system and funded by the electrical utility companies.

Ventricular fibrillation is the most common cause of death in both high and low voltage electrical injuries.[18]

Multiple experimental studies show AC to be more dangerous to the heart than DC.[19] These animal studies consistently showed that DC injury is less hazardous and produces fewer arrhythmias, myocardial infarctions, and lethalities. One researcher felt that the type of irregularity is related to the current density to which the heart is exposed.[20] At current density up to 25 mA, the cardiac rhythm is unchanged. At about 25-75 mA, the heart stops momentarily and resumes an irregular heart beat. At around 75-100 mA, ventricular fibrillation develops and persists unless stopped by defibrillation. Beyond 4 A, the heart locks in spasm, but resumes a normal beat provided the current is discontinued before ischemic damage. *(See Table 3.)*

Additional studies on the effects of frequency on the ventricular fibrillation threshold in animals show that the greatest hazard occurs at about 50-60 cycles—the frequency of power lines.[21]

It should be emphasized that these currents are surface currents. With a low-resistance conductor in the heart, alternating current "leakage" into the system would be dangerous in an amount that is a hundred times less than that required to produce fibrillation via surface electrodes. The increased danger of electrodes directly on the heart has been recognized for many years.[22]

The respiratory arrest often persists after the patient's ventricular fibrillation has been corrected. Ventilation must be continued until the patient has spontaneous respirations.

Electrocardiogram (ECG) findings are usually that of a diffuse coronary ischemia. The electrical injury often does not correlate well with standard patterns of ischemia, since the injury may not follow the coronary vessels. Posterior myocardial injury is a frequent ECG finding of ischemia, however.

Electrical injury may lead to long-term disease of conducting tissue or myocardial damage.[23] Subtle abnormalities, particularly of sinus node function, may pose diagnostic difficulties and may not present for many years. Long-term follow-up of patients with serious electrical burns may help to define the clinical spectrum of cardiac presentations of electrical injury.

Central Nervous System Effects. Central nervous system (CNS) dysfunction is a prominent feature of high-tension electrical injuries. Both acute and delayed central and peripheral neurologic effects have been described.

Acute CNS complications include respiratory arrest, seizures, mental status changes, coma, amnesia, quadriplegia, and localized paresis. Motor deficits appear to occur more frequently than sensory losses. If the current passes through the skull, coagulation of the brain parenchyma, epidural and subdural hematomas, and intraventricular hemorrhages may occur.

Peripheral nerve injury may result from the direct heating effects of the passage of current through the nerves or vascular damage from the current. Compartment syndromes, as discussed below, frequently compress nerves and cause subsequent peripheral neuropathy.

Unusual manifestations of electrical injury are delayed neurologic complications. These delayed complications include ascending paralysis, transverse myelitis, and amyotrophic lateral sclerosis. Mechanisms of these late manifestations are unclear and the prognosis for recovery after development of late complications is not good.[15]

Renal Injuries. The renal manifestations found in electrical injuries are similar to those found in crush injuries. Electrical injuries are associated with a higher incidence of renal failure than burns. Myoglobinuria occurs frequently and is proportional to the amount of muscle damaged by the electric current. As a direct toxin to the kidney, myoglobin causes acute renal failure.

Vascular Injuries. Vascular injuries fall into two broad categories: those due to the passage of the current and those due to the damage to the surrounding tissue.

Compartment Syndrome. The loss of intravascular fluid into an extremity damaged by high current flow results in marked swelling of the contents of the relatively inelastic fascial compartments. The fascial investments limit the amount of swelling with a resultant rising of the interstitial pressure and a consequent reduction of capillary perfusion pressure. The consequences of the decrease in capillary perfusion are tissue hypoxia, resultant increased capillary permeability, and extravasation of further fluid. This vicious cycle results in increased interstitial pressure of the compartment.

Since this is primarily an ischemic phenomenon due to damage to the surrounding tissues, it is potentially a reversible injury. After six hours of this cycle, however, the muscle damage is usually irreversible.[16] The compartment syndrome can be recognized by the classic symptoms of peripheral vascular disease: pain, pallor, paresis, and pulselessness. The most consistent finding is deep diffuse pain that is out of proportion to the purported injury. This may be difficult to assess in child with an electrical injury. Passive movement of the extremity frequently intensifies the pain and may be an early indication. Absent pulses, capillary refill, and pallor are late signs of a compartment syndrome.

In a flame burn or an electrical burn with a component of thermal injury, these diagnostic signs may be difficult to apply because the leathery eschar may render the skin insensitive. The treatment of both flame burns and electrical injuries with potential compartment syndromes is identical. Escharotomy and possibly fasciotomy is indicated early to ensure salvage of the ischemic limb. Any conservation of tissue in the burned upper extremity is of great significance in reconstruction. Hand and digital escharotomy, in particular, reduces the frequency of phalangeal losses.[17,24]

Another complication of the compartment syndrome is a consequence of the necrosis of muscle by ischemia. The resulting breakdown of muscle releases CPK and myoglobin. The results are indistinguishable from the muscle injury due to primary electrical burn of the muscle.

Myoglobinuria can be treated with an initial bolus of 25 gm of mannitol in the adult or 0.5-1 g/kg in the child. This bolus should be followed with a drip of 0.5 g/kg/h. Fluid resuscitation *must* be assured when using this drug. Acidosis should be corrected with bicarbonate and is best guided with arterial blood gases.

Direct Vascular Trauma. Because blood vessels are basically pipes carrying electrolytes, they carry electricity efficiently. Electrical energy tends to flow along blood vessels and may cause severe injury. The veins tend to thrombose first because they are low flow and do not dissipate heat as well as the higher flow arterial pathways. The resulting flow into an extremity without outflow provides rapid swelling, capillary damage, and subsequent compartment syndrome.

Other Complications. *Cataracts.* In electrical injuries involving the head and neck, the delayed development of cataracts is not uncommon. Cataracts caused by electric injury often occur 4-6 months after the accident and usually are associated with a point of contact near the affected eye. Those at highest risk are patients who have been exposed to greater than 1000 volts and those with injuries about the head or neck.[25] The incidence in these patients is between 5% and 20%. Ophthalmologic referral and long-term follow-up is indicated in all high-voltage injuries of the upper chest, neck, and head.

Abdominal Injury. A wide spectrum of intra-abdominal complications have been reported following high-voltage electrical injury. These injuries may result from either the passage of electrical current through the abdominal viscera or vessels supplying it or through direct injury to the intra-abdominal structures from an entry or exit point. Nausea, vomiting, and adynamic ileus are seen in up to 25% of electrical injuries. Stress ulcer (Curling's burn ulcer) is frequently reported in conjunction with severe electrical injuries. Injuries to the pancreas, gallbladder, and intestines all have been reported in association with major electrical burns.[26] Bowel injuries are particularly troublesome, because ascertaining viability of tissue is often difficult. Both wound and bowel anastomoses have a high frequency of dehiscence after electrical injuries.[27]

Fractures and Bone Complications. Patients with an electrical injury must be inspected for fractures and dislocations caused by severe muscle contractions. Falls after the shock also may be associated with fractures.

The high resistance of bone to the passage of the electrical current may result in local bone destruction that is difficult to diagnose at the time of initial debridement of the wound. Long-term complications of bony areas are common and should be suspected.

Infection. Infection secondary to tissue necrosis is a common complication of the electrical injury and may be the most common cause of death in those who survive the initial resuscitation period. With the large amounts of necrotic tissue found with major electrical injury, patients are at increased risk for clostridial infections to include both gas gangrene and tetanus. Topical antibiotics rarely penetrate sufficiently and debridement is preferable. A burn surgeon should be consulted prior to administration of any antibiotics for prophylaxis. Tetanus prophylaxis should not be overlooked.

Pregnancy and Electrical Shock. Management of the pregnant woman following an accidental electric shock should address the well-being of both the mother and the fetus. Multiple prior case reports have noted that electrical shock to the mother is likely to be fatal to the fetus in as many as 76% of shocks.[28] These were case reports and, thus, biased to more severe injury. Interestingly, the only prospective cohort study of electric shock injury in pregnancy noted that low-voltage injuries are unlikely to damage the fetus.[29] In their study of 31 patients, there were only two miscarriages following electric shock, well within the expected number for that many pregnancies. The authors hypothesize that prior studies suffered from substantial reporting bias.

A potential concern for the pregnant woman in what looks like a trivial electric shock is the remote possibility of late cardiac arrhythmia. An electrocardiogram should be done in any woman who has had an electric shock of greater than 220 volts and probably any time if she was wet or had tetany or if a current pathway that crossed the heart. Cardiac monitoring for 24 hours should be done in any woman with an abnormal initial electrocardiogram or with a history of loss of consciousness or any cardiovascular symptoms. To detect fetal movement and assure that the fetus is still alive, fetal heart Doppler monitoring should be done after the electric shock.

Prehospital Management

The most important factor in the prehospital management of the electrical injury is the safety of the rescuer. If the injury occurs because a child is playing with a power socket, there is usually no danger to the rescuer. Likewise, when an electrical appliance has contacted water, it only needs to be unplugged. The dangerous situation for the rescuer occurs when high-voltage power lines are involved in the accident. If the power line is intact, this is not usually a problem. If the power line is down, there has been an accident, or the current source is still active, then the rescuer needs special equipment and training. If circuit breakers are readily available, these should be shut down.

Numerous items have been advocated for removal of downed power lines including brooms, ropes, sticks, and tree branches. All of these techniques are hazardous. Special-purpose electrical gloves, if tested and kept in good condition, will allow handling of the downed power line. Unfortunately, gloves that are not inspected and sealed prior to use may have unacceptably dangerous current leaks. "Hot sticks" and polypropy-

Table 4. Treatment Algorithm for Major Electrical Injuries

PERFORM PRIMARY ASSESSMENT

- Check ABCs
- Establish airway if necessary
- Oxygen
- Ventilate, if necessary
- Establish intravenous access
- Give CPR if necessary
- Immobilize cervical spine
- Give fluid resuscitation as needed
- Monitor cardiac function

PERFORM SECONDARY ASSESSMENT.

- Order lab tests, x-ray films, and CT scans as indicated by the secondary assessment
- Monitor urine output
- Give tetanus prophylaxis, if needed
- Treat specific injuries
- Treat entry/exit wounds and burns

ADMIT PATIENTS WHO HAVE THE FOLLOWING

- Cardiac arrest
- Major bums or trauma
- ECG abnormalities
- Lip commissure burn
- Loss of consciousness
- Hypoxia
- Myoglobinuria or markedly elevated CPK
- Transthoracic current path
- Exposure to high voltage (> 1000 volts)

lene throw lines are somewhat safer when dry but also conduct well when wet. None of these techniques is safe when dealing with the very high-tension line. The safest technique is to allow the electric utility company to remove the downed power line. This may mean leaving a victim until the utility company can respond.

Victims in cars, trains, and buses pose a special circumstance. They are actually safe and should be advised to stay where they are, unless there is another reason, such as fire, which forces an evacuation.

As soon as the patient has been removed from the current source, the ABCs assume priority. Oxygenation, cardiopulmonary resuscitation, and intubation remain the mainstays of care. Arrhythmias will respond to the same medications as for any medical emergency. Cervical spine immobilization is indicated if there is any suspicion of cervical injury by either mechanism of injury or findings. The EMS provider should always presume cervical injury in the unconscious patient with an electrical injury.

Since cardiac and vascular injuries are so common in the major electrical burn, these patients should be carefully monitored in the field. Pulses and capillary refill should be checked in all extremities, documented, and repeated at frequent intervals. Cardiac monitoring is essential for all patients with major electrical injuries.

Fluid requirements in the major electrical burn are often far greater than the surface burns would indicate. Large-bore intravenous lines should be started in at least two locations. Access should be avoided in extremities which have entrance or exit points, if possible. Slowly developing vascular thrombosis will render intravenous lines in involved extremities worthless. Either Ringer's lactate or normal saline is appropriate for an intravenous solution.

The major electrical burn victim should be transported by the most expeditious means available to the closest facility able to handle the special problems of the electrical injury. Any patient with a serious electrical injury should be sent to a burn center that is equipped to handle the major, multiple systems injuries involved. These centers also usually have integral physical and occupational therapy and can manage the patient who may require amputations and subsequent therapy and counseling.

Minor electrical injuries can be safely transported to the closest medical facility that is equipped to deal with the child. These patients should have electrocardiographic monitoring during transport. An intravenous line is discretionary. Cervical immobilization is not usually necessary unless there has been a loss of consciousness.

Emergency Management

Hopefully, the diagnosis of an electrical injury will be obvious. In suspected cases, with unconscious patients, a careful examination of the patient's body may show characteristic burns of exit and entry wounds. Kissing burns of the flexor creases at the wrist, elbow, or axilla may help affirm the diagnosis. The palmar surface of the hands and fingers and the mouth are the most likely site for entrance wounds in toddlers. In older children, scalp wounds may be involved. In rare cases, a history of finding the patient in a tub or shower with an electric appliance with the patient may give the diagnosis.

High-Voltage Injuries. The high-voltage injury is an infrequent event with substantial morbidity and mortality. Upon arrival at the ED, the patient's cardiac and respiratory status should be reassessed and corrected as needed. *(See Table 4.)* The estimated voltages involved, contact times, and prior medical illnesses, history, and allergies should all be ascertained. The patient should be carefully examined for other actual and potential injuries.

Because many patients will be persistently apneic, the patient should be ventilated with high-flow oxygen and intubation strongly considered. The cervical spine should be immobilized prior to intubation.

An abnormal neurologic status may result from intracerebral hemorrhage, blunt injury, vascular spasm, hemorrhage, electrical effects, or thermal injury to the brain. Deterioration of the level of consciousness should prompt evaluation for an intracranial injury and rapid cranial computed tomography scanning.

Radiography of the cervical spine and skull should be considered in those patients who have sustained falls or cranial burns. A chest x-ray is useful as a baseline. Other specific x-rays are indicated in those with complaints or findings of fracture or dislocation.

If not already in place, two large-bore intravenous lines should be started in uninvolved extremities. Blood should be drawn for arterial blood gases, complete blood count, electrolytes, blood sugar, creatinine, blood urea nitrogen, CPK, prothrombin time, partial thromboplastin time, calcium, uric acid, and phosphates at a minimum.[30-32] A type and crossmatch of blood should be considered in all high voltage electrical injuries. A Foley catheter should be inserted and urine sent for analysis and myoglobin determination.

After the ABCs are assured, a complete physical survey to evaluate the extent of injuries should be done. The wounds and associated fractures and dislocations should be managed with usual techniques. Neurologic deficits should be recorded and peripheral pulses confirmed with Doppler flow techniques.

Fluid Replacement. Fluid replacement is essential and adequate rates are far more difficult to estimate than with the thermal injury. A crystalloid challenge of 20- 40 mL/kg is an appropriate starting point for fluid replacement. Fluid losses are greatest in the first 24 hours, and urine output and vascular pressure monitoring should be used as a guide for fluid replacements in all major electrical injuries. Urine output should be maintained at about 0.5 to 1.5 mL/kg/hr. Serial measurements of the hematocrit and electrolytes may aid in estimation of the fluid requirements.

As previously noted, hypovolemia, combined with myoglobinuria, will lead quickly to an acute tubular necrosis. Hypovolemia may be quite pronounced in these patients due to the large masses of tissue damaged. Intravenous bicarbonate to alkalinize the urine may be used based upon appropriate urine and blood pH measurements. A blood pH below 7.2 should mandate sodium bicarbonate administration to correct the pH in the electrically injured patient.

Debridement. Debridement is best done by the burn surgeon who is going to manage the patient on a long-term basis. Muscle debridement is particularly difficult because the current flow is often not uniform and leaves spotty areas of necrosis within muscles. Amputation and repair of damage should be left to the burn specialist.

Remember that the compartment syndrome is far advanced when the examiner waits for signs of pulselessness. Measurement of compartment pressures and prompt fasciotomy for decompression are the mainstays of therapy in this common complication of electrical injuries. Fasciotomy and escharotomy should, however, be performed whenever there is vascular or respiratory compromise; do not wait for a burn surgeon or transfer to a burn unit.

Low-Voltage Injuries. Unlike the extensive coverage in modern medical literature about major injuries, minor electrical injuries have limited coverage in the usual medical text or review article. In one recent exhaustive review totaling some 44 pages, scant attention was paid to the low voltage minor injury. Indeed, when talking about low-voltage injuries the author pointed out that 400-600 volt transportation accidents were defined as low voltage injuries.[33] When injuries with this voltage range are reviewed by other authors, there is indeed substantial morbidity and mortality, enough that the article proposes an intermediate voltage category or redefining high voltage to include 500+ volts.[34]

This emphasis on high-voltage injury is truly referral bias, since the vast bulk of household electrical injuries are neither admitted nor require any surgery. In one series of 145 electrical burns, there were 128 low-voltage injuries admitted.[35] Of these patients, only the patients with high-voltage injuries had any complications beyond 24 hours. All patients with complications had those complications on arrival in the ED. The authors suggest that if there are no cardiac complications on arrival to the ED with a low-voltage injury, then the patient is unlikely to develop any cardiac problems. Other authors echo this feeling that these patients are unlikely to develop other systemic problems.[2,4,5,36-38]

Typical findings are local burns which are limited to points of contact where the current entered or exited the body, and involve mainly distal parts of the limbs or the skull.

An ECG and observation for a few hours should be all that is needed for most minor electrical injuries.[2-5,8] Referral to a burn unit appears to be unnecessary. Obviously, the local injury should dictate the need for consultation and more extensive therapy and evaluation. Lip injuries should be referred to a plastic surgeon, orofacial surgeon, or surgeon familiar with management of this injury.

Tetanus. The burn is a tetanus prone wound and electrical injuries are no exception to this. Tetanus immunization should be ascertained and corrected if needed. Standard tetanus prophylaxis is appropriate.

Laboratory Determinations. The laboratory investigations that are most frequently recommended for evaluation of the electrical injury include CPK, CPK isoenzymes, and urinalysis with measurement of urinary myoglobin

Creatinine phosphokinase. Breakdown of the muscle leads to elevated CPK and myoglobin in both serum and urine. Mild elevation of the CPK is quite common in even minor electrical injuries. Markedly elevated CPK reflects the deep muscle damage found with high tension electrical injuries.

In low-voltage burns of children, CPK may be modestly elevated, but this does not usually correlate with any negative outcome or complication.[3] In one study, 16 of 88 (18.1%) had abnormal CPK determinations.[8] Therefore, it could be inferred that a modest elevation in total CPK level is not a diagnostic indicator of muscle injury in the low-voltage electrical burn patient with small surface area burns.

Urinalysis. Urinalysis with determination of the urinary myoglobin is recommended, but multiple studies have shown few abnormalities and none that required therapy in patients with minor electrical injury.[3,8] This is not true for the patient with a high-tension electrical injury or when the patient has been partially immersed in water during the electrical injury.

Local Therapy. Many authorities advocate mafenide acetate (Sulfamylon) as a topical agent in the electrically injured patient due to its greater penetration through the skin.[30,39] If this is not readily available, silver sulfadiazine may be substituted. Metabolic acidosis and pain at the site of application are frequent complications of mafenide acetate. Lip and oral cavity burns should be cleansed and dressed. Splints and tube feedings may be prescribed for some oral electrical burn patients.

The patient's family should be cautioned about the incidence of labial artery bleeding associated with oral electrical burns. The family can be taught the technique of direct pressure for bleeding control. These careful discharge instructions change the whole character of the repeat visit if the child does suffer a delayed bleed.

Admission or Transportation Decisions

The major electrical burn injury is difficult to treat and carries abundant complications and pitfalls. It is, perhaps, the one injury for which the emergency physician should consider rapid stabilization and transport to a specialized burn center to be the most appropriate therapy. Any patient with significant electrical injuries should receive the care offered by trained burn specialists with equally trained supporting staffs.

During transport of these patients, they should be monitored for both cardiac arrhythmias and hemodynamic stability. Unlike the thermal injury, these patients are quite likely to become hypovolemic early in transport. Although airway edema is not potentially as dangerous in the electrical burn, cardiac dysrhythmias and late apnea are more common.

Relatively benign appearing wounds can be associated with life-threatening cardiac arrhythmias, limb-threatening vascular compromise, and acute renal failure secondary to myoglobinuria. These concerns have led to the widespread practice and recommendations for admission of all electrical bums for 24-48 hours of observation, cardiac monitoring, and laboratory evaluation, with no distinction between patients injured by low-voltage vs. high-voltage injury.

Where there is little argument about management of the severe high-tension electrical injury, care of the minor electrical injury is more controversial. There is a growing body of evidence that healthy children with household voltage injuries with a small partial-thickness burn, a normal electrocardiogram, and who have no evidence (over the first few hours) of cardiac or neurovascular injury, do not appear to need hospital admission.[2-5,37]

Other associated injuries may require admission but should be assessed independently. Certainly, the oral low-voltage electrical burn may be successfully managed by many plastic or oral surgeons. Low-voltage injuries rarely cause deep tissue destruction. The smaller, lower voltage isolated wound of an extremity also may be successfully managed by orthopedic, general, or plastic surgeons. Guidelines for these minor burns should be arranged in advance to expedite the care and decisions.

Prevention

There are two dominant themes in pediatric electrical injuries.[40] Household electrical cords are the major hazard for electrical injuries in children younger than 12 years of age. Oral contact was by far the most common etiology in this younger age group. Interestingly enough, most injuries were caused by electrical extension cords. Although many campaigns have focused on wall socket safety, and blank plugs are commonly recommended by pediatricians, wall sockets caused less than half of the injuries that extension cords caused.

Extension cords are found in many households and the digital age has increased the number in use. Emergency physicians could help by encouraging parents to discard old, frayed, and damaged extension cords.

In children older than 12 years of age, greater than 90% are high tension electrical injuries. Most of these were associated with the well-known, risk-taking behaviors of teenagers. Children who climb trees, poles, transformer towers, and high tension line towers can also sustain fractures during falls from these high places, when electrical injuries occur.

Conclusion

Since the vast majority of electrical injuries are preventable, injury prevention should be paramount. A careful history and physical examination should characterize the injury as high-voltage or low-votage. High-voltage injuries require aggressive resuscitation. The majority of low-voltage injuries require a comprehensive assessment and appropriate care of any tissue injuries.

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Physician CME Questions

1. Of the following tissues, which has the highest resistance to the passage of electricity?
   A. Muscle
   B. Bone
   C. Dry skin
   D. Nerve
   E. Blood

2. Which of the following is not a determinant of the amount of damage caused by an electrical injury?
   A. Tissue resistance
   B. Pathway of the current
   C. Age
   D. Amount of current passing through the tissue
   E. Frequency of the current

3. Cardiac monitoring is essential in all patients with major electrical injuries.
   A. True
   B. False

4. A 2-year-old child presents to the ED with an electrical burn to the lip from chewing on an electrical extension cord. What late complication should you counsel the parents to be wary of?
   A. Bleeding
   B. Cataracts
   C. Personality changes
   D. Intravascular thrombosis
   E. Compartment syndrome of the lip

5. Which of these electrical accidents would not be expected to have either an exit or an entrance wound?
   A. A 13-year-old male who touched two contacts in a 440-volt junction box with his hand.
   B. A 15-year-old female who dropped her hair dryer into her bath.
   C. A 2-year-old female who chewed on an electrical extension cord.
   D. A 14-year-old male who attempted to retrieve a Mylar aluminized kite from the overhead high tension lines.
   E. A 2-year-old who stuck a key in an electrical outlet.

6. Which of the following statements is true?
   A. Cardiac monitoring is essential for all patients with major burns.
   B. Antibiotics should be given to all children with electrical injuries.
   C. Patients with electrical injuries should be fluid restricted.
   D. Muscle debridement should be done in the ED.

7. Which of the following tests or studies is not indicated in the evaluation of the unconscious pediatric patient with a serious electrical injury from a high voltage source?
   A. Creatinine phosphokinase (CPK)
   B. Cervical spine series
   C. Skull films
   D. Electrocardiogram
   E. Urinalysis

8. At what current density should ventricular fibrillation be expected?
   A. 10-20 mA
   B. 50 mA
   C. 100-300 mA
   D. 300 mA-4 A

In Future Issues: Group A Beta-Hemolytic Infections in Children