Electrical injuries

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Electrical injury is a relatively infrequent but potentially devastating form of multisystem injury with high morbidity and mortality. Most electrical injuries in adults occur in the workplace, whereas children are exposed primarily at home. In nature, electrical injury occurs due to lightning, which also carries the highest mortality. The severity of the injury depends on the intensity of the electrical current (determined by the voltage of the source and the resistance of the victim), the pathway it follows through the victim's body, and the duration of the contact with the source of the current. Immediate death may occur either from current-induced ventricular fibrillation or asystole or from respiratory arrest secondary to paralysis of the central respiratory control system or due to paralysis of the respiratory muscles. Presence of severe burns (common in high-voltage electrical injury), myocardial necrosis, the level of central nervous system injury, and the secondary multiple system organ failure determine the subsequent morbidity and long-term prognosis. There is no specific therapy for electrical injury, and the management is symptomatic. Although advances in the intensive care unit, and especially in burn care, have improved the outcome, prevention remains the best way to minimize the prevalence and severity of electrical injury. (Crit Care Med 2002; 30[Suppl.]:S424–S430)

Key Words: high- and low-voltage electrical injury; lightening; multiple system organ failure

Although electricity is a relatively recent invention, humans have always been exposed to electrical injuries caused by lightning. The devastating power of lightning was viewed with awe, and understandably, it was attributed to supernatural powers. Zeus, the ruler of the ancient Greek gods, was characteristically depicted holding thunderbolts, which he used as warning or punishment against those who disobeyed him. The discovery and widespread use of electricity in the mid-1800s took away (to some extent) the supernatural aura surrounding electrical power but, in return, made electrical injury a common problem at work or at home, with the first electrical fatality recorded in France in 1879 (1).

Despite significant improvements in product safety, electrical injury is still the cause of many fatalities and of considerable morbidity. Electrical injuries (excluding lightning) are responsible for >500 deaths per year in the United States. A little more than half of them occur in the workplace and constitute the fourth leading cause of work-related traumatic death (5–6% of all workers' deaths) (2). Electrocutions at home account for >200 deaths per year, and they are mostly associated with malfunctioning or misuse of consumer products (3). Electrical injuries are also the cause of considerable morbidity. Electrical burns account for approximately 2–3% of all burns in children that require emergency room care (>2000 cases per year). The vast majority of electrical burns in children take place at home and are associated with electrical and extension cords (in about 60–70% of the incidents) and with wall outlets, which account for another 10–15% of the cases (3). Lightning is responsible for an average of 93 deaths annually in the United States, whereas the morbidity is estimated to be 5 to 10 times higher than that due to other forms of electrical injury. (4)

Because severe electrical injuries tend to occur primarily in the workplace, they usually involve adults, and therefore, they account for only a small percentage of the overall number of admissions to pediatric intensive care units (ICUs). However, considering that both the home and work environments are full of electrically powered devices, the potential of accidental injury is ever present, and it is necessary for the intensivist to know the characteristics and the principles of management of this type of injury. Of particular importance is the possibility of iatrogenic electrical injury in the ICU (and in the operating room and electrophysiology suites), where several procedures are performed utilizing high-voltage energy for diagnostic and therapeutic purposes (e.g., defibrillators, pacemakers, electrosurgical devices) (5–8).

PRINCIPLES OF ELECTRICITY

Electricity is the flow of electrons (the negatively charged outer particles of an atom) through a conductor. An object that collects electrons becomes negatively charged, and when the electrons flow away from this object through a conductor, they create an electric current, which is measured in amperes. The force that causes the electrons to flow is the voltage, and it is measured in volts. Anything that impedes the flow of electrons through a conductor creates resistance, which is measured in ohms (1). An electrical injury will occur when a person comes into contact with the current produced by a source. This source can be a human-made one (e.g., the power line of a utility company) or a natural one, such as a lightning.

Electrical power is generated and transmitted via a system of three conductors with the same voltage but with waveforms that reach their peak at a different phase. This three-phase system allows for a more efficient generation and transmission of power. Power lines used by utility companies are classified according to their voltage from phase to phase, and they range from "low" (when they carry

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DOI: 10.1097/01.CCM.0000035099.55766.EA

<600 V) to "ultrahigh" (with voltage of >1 million volts). Utility power lines with high voltages tend to be located in sparsely populated areas, and therefore, the possibility of an accidental contact with them is relatively limited for the general population (9).

Through a succession of transformers, the voltage is gradually reduced, and the power lines that distribute electricity for homes, buildings, and the general industry carry low voltage, defined by the National Electrical Code as <600 V. Most homes and buildings in the United States and Canada have a 120/240 V, single-phase system that provides the 240 V for the high-power appliances and the 120 V for general use. The latter accounts for most of the accidental injuries. The household voltage in most other countries (Europe, Australia, Asia) is usually higher (220 V) (9). Table 1 shows the different physiologic effects of electrical currents generated by common household voltage.

Electrical current exists in two forms, the alternating current (AC) and the direct current (DC). In the former, the electrons flow back and forth through a conductor in a cyclic fashion. This type of current is the most commonly used in households and offices, and it is standardized to a frequency of 60 cycles/sec (60 Hz). When the current is direct, the electrons flow only in one direction (1, 10). This type of current is produced by various batteries and is used in certain medical equipment such as defibrillators, pacemakers, and electric scalpels. Although AC is considered to be a far more efficient way of generating and distributing electricity, it is also more dangerous than DC (approximately three times) because it causes tetanic muscle contractions that prolong the contact of the victim with the source (10). This issue of safety over efficiency became a dominant one in the early days of electricity when Thomas Edison (who developed and popularized DC) was fighting against George Westinghouse (who developed AC). To illustrate the dangerous nature of AC, Edison convinced the New York State legislature to use AC for the first death penalty by electrocution (coined as "Westinghoused").

Lightning is a form of DC that occurs when the electrical difference between a thundercloud and the ground overcomes the insulating properties of the surrounding air. The current of a lightning strike rises to a peak in about 2 μsec, and it lasts for only 1–2 msec. The voltage of a lightning strike is in excess of 1,000,000 V and it can generate currents of >200,000 A. Transformation of the electrical energy to heat can generate temperatures as high as 50,000°F. However, the extremely short duration of lightning prevents struck objects from melting (11, 12). Table 2 presents a comparison between the major characteristics and effects of lightning vs. high- and low-voltage electrical currents.

DETERMINANTS OF ELECTRICAL INJURY

Electrical injury involves both direct and indirect mechanisms. The direct damage is caused by the actual effect that the electric current has on various body tissues (e.g., the myocardium) or by the conversion of electrical to thermal energy that is responsible for various types of burns. Indirect injuries tend to be primarily the result of severe muscle contractions caused by electrical injury.

In general, the type and extent of an electrical injury depends on the intensity (amperage) of the electric current (1). According to Ohm's law, the electric current is proportional to the voltage of the source and inversely proportional to the resistance of the conductor: current = voltage/resistance (1). Thus, exposure of different parts of the body to the same voltage will generate a different current (and by extension, a different degree of damage) because resistance varies significantly between various tissues (10). The least resistance is found in nerves, blood, mucous membranes, and muscles; the

Table 1. Pathophysiologic effects of different intensities of electrical current

Current Intensity	Probable Effect
1 mA	Tingling sensation; almost not perceptible
16 mA	Maximum current a person can grasp and "let go"
7–9 mA	"Let-go" current for an average man
6–8 mA	"Let-go" current for an average woman
3–5 mA	"Let-go" current for an average child
16–20 mA	Tetany of skeletal muscles
20–50 mA	Paralysis of respiratory muscles; respiratory arrest
50–100 mA	Threshold for ventricular fibrillation
>2 A	Asystole
15–30 A	Common household circuit breakers
240 A	Maximal intensity of household current (U.S.)

Based on data obtained from References 1, 9, and 10.

Table 2. Comparison between lightning, high-voltage, and low-voltage electrical injuries

	Lightning	High Voltage	Low Voltage
Voltage, V	$>30 \times 10^6$	>1,000	<600 (<240)
Current, A	>200,000	<1,000	<240
Duration	Instantaneous	Brief	Prolonged
Type of current	DC	DC or AC	Mostly AC
Cardiac arrest (cause)	Asystole	Ventricular fibrillation	Ventricular fibrillation
Respiratory arrest (cause)	Direct CNS injury	Indirect trauma or tetanic contractions of respiratory muscles	Tetanic contractions of respiratory muscles
Muscle contraction	Single	DC: single; AC: tetanic	Tetanic
Burns	Rare, superficial	Common, deep	Usually superficial
Rhabdomyolysis	Uncommon	Very common	Common
Blunt injury (cause)	Blast effect, shock wave	Muscle contraction, fall	Fall (uncommon)
Mortality (acute)	Very high	Moderate	Low

DC, direct current; AC, alternating current; CNS, central nervous system.

highest resistance is found in bones, fat, and tendons. Skin has intermediate resistance (10).

From a practical standpoint, one could make a distinction between the external resistance (represented by the skin) and the internal resistance (which includes all the other tissues) of the body. The skin is the primary resistor against the electrical current, with a resistance ranging in adults between 40,000 and 100,000 Ω, depending on its thickness (i.e., the thicker the skin, the higher its resistance). Thus, the intensity of the electrical shock produced by a certain voltage will vary between victims of different sex and age. For example, exposure to the common household voltage (120 V) of an adult laborer with thick, calloused palms whose resistance may be in excess of 100,000 Ω will create a current of approximately 1 mA, which is barely perceptible. In contrast, the same exposure on a newborn infant whose skin is very thin and has a high water content (which markedly lowers its resistance) will probably cause significant injury. Even more important than the thickness is the moisture of the skin (1, 10, 13). Presence of simple sweat may decrease the resistance of the skin to $<$1000 Ω. Wet skin (e.g., electrocution of a person in a bathtub or in a swimming pool) offers almost no resistance at all, thus generating the maximal intensity of current that the voltage can generate. Moist mucus membranes also have negligible resistance, thus maximizing any current with which they come into contact. This causes significant orofacial injury to infants and toddlers who tend to put live wires in their mouths.

The internal resistance of the body comprises all the other tissues and is estimated to be between 500 and 1000 Ω. Although bones, tendons, and fat offer the most resistance to electric current, they are not likely to be contact points. When exposed to electric current, they tend to heat up and coagulate before conducting the current (10). Nerves and blood vessels, on the other hand, are the best conductors: the former because they are designed to carry electrical currents and the latter due to their high water content. It has been suggested that these properties create the path of least resistance for current after it enters the body, thus affecting primarily the nerves and blood vessels. In reality, it seems that internal tissues of the body act as a single resistor and not as a compendium of multiple resistors (14).

The duration of the contact with electrical current is an important determinant of injury. Thus, an electric shock caused by AC will produce greater injury than a shock caused by DC of the same amperage because the DC causes a single muscle contraction that "throws" the victim away from the power source, thus minimizing the injury (10). These differences have practical significance only at low voltages, whereas in high voltages, both currents have a similar effect.

The pathway of the current through the body (from the entry to the exit point) determines the number of organs that are affected and, as a result, the type and severity of the injury. The determination of the electrical pathway is important both for acute management and for overall prognosis. A vertical pathway parallel to the axis of the body is the most dangerous because it involves virtually all the vital organs (central nervous system, heart, respiratory muscles, and in pregnant women, the uterus and the fetus). A horizontal pathway from hand to hand will spare the brain but can still be fatal due to involvement of the heart, respiratory muscles, or spinal cord. A pathway through the lower part of the body may cause severe local damage but will probably not be lethal (15).

Whereas electric shock from a low-voltage line is delivered on contact of the victim with the source, in high-voltage injury, the current is carried from the source to the person through an arc before any actual physical contact is made. The arc may form into or over the body of a person. Arcs can generate extremely high temperatures (up to 5000°C) that are usually responsible for the severe thermal injuries from high voltage (9). Lightning current strikes the victim in an altogether different way than low or high voltage. At least four primary modes of lightning injury have been described: direct strike, in which the major pathway of lightning current is through the victim; side flash, in which a direct strike to an object (or a person) is followed by a secondary discharge from the object to a nearby victim; stride potential, in which the lighting hits the ground and then enters the victim's body from one foot and exits from the other foot; and flashover phenomenon, when the energy flows outside the body, often causing vaporization of surface water with a blast effect to clothing and shoes (9–11).

ELECTRICAL INJURY TO SPECIFIC TISSUES AND ORGANS

Electrical injury should be viewed and managed as a multisystem injury, and there is virtually no organ that is protected against it. Although multisystem injuries can be very extensive, it is damage to the vital organs that may require intensive care and accounts for the fatalities. The most important potential injuries are as follows:

Cardiovascular System

Pathophysiology. Electrical injury may affect the heart in two ways: by causing direct necrosis of the myocardium and by causing cardiac dysrhythmias. To some extent, the degree of the myocardial injury depends on the voltage and the type of current, being more extensive with higher voltage, and for any given voltage, it is more severe with AC than with DC. The injury may be focal or diffuse and usually consists of widespread, discrete, patchy contraction band necrosis involving the myocardium, nodal tissue, conduction pathways, and the coronary arteries (16–19).

Rhythm disturbances may be produced with exposure to relatively low currents. A current of more than 50–100 mA (which is less than half of the maximal current that can be generated after exposure to regular household current) with hand-to-hand or hand-to-foot transmission can cause ventricular fibrillation. Exposure to high-voltage current (AC or DC) will most likely cause ventricular asystole. Lightning acts as a massive cosmic countershock that causes cardiac standstill. Interestingly, because of the inherent automaticity of the heart, sinus rhythm may spontaneously return (20).

A variety of other (usually transient) cardiac dysrhythmias have been reported in survivors of electrical injuries, and their pathogenesis is rather unclear and most likely multifactorial. Possible mechanisms include arrhythmogenic foci due to myocardial necrosis, alterations in the Na^+-K^+–adenosine triphosphatase concentration, and changes in the permeability of myocyte membranes. Finally, cardiac injury and rhythm disturbances can be caused by anoxic injury in cases in which respiratory arrest precedes the injury to the heart. Although delayed dysrhythmias are possible, they tend to occur only in patients who had some other form of dysrhythmia on presentation. Late dysrhythmias are probably due to arrhythmogenic foci secondary to patchy myocardial necrosis and especially due to injury of the SA node (16–21).

Electrical injury may cause direct and indirect effects on the vascular bed, which due to its high water content, is an excellent conductor. The effects of the electric current vary among different size vessels. Large arteries are not acutely affected because their rapid flow allows them to dissipate the heat produced by the electric current. However, they are susceptible to medial necrosis, with aneurysm formation and rupture. Smaller vessels are acutely affected due to coagulation necrosis and tend to be affected primarily as a result of a high-voltage injury (but only rarely with lightning). Vascular injury in the extremities is very likely to cause compartment syndrome that further compromises the circulation (10, 22).

Clinical Manifestations. Cardiac standstill and ventricular fibrillation are obviously the most serious of the cardiac complications of electric injury and are invariably fatal unless immediate resuscitative efforts are undertaken. However, there are also several other dysrhythmias that have a much better prognosis. Among the most common are sinus tachycardia and nonspecific ST- and T-wave changes. Conduction defects, such as various degrees of heart blocks, bundle-brunch blocks, and prolongation of the QT interval, are also common. Finally, supraventricular tachycardias and atrial fibrillation have been reported. In the majority of cases, these dysrhythmias do not cause significant hemodynamic compromise. On echocardiogram, there may be some depression of the right and left ejection fractions (16–20).

Cutaneous Injuries and Burns

Pathophysiology. Exposure to currents generated by low-voltage sources (including household electric sources) may cause a variety of cutaneous injuries from the transformation of electrical to thermal energy. The injuries can range from local erythema to full-thickness burns. The severity of the burn depends on the intensity of the current, the surface area, and the duration of exposure. First-degree electrical burns require an exposure of at least 20 secs to a current of $>$20 mA/mm^2, whereas a second or third degree burn requires exposure to at least 75 mA/mm^2, which is well within the range capable of causing ventricular fibrillation (Table1). In other words, a patient may die before there is time to cause significant surface burns (9, 13, 23). In addition, because the resistance of the skin may be markedly altered by moisture, electric current may be transmitted to deeper tissues before it causes significant damage to the skin. Electric current may be retained by resistant bony structures, and the heat may cause massive coagulation and necrosis of deep muscles and other tissues, almost completely sparing the skin. Thus, in contrast with burns caused by fires, the severity of the skin burns cannot be used to assess the degree of internal injury in an electrical accident with low voltage (15, 23–25).

More serious burns are usually caused by exposure to arcs that are created in accidents with high-voltage currents ($>$1000 V). In such cases, the severity of the burn depends not only on the temperature but also on the energy within the arc. Exposure to an arc may rapidly break down the epidermis of the skin (as fast as 1 msec), thus decreasing the body resistance to that of the internal organs (500–1000 Ω). The combination of high temperature and high current in an arc causes a variety of burns including: "flush burns," which are thermal burns due to the heat generated by the arc; "electrothermal burns," due to the passage of the electric current through the body; and "flame burns," usually from ignition of clothing. Burns due to lightning are common (up to 89% in one series), but despite the massive energy and heat that lightning generates, its short duration and flash-over effect play a protective role. As a result, deep burns occur in only 5% of victims (26). When they occur, burns may be of different types, including partial-thickness linear (mostly in areas of high sweat concentration), punctate (groups of small, deep, circular burns), thermal (usually from ignition of clothes or contact with metal objects), and feathering burns. The latter (also called Lichtenburg figures, ferns, or keraunographic markings) are cutaneous marks that are considered pathognomonic of lightning, but it is unclear whether they are actual burns (27).

Special mention should be made of oral electrical burns in children and burns caused by lightning. The most common mode of electrical shock in young children is from chewing or biting on electrical cords. In such cases, arcing of the current through the lips causes the burn. The burn may be full thickness, involving the mucosa, submucosa, muscle, nerves, and blood vessels. Significant edema and eschar formation follow within hours after the injury. The eschar usually falls off after 2–3 wks, being replaced by granulation tissue and scarring that may cause considerable deformity. Injury to the labial artery may cause significant bleeding. However, because the eschar is usually covering the artery, bleeding may not present until the eschar falls off days after the initial injury (10, 28).

Clinical Manifestations. Clinical manifestations of burns will depend on their extent and severity. When extensive flash and flame burns are present the patient is expected to develop severe hemodynamic, autonomic, cardiopulmonary, renal, metabolic, and neuroendocrine responses that accompany more common thermal burns and that are described in detail in another section of this journal. Burns caused by lightning rarely require special care.

Nervous System

Pathophysiology. Although nervous system injury (involving the central and the peripheral nervous system) is a common clinical manifestation of electrical injury, there is no specific histologic or clinical finding that is considered pathognomonic. Furthermore, in many instances, nervous system injury is not due to the direct effect of the electrical current itself but due to trauma or dysfunction of other organ systems (usually cardiorespiratory).

Among the acute direct effects of passage of electrical current through the brain, the most serious is injury to the respiratory control center that results respiratory arrest. Acute cranial nerve deficits and seizures may also occur after electric injury to the brain. Direct injury to the spinal cord with transection at the C4–C8 level may occur with a hand-to-hand flow. Even relatively low-intensity current (30 mA) at the frequency of household current (60 Hz) may induce an indefinite refractory state at the neuromuscular junction, causing continuous tetanic contractions of involved muscles. These tetanic contractions are responsible for the "locking-on" phenomenon that prevents the victim's hand from separating from the electrical source and for suffocation that is caused by contraction of respiratory muscles. Among the most common indirect injuries causing significant central nervous system injury are brain ischemia or anoxia secondary to antecedent cardiorespiratory arrest and traumatic brain or spinal cord injury secondary to a fall. Peripheral nerves may incur secondary damage due to local burns or entrapment from scar formation, vascular injury, or edema. Upper-motor neuro-deficits are relatively common, affecting primarily the lower limbs (10, 15, 29–33).

Clinical Manifestations. Loss of consciousness, confusion, and impaired recall tend to be very common among victims of electrical injury. If there is no other associated injury, they tend to recover well. Dysfunction of peripheral motor and sensory nerves acutely causes a variety of motor and sensory deficits. Seizures, visual disturbances, and deafness may be present. In more severe cases involving brain hemorrhage or other traumatic or ischemic/anoxic injury, the patient may become comatose. Hemiplegia or quadriplegia are common with significant spinal cord injury. Transient paralysis (keraunoparalysis) and autonomic instability causing hypertension and peripheral vasospasm have been described primarily in the context of electrical injury due to lightning, and they are believed to result from massive release of catecholamines (10, 15, 29–33).

Respiratory System

Pathophysiology. Although respiratory arrest is one of the common causes of acute death in serious electrical injuries, there are no specific injuries to the lungs or the airways directly attributable to electric current. Respiratory arrest is usually the result either of direct injury to the respiratory control center, causing cessation of respiration, or to suffocation secondary to tetanic contractions of the respiratory muscles, which occurs when the thorax is an involved pathway for the electric current. It is speculated that in a number of fatalities it is actually the anoxic injury rather than the electric current that causes irreversible injury to the brain and the heart. Thermal burns of the airways or inhalation of toxic fumes and hot debris may occur, especially in cases of industrial accidents. Blunt trauma to the chest with pulmonary contusion and associated respiratory dysfunction is also possible, especially with exposure to a high-voltage current that knocks the victim to the ground.

Clinical Manifestations. In addition to apnea in cases of respiratory arrest, patients may exhibit a variety of nonspecific respiratory patterns that reflect disturbances of other organ systems (e.g., hyperpnea or hypopnea due to central nervous system dysfunction, fluid shifts, cardiac dysfunction, and pain) rather than from specific injury to the respiratory system. Of course, as is the case with almost every other critical illness, survivors of electrical injury may develop respiratory complications as a result of their injury or treatment (e.g., acute respiratory dysfunction syndrome secondary to ischemia or aggressive fluid resuscitation, ventilator-associated pneumonia) (10).

Other Systems

Among other organ systems that may incur significant damage due to electrical injury, the kidneys are of particular importance. Although direct injury from electric current is unusual, the kidneys are very susceptible to anoxic/ischemic injury that accompanies severe electrical injury. In addition, vascular compromise and muscle necrosis may cause renal tubular damage, leading to renal failure from release of myoglobin and creatinine phosphokinase.

The skeletal system may have fractures either from severe muscle contractions or from injury due to falls from significant heights. Fractures are more common in upper limb long bones and in vertebrae. The latter may cause spinal cord injuries, further complicating the problem.

The eyes and the ears may be entry points for a lightning strike and present a number of problems. Transient autonomic disturbances may cause fixed pupils after a lightning injury that in association with an often unconscious patient, may be perceived as severe brain injury or even death. Up to 50% of patients may experience rupture of the tympanic membranes and temporary sensorineural hearing loss. Cataracts are a very common complication of lightning injury but are rarely acutely present, especially after lightning injury (10, 12, 15).

MANAGEMENT OF ELECTRICAL INJURIES

The management of severe electrical injuries requires a combination of cardiopulmonary resuscitation and acute multiple trauma care. Treatment generally follows the same principles of pediatric and adult resuscitation as any other traumatic injury. The type of care that the victim of an electrical injury requires varies according to the type and severity of the initial injury. However, certain conditions need to be evaluated, monitored, and treated in almost all cases. Specifically for patients admitted to the ICU, the following issues should be considered:

- Thorough evaluation for hidden injury (especially spinal cord injury) and for blunt thoracic or abdominal trauma.
- Serial evaluation of liver, pancreatic, and renal function for traumatic and anoxic/ischemic injury (in case of cardiorespiratory arrest), supplemented by appropriate imaging studies (e.g., computed tomography or abdominal sonogram) as necessary.
- CT scan of the head is indicated in all severe cases of lightning injury, of injuries due to a fall, and if there are persistent abnormal findings in the neurologic examination.
- Preventive treatment for stress ulcers.
- Psychiatric assessment and support as soon as the patient is conscious and hemodynamically stable.

Patients with high-voltage injury also require the following:

- Evaluation for rhabdomyolysis and myoglobinuria (uncommon in lightning injury).
- Evaluation of the limbs for compartment syndrome that may require fasciotomy (rare in lightning injury).
- Nutritional support due to increased energy expenditures.
- Ophthalmologic and otoscopic evaluation (common in cases of lightning injury).

SPECIAL CONSIDERATIONS

In contrast with other traumatic injuries, electrical injuries present some rather unique problems that require special consideration.

Access to the Victim. In contrast with other types of trauma, electrical injury poses the same threat to the rescuer as it does to the victim because, if the victim is still in contact with the source of the current (as commonly happens with AC), he or she becomes a conductor that may electrocute the rescuer. Similarly, in cases of injury with high voltage, the ground (especially if it is wet) may conduct current to the rescuers. Thus, no attempt to provide medical care should be made until either the source of the electrical current has been cut off or the victim has been extricated safely away from the current source with the use of properly insulated equipment. In contrast to popular belief, contact with a lightning victim does not pose any threat to the rescuer; therefore, treatment may be started immediately.

Triage. It is not unusual for electrical injuries (especially lightning injuries) to cause multiple casualties (11, 12). In general, in cases of several injured people, patients believed to be already dead are given the least priority, and efforts are focusing on those who have signs of life. Lightning victims are an exception to this rule because patients struck by lightning may become acutely apneic due to paralysis of the central respiratory control, may have dilated nonreactive pupils due to autonomic dysfunction, and may be pulseless due to the cardiac standstill caused by the mega-countershock of the lightning strike. Because of its inherent automaticity, it is possible for the heart to recover spontaneously. Considering that the majority of lightning victims tend to be relatively young and previously healthy individuals, the possibility of successful resuscitation is high if proper care is instituted immediately. Therefore, administration of oxygen and ventilation with bag and mask should be started immediately on an apneic victim, and an artificial airway should be established as soon as possible to minimize the effects of anoxia, a major cause of mortality. The potential for successful resuscitation has led people to believe that lightning causes a state of "suspended animation" from which the victim can recover virtually unharmed. Unfortunately, this claim is not substantiated. If the patient remains apneic, anoxia will lead to further brain and cardiac damage refractory to treatment.

Severity of the Injury. Because the actual severity of the electrical injury depends on the pathway of the electric current, it is important to determine how the injury occurred. If the patient was exposed to DC, there may be visible burns at the entry and exit sites. In contrast, because of its cyclic movement, AC may not cause discernible entry and exit points. Another problem is that severe injury may occur when the skin is wet and its resistance is low, thus allowing current to travel freely and damage internal organs without leaving significant surface marks. Thus, although the presence of burns on the chest should raise the possibility of internal injuries, their absence does not preclude them. Similarly, skeletal injuries (including vertebral injury) may occur as a result of even a single severe muscle contraction, which can dislocate or fracture bones without any sign of external traumatic injury. Therefore, any victim of a severe electrical accident should be assumed to have a spinal cord injury and should be managed with the proper head and neck immobilization that is required for all victims with suspected or known spinal injury.

Fluid Management. The combination of extensive burns and significant internal visceral injury in cases of severe high-voltage electrical injury leads to increased fluid requirements due to fluid extravasation into third space compartments and to ongoing fluid losses. In addition, the massive muscle destruction that accompanies these injuries may cause significant myoglobinuria, which, if significant, may lead to renal failure (10, 15). Thus, it is important to establish good intravenous access as soon as possible and provide adequate fluids to maintain a normal urine output. If the patient presents with signs of hypovolemic shock, immediate fluid resuscitation is indicated. Otherwise, the overall fluid management should be judicious in consideration of other problems that may already be present or develop (e.g., syndrome of inappropriate antidiuretic hormone in case of traumatic or anoxic brain injury and acute respiratory dysfunction syndrome) and require fluid restriction.

Patient Monitoring. For most patients, disposition becomes clear after their initial evaluation in the emergency department. Victims of a low-voltage electrical injury or of a lightning injury who do not have cardiac arrest, have no loss of consciousness and no burns, and whose neurologic examination and electrocardiogram (ECG) are normal can be safely discharged home (34–36). Patients who experienced cardiopulmonary arrest, have abnormal neurologic findings suggesting central nervous system or spinal cord injury, or have severe burns and extensive visceral or vascular injury will obviously require admission to the ICU or to a specialized burn unit.

What has been less well defined is the need for cardiac monitoring after electrical injury. Although late cardiac problems after electrical injury have been reported, evidence from several studies suggests that the most severe cardiac complications present acutely, and it is very unlikely for a patient to develop a serious or life-threatening dysrhythmia hours or days later. Therefore, patients who are asymptomatic and have a normal ECG at admission to the emergency department do not need cardiac monitoring (34, 35). It is not clear whether this recommendation should apply to patients with a history of heart disease before the injury. In one retrospective study of adults who died due to electrical injury, a history of coronary heart disease was not found to be a risk factor between those who died acutely from an arrhythmia and those who died later from other causes (36). In another study, the same authors reported that none of the patients who were discharged from their hospital after electrical injury had late adverse effects, especially arrhythmias. But they nevertheless recommended an ECG and 24-hr cardiac monitoring for children with history of heart disease (37). Until more data become available on the actual risk that preexisting heart disease poses for the patient with electrical injury, it seems reasonable to monitor such patients for 24 hrs after the injury. Considering that the numbers of potential victims who fit this category is very small, such recommendation will not pose any unreasonable burden to ICUs or the cost of health care. On the basis of studies in adults and children, the criteria for cardiac monitoring after an electrical injury are the following: exposure to high voltage, loss of consciousness, abnormal ECG at admission to the emergency department, and past medical history of cardiac disease (especially a history of cardiac arrhythmia).

The type of recommended cardiac monitoring is also controversial. Traditionally, cardiac monitoring refers to continuous telemetry, serial ECGs, and serial measurement of cardiac enzymes. Although there is a consensus for the use of the telemetry and ECG, the prognostic value of the monitoring of cardiac enzymes (myocardial muscle creatine kinase isoenzyme, CK-MB) and the use of noninvasive and invasive imaging studies (echocardiography, thallium studies, and angiography) has been rather poor and inconsistent. The CK-MB fraction as an index of myocardial injury may be markedly elevated entirely due to skeletal muscle and not myocardial injury. It has been reported that muscle injured by an electrical current can contain up to 25% CK-MB fraction (as opposed to the normal 2–3%) (38). There is no information regarding the changes in troponin levels after electrical injury.

Electrical Injury in the Pregnant Patient. Electrical or lightning injury in a pregnant woman carries the additional risk of complications to the pregnancy or the fetus. Due to the small number of cases reported, the actual risks are unknown. Reports of fetal mortality vary widely, ranging from as high as 73% to as low as 15% after electrical injury and about 50% after a lightning strike. It is not clear whether fetal mortality is due to primary electrical injury of the fetus or secondary to injury to the mother.

PROGNOSIS

The long-term prognosis depends on the severity of the initial injury and the development and severity of subsequent complications. Due to the complexity of the problem, patients are at risk of developing multisystem organ failure that carries high mortality and even higher morbidity. Recent advances in ICU care in the areas of resuscitation, cardiorespiratory and nutritional support of the patients, and new medical and surgical interventions such as immunologic therapy, early wound excision, and skin substitutes have significantly improved the outcome (39). However, considering that electrical injuries are almost always preventable, it seems that the best way to manage electrical injuries can still be summarized by the old saying, "One ounce of prevention is worth a pound of treatment." Public education regarding electrical safety, careful inspection, and safe use according to specifications of electric equipment at home and at work are the best means of eliminating mortality and minimizing the morbidity of electrical injuries.

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