INTRODUCTION

Although severe electrical injuries are relatively uncommon, their true incidence remains unknown. Many electrocution victims (those who die as a result of an electric shock) fall from a height, present with a dysrhythmia, or are simply found dead, and in many of these cases, the significance, and even the occurrence, of an electric shock can be difficult to determine.

Electrical injuries tend to follow a trimodal age distribution, each accounting for approximately 20% to 25% of total injuries. The first peak occurs in toddlers, who generally sustain electrical injuries from household electrical sockets and cords. The second peak occurs in adolescents who engage in risky behavior around electrical power lines. The third population is made up of adults who work with electricity for a living.

The National Electronic Injury Surveillance System from the Consumer Product Safety Commission estimated that emergency departments treated over 6,000 patients for product-related electrical shocks in 2006.1 The majority of these incidents were minor, resulting in emergency department evaluation and subsequent discharge. The most frequent estimates place the annual death rate from electrical injury at 1,000 to 1,500 per year, with more than 60% occurring in adults 15 to 40 years of age. Electrocutions at home account for more than 200 deaths per year and are mostly associated with malfunctioning or misused consumer products.2 One in 10,000 electrical utility workers in the United States dies from electrical injuries.3 Electrical injury was the sixth most common cause of fatal occupational injury from 1992 to 2002.4

BASIC CONCEPTS AND PATHOPHYSIOLOGY

Electricity consists of a flow of electrons across a potential gradient from higher to lower concentration. Electricity requires a complete path (circuit) to create continuous flow and a potential difference (measured in volts [V]) to drive the electrons through the circuit. The volume of electrons flowing along this gradient is the current (measured in amperes [A]). Resistance is the impedance to flow of the electrons (measured in ohms [Ω]).

In direct current (DC), electrons flow constantly in one direction across the voltage potential. Batteries are a common source of DC current, and high-voltage DC current is commonly used as a means for the bulk transmission of electrical power. Alternating current (AC) results when the direction of electron flow changes rapidly in a cyclic fashion. In the United States, standard household current is AC flowing at 60 cycles per second (Hz) and 110 V. In much of the rest of the world the standard household current is 220 to 240 V flowing at 50 Hz.

Six factors determine the outcome of human contact with electrical current: voltage, type of current, amount of current, resistance, pathway of the current, and duration of contact.5 In many cases, the magnitude of only a few of these factors is known.

Low voltage is arbitrarily defined at less than 1,000 volts. As a general rule, high voltage is associated with greater morbidity and mortality, although fatal injury can occur with low voltage as well.

AC exposure to the same voltage is considered to be about three times more dangerous than exposure to the same voltage of DC current. The differences in the
two types of current have practical significance only at low voltages; at high voltages both currents have similar effects. Although AC current is more likely to produce explosive exit wounds, DC current tends to produce discrete exit wounds. AC current is also more likely to cause muscular tetany than DC current. However, high-voltage contacts to both AC and DC current can produce a single violent skeletal muscle contraction, leading to the person appearing to “be thrown” from a voltage source.

The physical effects of different amounts of current vary (Table 6.1). A narrow range exists between the threshold of perception of current (0.2 to 0.4 mA) and the “let-go current” (6 to 9 mA). The let-go current is the level above which muscular tetany prevents release of the current source. When AC current flows through the arm, even at the standard household frequency of 50 to 60Hz, flexor tetany of the fingers and forearm can overpower the extensors. If the hand and fingers are properly positioned, the hand will grasp the conductor tighter, leading to extended contact to the power source. However, current flow through the trunk and legs may cause opisthotonic postures and leg movements if the person has not grasped the contact tightly. Thoracic tetany is also possible and can occur at levels just above the let-go current, resulting in respiratory arrest. Ventricular fibrillation (VF) usually occurs at 60 to 120 mA.

| TABLE 6.1 |
| Effects of Exposure to Varying Amounts of AC Current |

<table>
<thead>
<tr>
<th>Current</th>
<th>Probable Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mA</td>
<td>Tingling sensation; almost not perceptible</td>
</tr>
<tr>
<td>3–5 mA</td>
<td>Let-go current for an average child</td>
</tr>
<tr>
<td>6–8 mA</td>
<td>Let-go current for an average woman</td>
</tr>
<tr>
<td>7–9 mA</td>
<td>Let-go current for an average man</td>
</tr>
<tr>
<td>16 mA</td>
<td>Maximum current a person can grasp and let go</td>
</tr>
<tr>
<td>16–20 mA</td>
<td>Tetany of skeletal muscles</td>
</tr>
<tr>
<td>20–50 mA</td>
<td>Paralysis of respiratory muscles; respiratory arrest</td>
</tr>
<tr>
<td>50–100 mA</td>
<td>Threshold for VF</td>
</tr>
<tr>
<td>&gt;2 A</td>
<td>Asystole</td>
</tr>
<tr>
<td>15–30 A</td>
<td>Common household circuit breakers</td>
</tr>
<tr>
<td>240 A</td>
<td>Maximal intensity of household current (United States)</td>
</tr>
</tbody>
</table>

As electrical current is conducted through a material, any resistance to that flow results in dissipation of energy and heat. This direct heating is the etiology of most tissue damage from electricity. The amount of heat produced during the flow of current can be predicted using Joule’s First Law:

\[ Q = F^2 R t \]

where \( Q \) is the amount of heat generated, \( I \) is the current flowing through a conductor, \( R \) is the amount of electrical resistance, and \( t \) is the time of exposure. Using Ohm’s Law \( (I = V/R) \), the relationship between voltage and heat generation can be derived as:

\[ Q = V^2 t / R \]

If resistance and other factors remain constant, the heat from current flow through tissue increases with the duration of current flow, the square of the current intensity, and the square of the voltage differential.

Electricity requires a complete circuit for continuous flow. The path of the flow of electricity determines the tissues at risk, the type of injury, and the degree of conversion of electrical energy to heat. Current passing through the heart or thorax can cause arrhythmias and direct myocardial damage, whereas cerebral current can cause respiratory arrest, seizures, and paralysis.

Nerves, blood vessels, mucous membranes, and muscle tend to have the least resistance because of their high concentration of electrolytes (Table 6.2). The tissues that have the highest resistance to electricity (skin, bone, and fat) tend to increase in temperature and coagulate. Bone, which has a very high resistance to electrical current, tends to generate a significant amount of heat and often causes damage to nearby muscles. Skin can have a wide range of resistance to electricity, with dry skin having a higher resistance than moist skin. As a result, a patient with dry skin may have extensive superficial tissue damage but more limited conduction of potentially harmful current to deeper structures.

Electrocution causes injury in several ways. The conversion of electrical energy to thermal energy can result in massive external and internal burns. The direct effect of current on body tissues can lead to asystole, VF, or apnea. In addition, electroporation, defined as the creation of pores in cell membranes by means of electrical current, can be caused by electrical charges insufficient to produce thermal
damage but strong enough to cause protein configuration changes that threaten cell wall integrity and cellular function. Finally, muscle contractions or falling can result from blunt mechanical injury from exposure to high voltage.

**EVALUATION AND TREATMENT**

**Scene Safety**

The scene of an electrical injury may present many hazards for rescue personnel, so extra consideration must be taken to ensure scene safety. High-voltage power lines are almost never insulated but may appear insulated from atmospheric contaminants deposited on the lines over time. A rescuer standing on the ground touching any part of a vehicle that is in contact with a power line is likely to be killed or seriously injured. In fact, electrocution can occur from ground current simply by walking too close to a downed power line. A common error is establishing a safety perimeter that is too small. The recommended isolation distance is one full span between the adjacent poles or towers in all directions from a break in the wire or from the point of contact with the ground. At a minimum, personnel should stay at least 3 to 9 m (10 to 30 ft) from downed power lines until the utility company unequivocally confirms that power to the lines is off.

Electrical shock is not prevented by the rescuer wearing rubber gloves and boots unless these are specifically designed for the voltage present. The gloves must also have been recently tested for insulation integrity. A microscopic hole in a glove can result in an explosive injury to the hand inside it because thousands of volts from the circuit concentrate there to enter the glove.

Ideally, it is best to turn off the source of electricity before contact with the victim. Some texts suggest using a nonconductive material, such as a broom handle, to attempt to remove a victim from electrical contact. This should be done only with extreme caution because when voltages are above approximately 600 V, dry wood and other materials may conduct significant amounts of electric current, presenting danger to the rescuer.

There are other hazards present at scenes of downed power lines. When voltage is reapplied to downed lines as circuit breakers reset, the lines may physically jump with great force. Also, although the metal cables that support telephone and power poles are normally grounded, they may become energized if they break or disconnect from an attachment and make contact with a nearby power line.

**Management**

The most common causes of death from electrical injury are cardiac arrhythmia and respiratory arrest. AC current is more likely to cause VF, whereas DC is more likely to cause asystole. Rescue breathing should be instituted as soon as possible for lineworkers in respiratory arrest, even while still on utility power poles. As soon as the victim is lowered to the ground, chest compressions should be initiated if the patient is in cardiac as well as respiratory arrest.

Cardiac monitoring is essential in patients who have suffered significant electrical injuries. Almost 50% of patients exhibit electrocardiographic changes or rhythm disturbances after significant electrical injury. The most common electrocardiographic alterations are sinus tachycardia and nonspecific ST-T-wave changes, which usually revert with time. Because most dysrhythmias are transient, therapeutic interventions are rarely needed. Sometimes an injury pattern mimicking infarction may be seen on the ECG; such patterns are generally due to direct myocardial injury and not coronary thrombosis. The difficulty is identifying the existence of new myocardial damage and determining its physiological significance.

Once cardiac dysrhythmias and respiratory arrest are addressed, patients with electrical injury should be initially evaluated as trauma patients, treating any blunt injuries and caring for burns.

Because many victims are young and have no prior cardiovascular disease, resuscitation efforts should be aggressive. It is often not possible to predict the outcome of attempted resuscitation based on age.

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**TABLE 6.2**

<table>
<thead>
<tr>
<th>Area of body</th>
<th>Resistance (Ω/cm²)</th>
</tr>
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<tbody>
<tr>
<td>Mucous membranes</td>
<td>10</td>
</tr>
<tr>
<td>Most skin</td>
<td>300–40,000</td>
</tr>
<tr>
<td>Soaked skin (e.g., while bathing)</td>
<td>1,200–1,500</td>
</tr>
<tr>
<td>Diaphoretic skin</td>
<td>2,500</td>
</tr>
<tr>
<td>Sole of foot</td>
<td>100,000–200,000</td>
</tr>
<tr>
<td>Heavily calloused palm</td>
<td>1,000,000–2,000,000</td>
</tr>
</tbody>
</table>
and initial rhythm in electric shock-induced cardiac arrest. Normal BLS or ALS resuscitation protocols should be used, keeping in mind any necessary adjustments for rescuer safety and patient access.

In-line immobilization of the spine, IV access, cardiac monitoring, and measurement of oxygen saturation should be started after the primary survey is completed. Rescuers should assume that victims of electrical trauma have multiple traumatic injuries. A large percentage of high-voltage electrical trauma patients have either fallen from a height or been thrown by the force of the electric current. Falls, being thrown from the electrical source by an intense muscular contraction, or blast effect from explosive forces that may occur with electric flashes can cause significant secondary blunt trauma. In addition, fractures and joint dislocations can be caused by forceful muscle contractions.

The primary electrical injury is the burn. There are two general patterns: surface burns and internal current flow. Appropriate burn care should be instituted for external burns. Constricting rings and other jewelry should be removed. Patients with high-tension burns should be taken to a trauma center. Because visible cutaneous damage generally underestimates internal damage, fluid requirements may be exceed prediction using standard thermal burn injury formulae such as the Parkland formula. Most sources advise that an initial fluid volume of 20 to 40 ml/kg over the first hour is appropriate for most patients with significant electrical injuries. Further fluid administration will be guided by continued clinical and hemodynamic assessment.

LIGHTNING INJURY

Background and Pathophysiology

Lightning is a unidirectional cloud-to-ground current resulting from static charges that develop when a cold high-pressure front moves over a warm and moist low-pressure area. It is neither a direct nor an alternating form of current. Although lightning can release greater than one million volts of energy, generate currents greater than 200,000 A, and reach temperatures as high as 50,000°F, the actual amount of energy delivered may be less than that typical of high-voltage injuries because its duration is as short as a few milliseconds.

In the United States, lightning kills approximately 80 to 90 people per year, although 70% of lightning strikes are not fatal. Because people tend to seek shelter from lightning storms together, 30% of lightning strikes involve more than one patient.

There are five basic mechanisms of injury that occur with lightning strikes:

1. Direct strike: A direct strike is more likely to hit a person who is in the open and unable to find shelter. This type of lightning strike is usually fatal.
2. Splash injury: This occurs when lightning strikes an object (such as a tree or building) or another person, and the current “splashes” to a victim standing nearby. Current can also splash to a victim indoors via plumbing or telephone wires.
3. Contact injury: This occurs when the victim is in physical contact with an object or a person directly struck or splashed by lightning.
4. Step voltage/ground current injury: When lightning hits the ground, the current spreads outward in a radial pattern. Because the human body offers less resistance to electrical current than does the ground, the current will preferentially travel through the body (e.g., up one leg and down the other) between the body’s two points of ground contact.
5. Blunt trauma: Victims of lightning strike may be thrown by the concussive forces of the shock-wave created by the lightning. A lightning strike can also cause significant opisthotonic muscle contractions, which may lead to fractures or other trauma.

Patient Assessment

Although lightning strikes may cause multisystem injuries, the most common cause of death is immediate cardiorespiratory arrest. Unlike the typical trauma patient, however, lightning victims have significant resuscitation potential, which gives rise to the EMS lightning-triage mantra, “resuscitate the dead.” The cardiac effects of lightning injury can include anything from nonfatal arrhythmias (including bradycardia, tachycardia, premature ventricular contractions, ventricular tachycardia, and atrial fibrillation), to myocardial depolarization and asystole. Lightning may also cause paralysis of the medullary respiratory center, leading to prolonged respiratory arrest. With early and sustained respiratory support by EMS providers, many patients have excellent prognoses.
Although lightning produces significant heat and voltage, severe burns are uncommon because of the short duration of exposure.\textsuperscript{23,24,28,32} Compared with high-voltage electrical injuries, burn care and aggressive volume resuscitation for deep tissue injury are less important considerations. Full-thickness entry and exit burns are occasionally present, but deep burns and tissue damage are less common than in typical high voltage electrical injury.\textsuperscript{24,28} In many victims struck during rain, the low resistance of wet skin results in a “flashover” effect, decreasing the current transit through the body, and thus decreasing the risk of severe internal injury.\textsuperscript{23,24} Flashover occurs when the lightning strikes a victim, and the current flashes over the outside of the body along the wet skin surface, vaporizing the moisture and causing superficial burns—and often blowing shoes and clothing off the victim’s body.\textsuperscript{24} Linear and punctate burns may be seen along the paths of sweat or rainwater accumulation. Full-thickness burns may occur at sites of contact with metal objects, such as jewelry.\textsuperscript{24} Lichtenberg figures, or feathering burns, are pathognomonic of lightning injury, but are not true burns.\textsuperscript{23,25} They are thought to be the result of electron showers that cause extravasation of red blood cells into the superficial skin layers along the current lines of the flashover.\textsuperscript{23,25,28,31}

Potential neurological effects of lightning injury include loss of consciousness, confusion, memory loss, seizures, persistent headaches, paralysis, mood disorders, chronic pain syndromes, cerebellar dysfunction, and peripheral neuropathies.\textsuperscript{22,23,28} Hearing loss may result from sensorineural damage or from direct otologic injury to the tympanic membrane or middle ear.\textsuperscript{24} Keraunoparalysis, or “lightning paraplegia,” is an immediate effect of lightning injury and consists of paralysis of the limbs with pallor, cool temperature, and absent pulses.\textsuperscript{32,34} It is not actually a neurologic phenomenon, but rather the result of severe arterial vasospasm from catecholamine release. It usually resolves within hours, but it can create a difficult and misleading initial patient assessment.

Other considerations in the lightning victim include blunt trauma, either from being thrown or from significant muscle contractions. The lightning victim may also have been struck by falling tree limbs or building debris. The appropriate precautions, including proper spinal immobilization, must be observed. Because deep tissue damage is less common in lightning strike victims than in victims of high-voltage electrical injury, myoglobinuria and acute renal failure is seen less frequently. However, acute renal failure has been reported in 3% to 15% of victims of major lightning strikes, so appropriate fluid resuscitation should be initiated in the prehospital setting.\textsuperscript{24}

**Critical Actions**

The first priority in responding to a lightning strike is scene safety. Contrary to popular myth, lightning can—and often does—strike the same place twice.

Rescuers should care for lightning strike victim using standard BLS and ALS principles but should amend multicasualty triage priorities, providing initial care to the apparently dead victims first. Victims who do not suffer immediate cardiac or respiratory arrest are unlikely to die from their injuries.\textsuperscript{22} Bystander CPR should be strongly encouraged. Dilated or nonreactive pupils do not indicate brain death in the lightning strike victims and should not be used to prognosticate.\textsuperscript{28} Patients should receive cardiac and pulse oximetry monitoring during transport, and trauma precautions (including spinal immobilization) must be observed. Because the extent of injury may not be readily apparent based on external signs, all lightning strike patients require transport for hospital evaluation. Lightning strike victims with obvious injuries (such as long bone fractures, external burns, respiratory compromise, cardiac arrhythmias, hypotension, or altered mental status) should be transported to a trauma or burn center for evaluation.

**Protocols**

Training of prehospital providers should emphasize the importance of scene safety. Providers must understand the potential hazards of an electrical injury scene as well as the common misconceptions about lightning behavior.

The most immediate concern in a high-voltage electrical injury or lightning strike incident is the victim’s cardiac and respiratory status. The typical advanced cardiac life support (ACLS) algorithms should be applied in such patients and, because of their significant resuscitation potential, aggressive and prolonged resuscitation efforts should be the standard. In multicasualty scenarios, the triage priorities should be reversed to resuscitate the dead first. All patients should receive cardiac monitoring because of the potential for cardiac arrhythmias.

 Patients should be treated using spinal immobilization precautions—even with no history of falling—because of the potential for fractures from
violent opisthotonic muscle contractions caused by
the electrical injury. Selective spinal immobiliza-
tion protocols may be applied to conscious patients
with no history of loss of consciousness, altered
mental status, distracting injuries, or alcohol or sub-
stance use.

IV access should be established and aggressive
volume resuscitation implemented in patients with
high-voltage injuries because of the likelihood of
deep tissue destruction. Providers must understand
that surface burns usually do not indicate the degree
of internal injury.

All victims of high voltage electrical injury or
lightning strike should be transported for hospital
evaluation. Transport to the closest trauma or burn
center is appropriate for those victims with evidence
of obvious injury.

**CLINICAL VIGNETTES**

**Case 1**

Paramedics are dispatched for a 13-year-old male
who climbed up a 30-foot fence to get a basketball
and grabbed an active power line while on the fence.
He is found lying next to the fence, pulseless and ap-
neic. There is a distinct burn on the right palm and
explosive-appearing burns on both feet. His initial
heart rhythm is asystole.

**Discussion**
The energy involved in this case is likely more than
100,000 V of DC current. Scene safety is the top pri-
ority for the responding agencies. However, because
there is not actually a power line down, this is likely
to be a safe scene. Cervical spine precautions must be
taken because of concerns of spinal trauma from the
fall or possibly from tetanic muscle contractions. Vig-
orous attempts at resuscitation should be performed
for this young, otherwise healthy, patient. This would
include high-quality CPR, airway management, and
appropriate pediatric ALS medications. IV crystal-
loids should be started at approximately 20 to 40
ml/kg per hour. The patient should ideally be trans-
ported to a trauma center for further treatment.

**Case 2**

You are called to the scene of a lightning strike on
a golf course with four male victims in their sixties.
One victim is in cardiorespiratory arrest. His two
friends, who also report being struck, have been
performing CPR. The fourth, who has an extensive
heart history, is sitting nearby, diaphoretic and
complaining of chest pain. Lightning is visible on
the horizon, and the rain is just starting to fall as
paramedics arrive on the scene.

**Discussion**
Although there are two high-acuity patients in this
scenario, scene safety must remain the first prior-
ity. Evacuation of the patients to the ambulances for
further evaluation and treatment should be the first
action taken.

The patient with the cardiac history experienc-
ing active chest pain will require urgent assessment
and treatment, but unlike typical multicasualty tra-
uma triage scenarios, the patient in cardiac arrest
should be tended to first, with rhythm evaluation
for potential defibrillation and appropriate airway
management. Appropriate spinal immobilization
precautions should be observed.

The man with chest pain should be treated
next, according to usual BLS and ALS protocols.
Although the third and fourth victims are not expe-
rriencing symptoms debilitating enough to prevent
them from performing CPR, they also should be
transported for hospital evaluation even without
any specific complaints.
REFERENCES