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AHC Media

Electrical and Lightning Injuries

Electrical Injuries

Although electrical injuries are rare, patients who present with these injuries to emergency departments pose particular challenges to emergency physicians and trauma surgeons. Electrical injuries can cause a spectrum of disease, from minor burns to significant injuries and multi-organ system dysfunction. Children and the working young are most commonly affected.

Epidemiology

Electrical injuries (both low and high voltage) account for approximately 1000 deaths per year in the United States.[1,2] Low-voltage injuries are sustained predominantly by children and high-voltage injuries by young adults in occupational exposures. The overall mortality rate is 3% to 5%.[1,2] Among patients who survive to hospitalization, the most common causes of death are multi-organ failure and infection. Patients with larger burns have a higher mortality rate, have a longer length of stay in the hospital, and are more likely to require intensive care, need intubation, and have renal failure requiring dialysis.[3]

Pathophysiology

Electricity is the flow of electrons, expressed as current. Current is equal to voltage divided by resistance. Current, measured in amperes, expresses the amount of energy that flows through the body. It becomes perceptible at approximately 1 milliampere (mA); the safe range for human exposure is 0.2 to 0.4 mA. The "let-go" current (the maximum current that a person can grasp and release prior to the onset of muscle tetany) is 6 to 9 mA for adults and 3 to 5 mA for children.[1] When the "let-go" level is exceeded, tetanic contractions of the flexors of the hand, for example, grasp firmly on the electrical source, not allowing the patient to "let go."

High voltage is defined as more than 1000 volts (V). High-voltage injuries typically occur in occupational settings and in situations involving high-tension power lines. (*See Table 1.*) Low-voltage injuries are usually associated with household electricity, which in the United States is 110 V for general appliances and 240 V for high-powered appliances. Although generally divided into high and low voltage, low voltage can be further subdivided into low voltage and intermediate voltage. Intermediate voltage is defined from 600 to 1000 V. Intermediate voltage is used in some train systems, such as the third rail in subway systems.[4]

In the human body, resistance is impedance to the flow of electrons based on the electrolyte and water content of tissues. Nerves, blood, mucous membranes, and muscles have low resistance and therefore conduct electricity well, while bones, fat, and tendons have high resistance and do not conduct electricity.

EXECUTIVE SUMMARY

- High voltage is defined as more than 1000 volts. High-voltage injuries typically occur in occupational settings and in situations involving high-tension power lines.
- Tasers are electroshock weapons commonly used by law enforcement officers. They impart neither alternating current (AC) nor direct current (DC), but, rather, deliver rapid pulses of 15 to 19 electrical shocks over 5 seconds, with an average current of 2.1 milliamperes.
- Searle and associates developed a protocol for the evaluation of pediatric and adult patients after low- and high-voltage injuries. Patients should first be assessed for a history of an initial cardiac arrest, an initial loss of consciousness, soft-tissue damage, and burns. Patients who do not meet these criteria, have no cardiac risk factors, have no electrocardiographic abnormalities, and are well-appearing may be discharged.
- Several factors determine the site and magnitude of an injury caused by a lightning strike: the voltage conveyed, the resistance of tissues, the type of current, the duration of contact, and the pathway traversed by the current.
- Unlike other mass casualty situations, patients in respiratory or cardiac arrest following a lightning strike should be given highest priority.
- Asystole is the most common cause of death after a lightning strike.
- The Wilderness Medicine Society recommends a screening ECG and echocardiography for high-risk patients. The characteristics of the high-risk category are suspected direct strike; loss of consciousness; focal neurologic complaint; chest pain or dyspnea; major trauma; cranial burns, leg burns, or burns affecting > 10% of total body surface area; and pregnancy.

Because of these differences, patients might have limited injury to the skin, but greater damage to the muscles and internal structures. Although the body has areas presenting different resistances, overall it acts a single resistor. The conductivity, however, is affected by factors such as wet skin, which conducts electricity better than dry skin, and thick skin such as callused hands compared to the thin skin of a child.[5]

Electricity is produced in two forms: alternating current (AC) and direct current (DC). Alternating current is found in homes and offices at a standard frequency of 60 cycles/sec (Hz). Direct current is generated by batteries and automobile electrical systems. With contact, AC conveys a cyclic flow of electrons that induces muscle to contract, causing a person to grasp the source and thus prolonging the exposure. Upon exposure to 20 to 50 mA, respiratory arrest can occur in response to thoracic muscle tetany. DC is usually high voltage but is associated with a comparatively brief period of contact — a large single muscle contraction throws the victim from the source. (*See Table 2.*)

In addition to these forms of voltage, the type and severity of electrical injury are influenced by the type of current, tissue resistance, the type of circuit, and duration of contact. As electrical current flows through the body, it generates heat and cellular depolarization, which contribute to the injury. Some studies have suggested that the pathway from the right hand to the feet is the most dangerous because the current passes through the axis of the heart.[6] Other studies found no difference in complications and mortality rates between different pathways through the body.[7]

Electrical injuries can be caused by direct trauma from the electrical current's impact on the body, trauma from the conversion of electrical energy to thermal injury, or mechanical effects of the electrical current, such as forceful muscle contraction or falls. Contact with particularly high voltage can produce electrical arcs as current flows between objects of different electrical potentials that are not in direct contact with each other. These arcs can travel indirectly from an electrical source to a person. These arcs can generate temperatures up to 5000° C, which will produce flash burns resulting from the ignition of clothing in addition to electrical burns.

Tasers are electroshock weapons commonly used by law enforcement officers. They impart neither AC nor DC, but, rather, deliver rapid pulses of 15 to 19 electrical shocks over 5 seconds, with an average current of 2.1 mA.[2,8] These weapons fire a barb attached to electrodes that induces involuntary muscle contraction and pain, making the targeted person fall to the ground.

Clinical Features and Presentation

Overview of Care. Electrical injuries can produce a spectrum of disease, from minor injuries to multi-organ dysfunction. Although electrical current can travel throughout the body and can injure any organ system, the most common areas of injury are the heart, vasculature, skin, nervous system, musculoskeletal system, kidneys, eyes, and ears. (*See Table 3.*) Other visceral structures can be injured as well.

Cardiovascular System. Electrical injuries can cause cardiac dysfunction through direct necrosis or the induction of arrhythmias. Direct injury can be either focal or diffuse across the myocardium and can be reversible. Arrhythmias are one of the most emergent consequences of electrical injury. With a current of only 50 to 100 mA, life-threatening arrhythmias can occur.[1] Exposure to low voltage tends to be associated with ventricular fibrillation; high voltages are associated with asystole. Several mechanisms leading to cardiac dysrhythmia have been suggested, including myocardial necrosis contributing to arrhythmogenic foci, alterations in electrolyte concentrations, and changes in myocyte membrane permeability.[5] Although ventricular fibrillation and asystole are the most serious cardiac arrhythmias, other common abnormalities are sinus tachycardia, nonspecific ST- and T-wave changes, heart blocks, bundle branch blocks, QT-interval prolongation, and atrial fibrillation. Searle and colleagues[8] observed that 28.7% of pediatric patients and 24.2% of adult

Table 1. Comparison of Electrical Properties[4]

	Low Voltage	High Voltage	Conducted Electrical Weapons (e.g., Tasers)
Amperage	< 1000	> 1000	Average 2.1 mA
Duration	Prolonged	Brief	Brief
Type of Current	Usually AC	Usually DC	Neither AC nor DC
Cardiac Arrest	Ventricular fibrillation	Asystole	Neither
Burns	Superficial	Deep	Uncommon
Rhabdomyolysis	Uncommon	Common	Uncommon
Mortality	Low	High	Uncommon

Table 2. Electrical Current Presentations

Current Threshold	Symptoms
1 mA	Imperceptible
3 mA	Mild tingling
10-12 mA	Pain
10-15 mA	Tetany ("let go" current)
20-50 mA	Respiratory arrest
50-100 mA	Ventricular fibrillation

patients who were struck by lightning had an initial mild cardiac arrhythmia on electrocardiogram (ECG) and none of them developed a cardiac arrhythmia that required intervention.

Vasculature. Blood vessels have low resistance and conduct electricity easily. Typically, larger vessels are not affected by electricity because of their higher flow rates, but they can be damaged by medial necrosis, aneurysm formation, and rupture. Smaller vessels are more susceptible to injury, leading to thrombosis and tissue necrosis, which can contribute to edema and compartment syndrome.

Skin. Electrical burns truly represent a spectrum of injury. Low-voltage injuries tend to exhibit a small, well-demarcated contact burn with an entry and exit site; high-voltage burns tend to be painless and depressed, with central necrosis.[2] Skin conducts current to the deeper soft tissues, muscles, and bones, thus lessening injury to the superficial cutaneous structures. For this reason, the appearance of a burn cannot be used to predict the severity of injury, as is the practice in evaluating thermal burns and calculating total body surface area affected.[9]

First-degree burns occur with exposure to current > 20 mA; second- and third-degree burns require at least 75 mA.[5] In a study of pediatric patients, low-voltage electricity caused mostly second-degree burns (80.6%), and 19.4% of patients had a combination of second- and third-degree burns. The degree of the burns had no significant relationship with risk of death.[11] Injury to the skin varies depending on its conductivity. Patients can experience electrothermal burns from flash injury and electrical arcs that can contribute significantly to skin injury. Oral burns can be produced in children when the current travels from one side of the mouth to the other and generates an arc. These patients tend to have significant edema and eschar formation.

Central and Peripheral Nervous System. The nervous system is especially susceptible to injury from electrical current. The most common neurologic symptom is loss of consciousness and confusion after the incident. Patients can also develop peripheral neuropathies, transient paralysis, paresthesias, and seizures.[1,5] Electrical current through the spinal cord can contribute to motor and sensory deficits. Electrical current flowing through the central nervous system (CNS) can cause injury to the respiratory centers of the brain, contributing to respiratory arrest. Cardiopulmonary arrest can lead to decreased mental status due to hypoxic brain injury. Long-term neurologic complications include seizures, peripheral neuropathies, delayed spinal cord injuries, and psychiatric disorders.[2]

Respiratory. Due to tetanic contractions of the thoracic muscles of respiration, patients may experience cessation of respiration and resulting hypoxia. Respiratory arrest can be caused by CNS dysfunction involving the respiratory control center. Usually, the lungs are not significantly damaged directly by electrical current, although a patient who is thrown from an electrical current or who falls can sustain blunt chest trauma, including rib fractures and pulmonary contusions. Due to electrical arcs and flash burns, patients can have airway burns that exacerbate respiratory distress.

Musculoskeletal Injuries. Exposure to electricity can cause significant musculoskeletal injuries due to either direct contact or a subsequent fall. Electrical injury can contribute to muscular coagulation necrosis, leading to muscle edema, rhabdomyolysis, and compartment syndrome. Falls and forceful muscle contractions can produce fractures and dislocations.

Renal Injuries. The kidneys are susceptible to acute injury when damaged muscles release myoglobin. Myoglobinuria can lead to renal tubular damage and renal failure.

Ocular and Auditory Manifestations. Electrical injuries can also contribute to hearing loss and cataracts. Hearing loss can result from perforation of the tympanic membranes as well as injury to the inner ear. Injury to cranial nerve VIII can contribute to hearing loss and vestibular symptoms.[1] Cataracts develop in approximately 6% of people with high-voltage injuries[1]; their emergence can be immediate, but a delayed presentation is more common.

Tasers. Studies evaluating the safety of electrical devices such as Tasers have shown that, overall, they are safe. Their use in a study of healthy volunteers showed no evidence of delayed cardiac arrhythmia or cardiac injury.[2,12] Most injuries from Tasers are induced by the barb penetration through the skin. There has not been strong evidence that Tasers produce direct significant injury

Table 3. Common Presentations

Cardiovascular	Arrhythmia Myocardial necrosis
Vasculature	Medial necrosis Aneurysm formation Small vessel thrombosis
Skin	Burns
Nervous system	Loss of consciousness Neuropathies Paralysis Seizures
Respiratory	Respiratory arrest
Musculoskeletal	Rhabdomyolysis Compartment syndrome Fractures, dislocations
Ocular	Cataracts
Auditory	Tympanic membrane rupture Hearing loss Vestibular syndrome

through their delivery of electrical current. Deaths after tasing have been reported, but most were attributable to other causes. Individuals who are under the influence of illicit drugs or alcohol are at particular risk of death after being tased.[8]

Diagnostic Studies

Patients presenting after an electrical injury should be treated as trauma patients. The spectrum of possible injuries includes disruptions caused by the electrical current and electrothermal burns, as well as the aftermath of falling and being thrown from the source. If there is evidence of additional trauma, laboratory and radiographic evaluations should be directed at the specific scenario and presentation of illness.

All patients presenting after sustaining an electrical injury should be assessed for cardiac injury and arrhythmias using a 12-lead ECG. In patients with minor injury and a normal ECG, laboratory testing might not be necessary; however, those with significant injuries or exposure to high voltages should undergo laboratory investigation. In patients with high-voltage injuries, the creatine kinase (CK) level can predict muscle injury, risk of amputation or death, and hospital length of stay.[1] The initial CK concentration also might predict which patients would benefit from early fasciotomy.[2] In a study of primary AC injury, CK levels were elevated in 8.7% of pediatric patients and 26.1% of adults.[9] CK-MB correlates poorly with myocardial damage, and troponins have been less extensively studied in electrical injuries; however, a troponin level is a more specific biomarker for myocardial injury and should be assessed in patients with a current pathway through the chest, an abnormal ECG, or chest pain.[1,2] Other laboratory data include obtaining a urinalysis to evaluate for myoglobinuria and a metabolic panel to examine electrolytes and creatinine to evaluate patients at high risk for rhabdomyolysis.

Management

Patients with electrical injuries can present with a spectrum of injuries depending on the form of electricity, voltage, current, and duration of exposure, but the approach to trauma resuscitation focuses on the same parameters of airway, breathing, circulation, disability, and exposure (ABCDE). As stated above, these patients could have significant traumatic injuries due to falls and being thrown from the electrical source and therefore should be treated like trauma patients. Each patient's airway should be evaluated thoroughly, whether the injury has a direct cause, such as chewing on an electrical cord, or an indirect cause, such as a thermal injury from an electrical arc. Airway injury from burns has the propensity to evolve. Patients can have respiratory compromise stemming from various mechanisms and might require ventilator support due to poor respiratory effort. Peripheral intravenous access should be established and fluid resuscitation should be initiated. Due to the likelihood of concomitant traumatic injuries, patients with significant injuries should have cervical spinal immobilization and possible full spinal immobilization, depending on mental status and neurologic deficits that are found on examination.

After the primary assessment, the patient should undergo secondary assessment for additional injuries. Patients may be predisposed to fractures and dislocations requiring reduction and splinting. Most patients should be started on continuous cardiac monitoring to evaluate for arrhythmias. These patients require aggressive fluid resuscitation. Typically, burn fluid algorithms, such as the Parkland formula, will not meet the fluid requirements needed, as superficial burns will not fully represent internal injuries. Fluid resuscitation in these patients is aimed at maintaining a urine output of 1 to 1.5 mL/kg/hr.[1] Although some authors suggest the use of bicarbonate to alkalize the urine, as well as the administration of mannitol and furosemide, there are no data to support this practice.[1]

Electrical burns are best managed in a burn center. Local management includes antibiotic dressings such as mafenide acetate, which penetrates charred wounds well, but should not be used on large areas due to the risk for acidosis. Silver sulfadiazine is used for burns with a body surface area greater than 15%. In children with electrical burns, silver sulfadiazine ointment is used commonly, and electrical burns have a slightly higher requirement for skin grafting and compression garments than chemical burns do. Patients with electrical burns might require more extensive rehabilitation and late surgery.[13] These patients should receive tetanus immunization. Electrical burns are at risk for clostridial myositis, but the use of prophylactic antibiotics is not recommended.[15]

These patients are at high risk of deep muscle injuries, leading to compartment syndrome. Surgical decompression should be performed if the patient develops progressive neurologic dysfunction, vascular compromise, increased compartment pressure, or systemic deterioration, due to the concern for myonecrosis.[1] Burned extremities should be splinted and elevated above the level of the heart to reduce edema. These patients should have frequent neurovascular checks to evaluate for compartment syndrome. Patients with high-voltage injury are at increased risk for compartment syndrome and need for fasciotomy.[13] Early fracture reduction provides more ideal stabilization, better wound care, and earlier patient mobility.[1] Patients with progressive neurologic dysfunction, vascular compromise, increased compartment pressure, and systemic clinical deterioration from presumed myonecrosis should receive surgical decompression.[13] Although immediate surgical decompression and surgical exploration constitute traditional management, there are no definitive data to show that immediate surgical decompression decreases the need for amputation.[14]

The resuscitation of children after electrical injury is similar to that for adults. Children typically sustain low-voltage injuries from household appliances and commonly sustain oral injuries from chewing on electrical cords. These oral burns can cause edema and bleeding, increasing the risk of airway compromise and aspiration. Patients with severe injury might require airway management or hospital admission for close airway observation and nutritional support.

The primary goal of treatment for electrical injuries in a pregnant woman is to treat and resuscitate the mother. The likely pathway of the electrical current could be important, as a transuterine course might induce serious fetal injury. After an electrical exposure, pregnant patients beyond 20 weeks should have fetal heart monitoring and tocodynamometry initiated with obstetric consultation.[1] These patients should also undergo ultrasound evaluation to assess fetal viability.

Disposition

Disposition is based on the type of electricity and the severity of illness on presentation. Patients exposed to high-voltage injury and those with significant burns require transfer to a burn center. Patients with an abnormal neurologic examination, vascular injury, or other pain should be admitted to a monitored bed to receive cardiac monitoring and frequent evaluation. Major burns, shock, hemodynamic instability, and loss of consciousness indicate the need for intensive care unit (ICU) admission. Gokdemir and colleagues found that ICU admission and length of hospital stay were associated with an increased mortality rate.[11] Patients with a history of loss of consciousness, arrhythmias before or after arrival in the emergency department, or electrocardiographic changes and those who were exposed to high voltage should be admitted for further monitoring.[1]

Searle and associates developed a protocol for the evaluation of pediatric and adult patients after low- and high-voltage injuries.[10] They suggest that patients first be assessed for a history of an initial cardiac arrest, an initial loss of consciousness, soft-tissue damage, and burns. Patients who do not meet these criteria, have no cardiac risk factors, have no electrocardiographic abnormalities, and are well-appearing may be discharged.[16,17,18]

Some pediatric studies reported that 3.3% of children showed early arrhythmia after exposure to electricity and suggested that an initial ECG is not necessary in children who did not lose consciousness, whose exposure did not involve contact with water, and who did not experience tetany or current flow across the heart region.[19,20] Some studies suggest that children with low-voltage injury who are asymptomatic in the emergency department and without evidence of arrhythmia or cardiac arrest in the field may be discharged safely without an initial ECG or any inpatient cardiac monitoring.[1] Despite the disparity in the literature on initial ECG in children, due to the risk of arrhythmia, patients should have an initial ECG. Like adults, pediatric patients with high-voltage injuries should be admitted for cardiac monitoring.

Children with labial injuries can be discharged if the injury is minor, if there is no bleeding or swelling, if the patient is tolerating oral intake, and if there are reliable parents or caretakers. Patients with more severe injury, airway edema, and bleeding may require hospital admission for airway observation and parenteral support.[1] If discharged, these patients should have close follow-up, and parents should be aware of the risk of delayed labial artery bleeding with eschar separation approximately 2 weeks after injury.

Pregnant patients are at risk for miscarriage and fetal demise after exposure to electrical current. Although there is limited literature on pregnant patients after an electrical exposure, case reports have shown a cumulative fetal demise rate of 73%, with complications such as spontaneous abortion, intrauterine growth retardation, oligohydramnios, and sudden cessation of fetal movement.[1] In a series of 31 pregnant patients exposed to mostly low-voltage electricity, one gave birth to an infant with a ventricular septal defect, two pregnancies aborted spontaneously, and the other 28 had otherwise healthy infants at delivery.[22] A transuterine pathway of electrical current may contribute to higher fetal demise and spontaneous abortion rates. If discharging a pregnant patient home after minor electrical injury, close outpatient OB/GYN follow-up should be ensured, and the patient should be advised to return to the emergency department if complications arise.

Patients being treated after being shot with a Taser can be discharged safely after dart removal and evaluation for traumatic injuries.

Additional Aspects

In the emergency department, the primary focus on care is resuscitation, monitoring, treatment, and proper disposition; however, patients with electrical injuries are at risk of long-term sequelae, which highlights the importance of the need for follow-up care. Patients can experience permanent peripheral neurologic injury at the site of the electrical current as well as other peripheral mononeuropathies and polyneuropathies. Electrical injuries can have neuropsychologic sequelae, including behavioral changes and difficulty with memory and cognition. Depression and post-traumatic stress disorder are also among the long-term consequences.[23]

Summary of Electrical Injuries

Patients with electrical injuries present the unique challenge of being complex trauma patients. Early resuscitation and critical care are essential considerations during their initial management. The interventions undertaken early in the emergency department phase of care can have a lasting impact on the lives of these patients. These injuries are rare,

Table 4. Lightning Facts From the National Weather Service (2004-2013)

Annual reported lightning deaths	33
Odds of being struck in a given year	1/960,000
Odds you will be affected by someone struck	1/1200

but the emergency physician must be prepared to recognize and treat them expeditiously.

Lightning Injury

The earth is constantly being struck by lightning. Lightning strikes number about 8 million per day and are usually associated with thunderstorms. Lightning is a major cause of storm-related deaths in the United States. The risk of being struck depends on the weather, terrain, and population density of a specific location.

Although lightning injury is a rare patient presentation, emergency care provideres such as paramedics, nurses, and physicians should be able to care for these patients in the field and when they arrive at an emergency department. Since lightning strikes can lead to death and significant long-term morbidity, it is important for the clinician to be ready to provide the appropriate resuscitation and care.

Epidemiology

From 2000 to 2015, the United States documented an average of 36 lightning-induced fatalities per year.[24] Ten percent of people who are struck are killed and 90% are left with some degree of disability. Based on estimates of population and number of lightning strikes, it can be estimated that one in every 960,000 Americans is struck by lightning each year. (*See Table 4.*) Many people with minor injuries do not seek treatment, so the actual incidence of human lightning strikes is likely underestimated.[25] Worldwide, the mortality rate associated with lightning strikes is estimated at 0.2 to 1.7 deaths per million people.[26,27]

Table 5. Risk Factors for Lightning Injuries

- Male sex
- Outdoor occupation
- Recreational enthusiast (campers, joggers, hikers)
- Boating or fishing
- Military personnel
- Months of June, July, and August

In the United States, Texas and Florida have the largest number of lightning-related deaths because of the frequency of thunderstorms as well as the population's proximity to water. However, Wyoming and New Mexico lead the nation in population-based calculations of death and injury resulting from lightning strikes.[28] Interestingly, the mortality rate associated with lightning strikes has been declining during the past few decades.[28] From 1968 to 2010, the number of deaths from lightning decreased 79% among males and 71% among females.[29] Several reasons can be postulated: Fewer Americans are involved in farming, more people live in urban communities, and emergency medical services are better prepared to stabilize and manage patients with lightning-induced injuries. Throughout most of the world, the incidence of lightning-induced death and injury peaks during the summer months. Central Africa has the greatest number of lightning strikes in the world because of its climate, which generates thunderstorms year round.

Lighting kills more people than any other natural event except flash floods.[30] The most common victims of lightning are people enjoying outdoor activities, such as athletes, joggers, and campers. In fact, Jensenius[31] reported that two-thirds of the people killed by lightning in the United States between 2008 and 2014 were outdoors, engaged in activities such as fishing or boating. Men are more likely to be struck than women, and military personnel are at higher risk than civilians.[32] (*See Table 5.*)

Worldwide, between 6000 and 24,000 people are killed by lightning strikes each year.[33,34] Many of those deaths are work-related, but the incidence of injuries among people engaged in outdoor recreation has increased.[35] Lightning injuries have been reported in individuals riding on bicycles, motorcycles, boats, and airplanes.[36,37]

Lightning Physics and Physiology

The "ingredients" of a thunderstorm are warm air on the surface of the earth, moisture, and wind. During the summer months, warm, moist air rises and comes in contact with ice crystals in the atmosphere. It is thought that movement of ice particles within a cloud forms an electrical gradient, which generates lightning.[38] With rising warm air, there is a redistribution of charges within a thundercloud, with lower layers of the cloud becoming negatively charged relative to the earth.[39] Usually the strong insulatory nature of air prevents a discharge from occurring. Nevertheless, when the difference between the charges becomes substantial, the intervening air may break down and the charge is "seen" as lightning.[39] A lightning strike can generate currents greater than 200,000 amperes (A) and temperatures up to 50,000° F.[40]

The most common lightning strikes occur between clouds or within a cloud. This article focuses on a third category, cloud-to-ground discharges, which account for 10% to 30% of all strikes and are the most relevant to emergency medicine because of the injuries they cause.[41]

Although lightning is most commonly associated with thunderstorms, it can also occur when the sky clears after a rainstorm, in a phenomenon known as a "bolt from the blue."[42] It can also be associated with a "thunder snowstorm," when the movement of snow pellets creates an electrical gradient, like high-altitude ice crystals on a warm summer day.[43]

Several factors determine the site and magnitude of an injury caused by a lightning strike: the voltage conveyed, the resistance of tissues, the type of current, the duration of contact, and the pathway traversed by the current. Lightning strikes can deliver DC or AC.[44] Although some say that lightning

Table 6. Common Differences Between Lightning Injuries and High-voltage Electrical Injuries

	Lightning Injuries	High-voltage Injuries
Voltage	30 million V	> 1000 V
Duration	Immediate	Brief to prolonged
Cardiac presentation	Asystole	Ventricular fibrillation
Rhabdomyolysis	Rare	Common
Blunt Injury	Blast effect	Fall or muscle contraction
Burns	Superficial	Deep; fasciotomy sometimes needed

Table 7. Types of Lightning Injury

- Direct strike
- Contact injury
- Side flash or "splash"
- Ground current or step voltage
- Upward streamer
- Blunt or blast injury

is neither a DC nor an AC phenomenon, the clinical approach is not the same as that for electrical injuries.[41] In fact, lightning may be described best as a "unidirectional massive current impulse" as opposed to the traditional AC or DC.[39] A massive amount of energy, 30,000 to 110,000 A, is delivered in a short time, 10–100 ms (much shorter than typical exposures to AC). Because of this short duration of exposure, energy transfer to the body is limited. (*See Table 6.*)

Lightning produces injuries in several ways (*see Table 7*)[41]:

Direct Strike (< 5%; most deadly mechanism). The person is struck directly and becomes a main part of the discharge channel. A direct strike induces a very short duration of current flow internally and an immediate flow of current around the body, known as a "flashover." It is thought that this current generates magnetic fields perpendicular to the body surface, which create secondary currents within the body.[45] These secondary currents are thought to be the cause of cardiac arrest and internal injuries.[46]

Contact Injury. The person is touching or holding an object (tree, tent pole, umbrella) that is struck. This type of injury can also occur to people who are indoors and presumed safe, for example, someone who is washing dishes when an electrical surge passes from outside to inside the house.

Side Flash or "Splash" Injury (30%). Lightning jumps from an object that is struck to a person a foot or two away, for example, in a group of people in a shelter that is not grounded.

Ground Current or Step Voltage. Lightning strikes the ground and current spreads to a person or animal standing near the strike point (50%). This mechanism has killed many farm animals because of their exposure to storms and because of their body span. The lightning enters the body at the point closest to the strike and exits from the point farthest from the strike. The longer the distance, the greater the potential for serious injury or death. In another scenario, when lightning strikes the ground, a nearby person can be injured depending on the distance between his or her feet. Because a body is a better conductor of electricity than the earth, the current flows preferentially between the legs rather than through the ground.

Upward Streamer. Current passes up from the ground, through the victim, who then serves as a conduit for transmission of the charge toward the clouds.

Blunt or Blast Injury. This injury involves primary (tympanic membrane rupture) or tertiary trauma (person is thrown or knocked down).

A lightning strike to the body induces electroporation, a reorganization of lipids in cell membranes, which can affect membrane permeability and transmembrane gradients.[45] These changes can lead to the death of skeletal muscle and nerve cells, resulting in direct injury as well as delayed neurologic effects.

Clinical Features and Presentation

Overview of Care. After a lightning strike, patients typically do not present with traditional high-voltage electrical injuries. Compared to other electrical DC or AC injuries, lightning is less likely to cause rhabdomyolysis, burns, and muscle tetany.[40] The vast majority of patients have minor injuries and will survive being struck. (*See Table 8.*) They tend not to have external signs of injury, such as severe burns, but many have cardiovascular and neurologic effects, which might be devastating, possibly lethal. Transmission of current through the body varies because of the resistance of the tissues: Bone has the highest resistance, followed by fat, tendon, skin, muscle, and nerves.

Most of the deaths caused by lightning strikes occur immediately after the event or after unsuccessful cardiopulmonary resuscitation.[47,48] The most common causes of death are asystolic cardiac arrest and hypoxia-induced cardiac arrest.[27] Intrinsic cardiac automaticity might be able to restore organized cardiac activity after a lightning strike; however, the entire myocardium might be depolarized, leading to asystole. In addition, chest muscle paralysis and suppression of brainstem respiratory effort could lead to respiratory arrest.[45] Even if cardiac activity returns, respiratory effort might not return immediately; therefore, ventilation must be supported to avoid a secondary hypoxic cardiac arrest.[49] For reasons that are unclear, a massive catecholamine release follows lightning injuries. Many patients present with hypertension, tachycardia, nonspecific electrocardiographic changes, and myocardial necrosis.[50] Myocardial infarction is not common.[51]

Pre-hospital Care/Triage. At the scene, all patients should be treated as having blunt trauma, and trauma protocols should be initiated immediately, with full spine immobilization and airway protection. Blunt trauma should be presumed since it may be unclear if the patient was thrown by the lightning strike, and mental status may be clouded. Lightning strikes can

Table 8. Common Injuries and Clinical Findings

- Tympanic membrane rupture
- Hearing loss
- Loss of consciousness
- Cataracts
- Burns: Linear, punctate, feathering, thermal
- Vasospasm
- Keraunoparalysis
- Altered mental status

Figure 1. Linear Burns

Linear burns from a 14-year-old male treated at the U.S. Army Institute of Surgical Research after a lightning strike. Reprinted with permission from: Ritenour A, Morton MJ, McManus JG, et al. Lightning injury: A review. *Burns* 2008;34:585-594.

create a mass-causality scenario, and, whether the response is in the field or in an emergency department, a "reverse triage" protocol should be implemented. Unlike other mass casualty situations, those patients in respiratory or cardiac arrest should be given highest priority. Those who appear to be dead should be resuscitated first, since they might need only airway support to be revived.[51] In particular, young patients who have no history of heart disease are amenable to resuscitation according to ACLS protocols if they are in cardiac arrest after a lightning strike. Immediate defibrillation should be administered to patients in ventricular fibrillation. Any smoldering clothing, including belts and shoes, should be removed to prevent thermal burns.

Head and Neck Injuries. The head is a common entry point for lightning, and some victims have burns at the point of contact. The blunt force of the strike can injure the cervical spine, so spine precautions should be maintained. About half of survivors have tympanic membrane rupture.[53] The tympanic membranes should be examined for perforation. Bloody debris may limit the ability to examine the tympanic membrane. Care should be taken with evaluating the membrane, and ear, nose, and throat (ENT) specialist consultation should be sought for full assessment. Hearing should be assessed with audiometry, as there may be sensorineural loss.[54] Hearing disability or deafness can be caused by ossicle disruption.

Cataracts might develop several months after the initial injury (20% within 3 years). Other possible eye injuries include intraocular hemorrhage or thrombosis, chorioretinitis, iridocyclitis, hyphema, and orbital fractures. Dilated pupils are not a reliable sign of brain death immediately after a lightning strike for unclear reasons.[55]

Cardiovascular Disruptions. As mentioned earlier, asystole is the most common causes of death after a lightning strike. Nonspecific ST-T wave changes and prolongation of the QT interval can be seen on the ECG.[39,56] Electrocardiographic changes can also include ST-segment elevation but coronary angiography can be normal.[57] A catecholamine surge accompanied by tachycardia and hypertension is seen soon after lightning injuries. It usually resolves within a few hours but can last for weeks or months.[58,59] Skeletal muscle injury can lead to an elevated CK-MB (creatine kinase) fraction that is due to skeletal injury as opposed to cardiac injury or infarction. Takotsubo cardiomyopathy, a severe acute presentation of cardiogenic shock, has also been documented following lightning injury.[60]

Skin Injuries. Since the duration of exposure is short, significant burns and tissue destruction are rarely seen; however, people who have been struck by lightning can have resultant linear, punctate, feathering, and thermal burns. Linear burns tend to occur under the arms or down the chest. (*See Figure 1.*) They are thought to be produced by the flashover phenomenon and vaporization of water on the skin.[61] The electron showers induced by lightning can make a fern-like pattern on the skin, causing feathering burns, also known as Lichtenberg figures.[62] They are transient and pathognomic for lightning injury and do not require treatment since they resolve within a few hours after injury.

Occasionally, clothing that is singed or catches on fire because of the strike causes thermal burns (severe burns are uncommon). Burns involving the cranium or legs are associated with an increase in mortality rate.[63] Any burn should be managed with standard wound care, and a burn specialist should be consulted if the patient has extensive or full-thickness burns. Most people struck by lightning suffer only superficial burns that heal quickly.

Musculoskeletal Injuries. Transient vasospasm can be severe, causing the arms or legs to appear cold, blue, mottled, and pulseless.[41] In most cases, circulation to the extremities tends to improve slowly and without direct intervention. Nevertheless, monitoring for compartment syndrome is important.

Central Nervous System (CNS) Effects. CNS abnormalities are common after a lightning strike and can have immediate and delayed manifestations. Cherington[64] identified four groups of injury:

Group 1: Immediate and Transient. This group of injuries includes loss of consciousness, confusion, headaches, weakness, paresthesias, and keraunoparalysis. Keraunoparalysis, or Charcot's paralysis, is a unique, temporary paralysis seen in patients after a lightning strike. It usually presents as lower extremity paralysis that resolves after a few hours.[64] A patient with these lower-extremity conditions should be presumed to have a spinal or cranial injury until proven otherwise.

Group 2: Immediate and Prolonged/Permanent. CNS injuries are the result of significant damage caused by hypoxic ischemia, hemorrhage (subarachnoid or intra-cerebral), or cerebral infarction.

Group 3: Possible Delayed Neurologic Syndromes. These injuries include motor neuron and movement disorders.[45] Progressive myelopathy has been seen in patients who have weakness or sensory loss after the initial injury.[65] Case reports have described cervical and thoracic cord damage that led to neurologic deficits.[66]

Group 4: Lightning-linked Secondary Trauma from Falls or Blast. Injuries related to the blast or a fall include subarachnoid hemorrhages, subdural hematomas, and epidural hematomas.

Psychiatric and Neurocognitive Effects. Long-term cognitive effects can present as post-traumatic stress disorder and depression. Abnormalities in memory and concentration can be seen. Depression, altered sleep patterns, emotional lability, and aggressive behavior are all possible after someone has been struck by lightning.[64]

Effects During Pregnancy. Lightning strikes affecting pregnant women are extremely rare. Among the few that have been reported, the fetal mortality rate is high because of the conductivity of the amniotic fluid.[67] Based on case reports, the maternal mortality from lightning strikes is close to zero, whereas the fetal mortality can be up to 50%.[68] Therefore, fetal monitoring should be part of the assessment of pregnant women struck by lightning, especially those who are past 20 weeks' gestation.[44]

Other Injuries. Lung contusion and hemorrhage can be caused by blunt trauma. Blunt abdominal trauma is rare.

Management

During a rescue for a person injured by lightning, the medical providers must be certain that retrieving the person does not put the rescuers at risk of another potential lightning strike. If there is an active thunderstorm with lightning, rescue may need to be delayed.[69] It is safe to touch a patient after lightning strike. Pre-hospital care providers should not be afraid of being shocked after the incident has occurred and the area has been deemed safe for entry. In a mass casualty scenario, as mentioned above, a reverse triage protocol should be implemented, in which priority is given to patients who appear to be dead or are in cardiorespiratory arrest. Aggressive resuscitation should be started in patients without a pulse or respirations. The carotid artery should be used to assess the pulse, since vasoconstriction in the extremities will likely render them unreliable for this assessment. Ventilation is imperative, since intrinsic cardiac activity may resume after the injury but respiratory drive might be delayed.

In the emergency department, ACLS, BLS, and trauma protocols should be initiated while obtaining an accurate history from paramedics and bystanders. The patient's clothing should be removed and all skin should be examined for signs of injury. All patients should have cardiac monitoring initiated, with intravenous access established for fluid resuscitation. An ECG should be obtained to evaluate for dysrhythmias. The initial laboratory workup should include a complete blood count, basic metabolic panel, hepatic function panel, CK-MB, creatine kinase, and urinalysis (even though lightning strikes usually do not produce severe abnormalities in any of these tests). Arterial blood gas concentrations and the lactic acid level can be checked as well to ensure adequate ventilation and perfusion. Cardiac enzymes including troponin can be checked, with the awareness that myocardial ischemia is rare from lightning strike alone.

Computed tomography (CT) imaging should be obtained on a case-by-case basis. Patients with altered mental status should have a head CT scan. Victims of lightning strikes can have altered mentation or confusion, which makes obtaining a correct history or physical difficult. Since the patient might have blunt trauma caused by the blast, the initial evaluation should include assessment for internal trauma. Furthermore, results of a neurologic exam should dictate the need for imaging of the spine as well as the level of concern about intracerebral injuries.

Disposition

Any patient who is resuscitated from cardiopulmonary arrest should be admitted to an intensive care unit for continued management and standard post-resuscitative care. Similarly, any patient with neurologic deficits or altered mentation should be admitted for further management and care.

The Wilderness Medicine Society recommends a screening ECG and echocardiography for high-risk patients.[44] The characteristics of the high-risk category are:

- Suspected direct strike;
- Loss of consciousness;
- Focal neurologic complaint;
- Chest pain or dyspnea;
- Major trauma;
- Cranial burns, leg burns, or burns affecting > 10% of total body surface area;
- Pregnancy.

Patients who sustained a direct strike or have an abnormal ECG or echocardiogram should be monitored with telemetry for a minimum of 24 hours.[44] Patients who are totally asymptomatic and have a normal physical examination can be discharged, with follow-up with their primary care provider. The emergence of neurologic sequelae is delayed in some patients after lightning strike; those who are at risk of this consequence should have appropriate follow-up with a neurologist. Patients with hearing loss or tympanic membrane rupture should have a follow-up appointment with an ENT specialist. All patients should be seen by an ophthalmologist, since they are at substantial risk for the development of cataracts.

Prevention

Since lightning injuries can lead to severe disability, it is important to avoid situations that increase the risk of being struck. (*See Table 9.*) People who engage in recreational activities outdoors or who work outdoors should take precautions when weather reports indicate rain or thunderstorms (lightning can occur in snowstorms as well). When thunder is heard, people should seek shelter in a building or motor vehicle, not under trees, on high ground, or near water or open spaces. It is advised to stay off ridges and summits and away from single trees. Metal can conduct electricity and it is advised to store all metal objects (ski poles, crampons, skis, or anchors). For those who are wearing a helmet for rock climbing or other outdoor activity, it is important to continue wearing the helmet, as it can prevent trauma from blast injuries. Crackling noises, hair standing on end, or a visible blue glow can all signal that a lightning strike is about to occur. Tall objects such as ski lifts, cell phone towers, and

Table 9. Prevention of Lightning Injuries

- Check the weather reports prior to outdoor activity.
- Seek shelter in buildings or motor vehicles.
- Avoid high ground or lone trees.
- Observe the "30-30 rule."
- Assume a crouching position.
- Move away from water.

isolated trees should be avoided. For outdoor activities, a "30-30 rule" states that a flash-to-thunder interval of less than 30 seconds places people at risk of a lightning strike, so they should seek shelter.[45] In general, larger buildings with plumbing and electrical wiring are safer structures. People should remain in the shelter for 30 minutes after the last lightning is seen or thunder is heard. The Wilderness Medicine Society recommends waiting a minimum of 30 minutes after hearing the last thunderclap before resuming outdoor activity.[44] For people outdoors without immediate shelter, it is advisable to move to a dense forest, cave, or ravine. The safest shelters are buildings and hard-topped vehicles.[44] People stranded in the open are advised to crouch with their feet and knees together. Sitting on a pack or sleeping pad can provide insulation from the ground while in the crouching position. For large groups, the Wilderness Medicine Society recommends separation of more than 20 feet, since lightning can leap from one person to another. If a storm approaches while people are in water, it is important for them to move to shore and then away from the water's edge as soon as possible. People on a boat are advised to go below deck. For large sporting or outdoor events, a lightning action plan should be developed to help evacuate large groups of people in a timely fashion.[70]

Summary of Lightning Injuries

Lightning can be a fascinating, beautiful natural event to witness. It is important to be aware of the dangers of lightning strikes and to avoid situations that could lead to injury and permanent disability. Although most people survive lightning strikes, delayed neurologic effects can lead to a lifetime of pain and cognitive impairment from a very quick injury. Medical professionals in the trauma and emergency fields should be prepared to handle the victims of lightning strikes; they are not commonly seen and can be stressful to manage. Nevertheless, with adequate training and education, healthcare providers can save lives from the potentially deadly aftermath of a lightning strike.

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CME/CE Questions

1. What is the correlation between skin burns in electrical injuries and the extent of injury?
   A. The TBSA calculation is used to measure extent of injury.
   B. Skin burns correlate with extent of internal injury.
   C. Skin injury in electrical burns does not correlate with deeper injury.
   D. Minor skin burns with pain and edema can easily be discharged from the emergency department.
2. What is most common injury from Tasers?
   A. Death
   B. Cardiac arrhythmia
   C. Cataracts
   D. Skin injury from barb penetration
3. What treatment should be started for patients with rhabdomyolysis?
   A. Empiric furosemide
   B. Empiric mannitol
   C. Immediate hemodialysis
   D. IV fluids to target urine output 1-1.5 mL/kg/hr
4. After initial primary and secondary survey, what diagnostic test is important to obtain?
   A. ECG
   B. Troponin
   C. Creatinine
   D. Creatine kinase
5. Which patient can be discharged from the emergency department?
   A. 85-year-old female with congestive heart failure presenting after low-voltage AC injury with atrial fibrillation on ECG
   B. 25-year-old male with no past medical history presenting after low-voltage AC injury with a normal ECG and asymptomatic
   C. 2-year-old female presenting after AC injury with initial cardiac arrest with return of spontaneous circulation in the field now awake with ECG sinus tachycardia
   D. 27-year-old male presenting after high-voltage injury after being thrown from the power lines with severe right arm and left leg pain and a normal ECG
6. If lightning jumps from an object that is struck to a person who is standing a foot or two away, this is known as a(n):
   A. contact injury.
   B. side flash or "splash" injury.
   C. direct strike.
   D. upward streamer.
7. What is the most immediate cause of death in lightning strikes?
   A. Burns
   B. Head injury
   C. Asystolic cardiac arrest
   D. Hypothermia

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