Electrical Injuries

Risk Stratification and Treatment

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Electrical injuries accounted for an estimated 10,000 US emergency department visits in 2010. Herein, we review basic electrical concepts as they relate to possible injuries and their presentation. Management and disposition recommendations are noted, and case examples are provided.

Ever since humans have been able to harness electrical energy, injury and death have resulted. Injury sources vary from simple static electrical charges to high-voltage electrical lines, and the range of insults spans dramatically from a simple, brief, painful exposure to cardiac arrest and death. Perhaps because of the protection afforded by modern safety mechanisms, the substantial morbidity and mortality that can be caused by exposure to electrical current is widely underrecognized. Even the current drawn by a 7.5-watt, 120-V lamp, passed from hand to hand or hand across the chest, is sufficient to cause electrocution and death.[1,2] Workplace incidents account for a considerable portion of electrocution injuries and deaths and have affected workers since the first electrical fatality was recorded in France in 1879, when a stage carpenter was killed by an alternating current of 250 V.[2,3]

Though lightning and electrical injuries are often thought to be similar, they differ markedly in their physics, pathophysiology, and related injury patterns. (See Desai B. Emergent management of lightning injuries. *Emergency Medicine*. 2011;43[10]:7-13.) This article will detail the physics and pathophysiology of electrical injuries, as well as discuss the emergent evaluation and management of both minor and severe electrical exposures.

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INCIDENCE

Exposure to electrical current is a considerable cause of injuries treated in US emergency departments. In 2010, according to estimates based on data from the US Consumer Product Safety Commission's National Electronic Injury Surveillance System, electrical injuries accounted for almost 10,000 emergency department visits, with 35% of these visits from patients younger than 16 years.[4] The Bureau of Labor Statistics, in their Census of Fatal Occupational Injuries for 2010, reported that contact with electrical current caused 4% (163 of 4,547) of fatal occupational injuries.[5] Between 1980 and 1992, an average of 411 workers were electrocuted each year, with an average annual rate of 0.4 per 100,000 workers. While total work-related fatalities decreased only 23% during this time period, the number of electrocution deaths decreased by more than 50%.[2]

PHYSICS OF ELECTRICAL INJURIES

Knowledge of basic physics is necessary to understand injury imparted by electrical current. Joule's and Ohm's laws govern energy transfer. According to *Joule's law,* energy = current^2 × resistance × time. According to *Ohm's law,* current = voltage / resistance. As can be seen from Joule's law, increasing current and/or exposure time increases energy transfer. In electrocution, the more energy that is transferred to human tissue, the greater the tissue damage.[6] Physiologically, resistance is variable and exposure time is usually not precise; thus, exact thermal power transfer from various electrical exposures is virtually impossible to calculate. An essential concept in understanding how electrical injury causes body injury is that injury severity is directly proportional to current (measured in amperes), resistance (measured in ohms), and duration.[7]

Resistance

Electrical resistance is a measure of the degree to which an object opposes the passage of an electrical current. Higher resistance to electrical flow leads to greater conversion of electric energy into thermal energy. In the human body, this causes heating of local tissues, eventually resulting in tissue destruction. The greatest physiologic electrical barrier in humans is skin.

Case 1

A plumber presents after sustaining an electrical shock from a 240-V circuit while installing a new appliance; the screwdriver he had been holding in his hand touched a live wire. The circuit was protected by a GFCI, which tripped during the exposure. The patient had no loss of consciousness, although initially he had some mild hand numbness. He is currently asymptomatic. On exam, no burns or other abnormalities are noted.

In this scenario, the patient's low-voltage electrical exposure is expected to have been quite brief because of the GFCI. Based on the history and clinical presentation, there is no indication for further diagnostic testing or evaluation. As the risk for delayed cardiac arrhythmia is exceedingly low, there is no need for extended evaluation in the emergency department, and the patient is discharged to home.

Dry, calloused skin has considerably higher resistance than sweaty or wet skin. The high resistance of dry skin causes more localized soft tissue injury with less internal injury, as less current reaches deeper organs. This observation holds true only for brief electrical exposures. When duration of contact with the electrical source increases, skin eventually begins to break down (lowering resistance), which results in greater transmission of damaging electrical current to internal organs.[8]

Current

Current is the amount of energy flowing through an object, or more specifically, the rate at which charge flows past a given point in an electrical circuit. When current is applied to muscle, the muscle contracts. As the flexor muscle groups are typically stronger than the extensor groups, a generally applied current will cause the appearance of muscle flexion. When current is applied across the hand, flexor muscles dominate, creating a muscle contraction pattern that mimics the grasping of an object. The "let-go" current is the maximum amount of current that can be applied to the upper extremity muscle groups with which an individual could still release a grasped object. The "let-go" current is usually less than 16 milliamperes (mA), although the actual threshold in individual persons depends greatly on muscle mass (Table).[2] Electrocution often causes the source of current to be grasped and pulled closer to the victim, which increases duration of exposure and therefore tissue damage. Injuries are often not prevented by standard household circuit breakers, as they do not trigger until current exceeds 15 to 20 amperes. Ground fault circuit interrupters (GFCIs) are an inexpensive lifesaver. The use of GFCIs has lowered the number of clinically significant electrocutions dramatically.[9] GFCIs are different from traditional circuit breakers in that they detect leakage currents rather than circuit overloads. A GFCI is a fast-acting switch that detects differences in current in a circuit. If the human body accidentally becomes part of the circuit (a situation known as a *ground fault*), the GFCI opens the circuit in less than 1 second. If a current as small as 4 to 6 mA does not pass through both circuit wires properly, but instead passes into the human body, the GFCI is tripped and the current is shut off.[9] GFCIs are thus able to de-

Table. Physiologic Effects of Alternating Current at 60 Hz

Physical Effect	Milliamperes
Tingling sensation	1 to 4
"Let-go" current	7 to 16
Respiratory arrest	> 20
Ventricular fibrillation	> 100

Adapted from National Institute for Occupational Safety and Health, US Department of Health and Human Services.[2]

tect the loss of current resulting from leakage through a person at the start of electrical exposure.

Voltage

Voltage is the difference in electrical potential between two points. Higher-voltage exposures result in more current and thus increased tissue damage. Injuries are usually categorized as high voltage (>1,000 V) or low voltage (<1,000 V).[8,9] Cutaneous burning tends to be less severe in low-voltage injuries, unless there is prolonged contact with the power source. Nonetheless, low-voltage exposures can cause serious injury, including cardiac arrest. This is best illustrated in bathtub- or other water-associated electrocutions. The presence of moisture from environmental conditions, such as standing water, wet clothing, high humidity, or perspiration, increases the likelihood of morbidity and mortality associated with low-voltage exposures.

Under dry conditions, the resistance offered by the human body may be as high as 100,000 ohms. Wet or broken skin may lower this resistance to 1,000 ohms.[2] The following examples illustrate Ohm's law and demonstrate how the presence of moisture can play an important role in morbidity and mortality associated with low-voltage electrocutions: (1) current = volts / ohms = 120 V / 100,000 ohms = 1 mA exposure; (2) current = volts/ohms = 120 V / 1,000 ohms = 120 mA exposure. Thus, under dry conditions, there is a barely perceptible level of current, but under wet conditions, there is sufficient current to cause cardiac arrest.[2]

It is not surprising that the likelihood of death is greatest when the skin is wet or immersed in a bathtub or pool of water. Given the low resistance of wet skin, it also makes sense that in almost 40% of deaths from low-voltage exposures, the affected individuals have no visible burns, since these exposures are often associated with wet or immersion situations.[10]

Alternating Current (AC) Versus Direct Current (DC)

The type of current encountered has a notable effect on injury severity. Alternating current is generally used in homes and businesses. Direct current powers electrical devices such as household computers after being converted from household alternating current; it is also produced by batteries. Direct current tends to cause an intense single muscle contraction, which most often releases the victim from the point of electrical contact. In evaluation of a patient exposed to direct current, it is advisable to maintain a heightened suspicion for secondary trauma that may result from the patient's having been thrown from the source. Alternating current is generally thought to be more deadly than direct current, as it is usually encountered at a frequency of 60 Hz, which induces tetanic muscle contractions and extends the duration of contact with the power source.[2] Both high-voltage alternating current and direct current can induce opisthotonic muscle spasms in the back and legs, throwing the victim from the source and causing significant blunt trauma in addition to electrical injury.

Current Pathway

The pathway of electricity through the body determines the extent of injury. If the pathway is more diffuse, it is likely that lower resistance has been encountered. With lower resistance, less heat is produced, resulting in a lower incidence of external thermal burns. Visible injuries are often concentrated at both the source and grounding point, as skin in these areas is exposed to the most current. Extreme diligence is required of the examining physician, since evidence of extensive internal injuries may not be externally visible. This phenomenon is especially true in high-voltage injuries.

DAMAGE TO ORGANS AND SYSTEMS

Cardiac

Current pathways through the thorax are most concerning, as they may lead to cardiac arrhythmias and/

Case 2

A 48-year-old man presents to the emergency department with bilateral upper and lower extremity electrical injuries. EMS reports the patient was carrying a long metal pole that struck low-hanging electrical wires. The patient was thrown approximately 10 ft after making contact with the electrical wire. He had a brief loss of consciousness before returning to his baseline normal mental status. On exam, the patient is in obvious distress due to pain. He has full-thickness entrance and exit burns involving the flexor surfaces of both hands, with some superficial burns of the bilateral forearms. He complains of severe pain with passive flexion and extension of the bilateral wrists and elbows. Forearm compartments are tense. No obvious injuries are noted to the head, neck, or torso. Also, he has full-thickness burns to the plantar surface of both feet, with partial-thickness burns to the lower legs.

Aggressive intravenous fluid therapy is instituted to maintain an adequate urine output. A FAST (focused assessment with sonography in trauma) exam is performed and reveals no pericardial or free intraperitoneal fluid. An initial ECG does not show abnormality. Because the patient experienced loss of consciousness associated with a significant trauma, CT of the head is performed, revealing a small subdural hematoma, which is managed nonoperatively. The patient is transported emergently to the operating room for bilateral upper extremity fasciotomies (due to concern for compartment syndrome) and wound debridement. Cardiac monitoring over the first 24 hours does not reveal evidence of arrhythmia. The patient is discharged on postoperative day 7.

or respiratory arrest. Sudden death due to ventricular fibrillation is more common in low-voltage alternating current exposures, while asystole is more common in high-voltage alternating and direct current electrocutions.[8] In one electrocution study involving 145 hospital admissions (88% low-voltage and 12% high-voltage) over a 5-year period, cardiac abnormalities were noted in four of 104 patients (3%) who underwent ECG within 24 hours of injury.[11] Three patients had occasional ectopic beats, which resolved spontaneously over the next 24 hours. The fourth patient, who had a high-voltage injury, developed atrial fibrillation that resolved following treatment. The authors concluded that cardiac complications are rare and are more frequent in patients who experience an initial loss of consciousness and in patients with a high-voltage injury.[11] Myocardial infarction is rare. Elevations of creatine kinase–MB (CK-MB) isoenzyme levels are caused more often by muscle damage than by associated myocardial infarction.

Respiratory

Respiratory arrest can be the result of electrical injury to the diaphragm and other muscles of respiration, chest wall noncompliance due to tetanic muscle contractions, or depressed CNS respiratory drive.

Skin

Burns from electrical injuries are either direct or indirect. Low-voltage direct burns are usually concentrated in areas in direct contact with either the source or the ground. High-voltage burns can be seen along the entire course of the current. Higher resistance results in greater heat production and thus an increase in burn severity. Unlike the damage from thermal burns, the extent of internal damage from high-voltage burns cannot be determined based on the size of visible cutaneous burns. Internally, heat production is greatest next to high-resistance deeper tissues, such as bone, causing underappreciated internal injury.

Direct burns occur most often on the hands and head, as these two areas are most likely to come into contact with an electrical source. Their appearance is diverse and depends on the voltage, resistance, and duration of contact. Full-thickness burns are often painless, appear depressed, and have an ischemic center (Figure 1). Additionally, multiple spark lesions can develop with high-voltage burns, giving the skin a crocodile-like texture.[12]

Indirect burns are usually the result of arc or flame exposure. An electrical arc can form between two objects of differing potentials that are not in contact with each other. As voltage increases, chances of an arc burn

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IMAGE: ST. STEPHEN'S HOSPITAL, LONDON/PHOTO RESEARCHERS, INC.

FIGURE 1. Full-thickness electrical burn with eschar formation.

without physical contact with the source increase. Arc burns often cause charring with surrounding blanching and erythema. Electrical arcing radiates heat and light, often at temperatures up to 35,000°F, causing deep thermal burns at the point of contact and igniting clothing.[9] A powerful concussive blast often accompanies electrical arcing; this can also cause blunt trauma to the victim. Flame burns result from burning clothes and are not directly related to electrothermal heating.

"Kissing" burns are a unique type of electrical burn confined to the hand. When an individual grasps an object that is in contact with an electrical source, current travels around the flexor creases of the fingers through the damp parts at the skin fold. This increases flexion of the fingers and leads to burns along the flexor creases.

Vasculature

Within the vascular system, electricity can cause vasospasm. An affected extremity may appear pale and pulseless. On the opposite end of the spectrum, electrical exposure can also cause immediate or delayed hemorrhage due to vessel rupture. Thrombosis can occur in arteries and veins, especially in small branches with less aggressive blood flow.

Nervous System

Neurologic dysfunction caused by electrical injury can be central, peripheral, or both and can be immediate or delayed. Nerves are damaged by immediate coagulation necrosis, indirect damage to the myelin sheath, and/or progressive edema from a surrounding compartment syndrome. Brain injuries with associated neurologic dysfunction can be slow to develop. Loss of consciousness caused by electrical injury is usually transient and spontaneously resolving. Persistent depressed level of consciousness suggests more severe underlying injury. Both traumatic and nontraumatic spinal injuries can also occur.

Ocular

Cataract formation can be a sequela of electrical injury and can occur weeks to years following electrical exposure. Cataracts occur most often if current is transmitted transcranially, although there are reports of cataracts developing in arc burns without transcranial or ocular conductance.[13]

Musculoskeletal

The extent of muscle damage from electrical exposure is often greater than exam findings would suggest. Compartment syndromes are common and require decompressive fasciotomy for definitive treatment. Muscle contractures are a common finding in high-voltage exposures and should be addressed early.

Assessment for the presence of long-bone fractures and dislocations should be part of the patient evaluation. Skeletal injuries result from tetanic muscle contractions and blunt trauma, which is usually caused by being thrown from the source, a fall from a height, or a concussive blast. A high-voltage arc can create an immense blast-pressure wave. A bystander at a distance of 2 ft from a 25,000-ampere arc feels a force of approximately 480 lb on the front of the body.[9] Posterior shoulder dislocations, shoulder girdle injuries, and spinal fractures from forceful muscular contractions are common.[14,15] On physical exam, posterior shoulder dislocations present with the arm flexed and internally rotated, with inability to externally rotate. Sometimes the humeral head is palpable under the acromion process posteriorly, but often there is no obvious deformity.[14] The axillary Y-view is the preferred plain radiograph to use for evaluation.[14] In complicated cases involving fracture and dislocation, CT may be helpful (Figure 2).

Gastrointestinal

Internal abdominal injuries (both solid and hollow organ) can occur from transmission of current through the abdomen or from blunt trauma. These injuries can be difficult to assess on physical exam alone. Viscous organ necrosis and perforation, ileus, and duodenal stress (Curling) ulcers all can occur. CT of the abdomen/pelvis may help with diagnosis of perforation and hollow viscous injury, although diagnosis of these injuries is difficult and often delayed.[14]

Renal

Acute renal failure can occur in high-voltage electrical injuries. This results from direct electrothermal injury to the kidneys and/or deposition of hemochromogen from muscle damage into the tubules. Myoglobinuria (which contains hemochromogen) is present in a minority of electrical injuries (14%).[16] Predisposing factors for myoglobinuria include high-voltage exposure, prehospital cardiac arrest, full-thickness burns, and compartment syndromes.[16] In general, household-level voltages are insufficient to result in muscle damage capable of causing myoglobinuria, unless there is more than brief contact with the electrical source.

PEDIATRIC CONSIDERATIONS

Most children (90%) presenting to the emergency department with electrical injury have sustained minor injuries caused by household electrical current originating from cords or outlets.[17] In a minority of children, the injury is severe and is associated with high-voltage or water contact. Two-thirds of pediatric electrical exposures involve preschool-age children. Higher-voltage injuries occur most often in older children.[17]

Children who chew on an electrical cord often sustain a facial burn with a characteristic complication. This type of electrical injury is usually an arc burn involving the upper lip. An eschar usually develops at the site of the burn. Initially, bleeding may not be apparent due to labial artery spasm, thrombosis, or the overlying eschar. In 10% of patients, delayed severe bleeding from the labial artery occurs when the eschar separates.[7,14] This usually occurs within 5 days but can occur up to 2 weeks following the initial incident. Bleeding can usually be controlled with direct pressure; therefore, it is

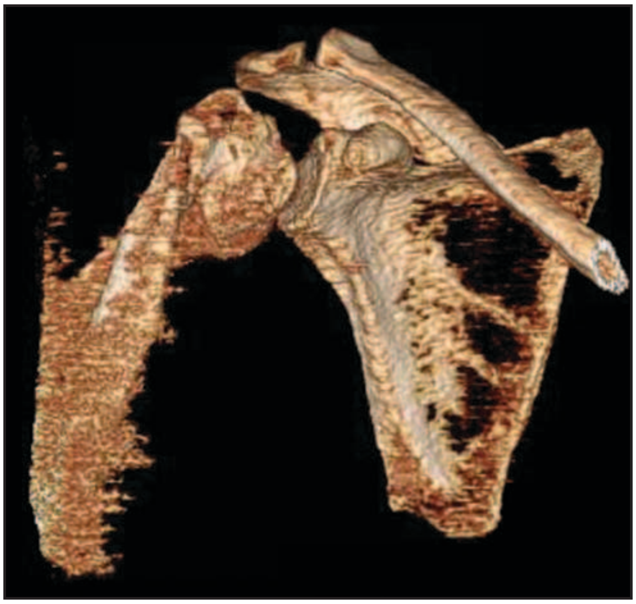

IMAGE COURTESY OF BARRY KNAPP, MD

FIGURE 2. Electrical injury involving the shoulder. Reformatted CT image shows posterior right shoulder dislocation along with spiral fracture of the humeral head.

imperative to provide appropriate education to parents or caregivers. Early plastic or oral surgery follow-up (within 1 to 2 days) is recommended for these types of injuries.

EVALUATION AND MANAGEMENT

The medical literature does not clearly define an evidence-based approach to the evaluation and management of patients with electrical injuries. Even so, many of the treatment priorities and modalities parallel those that are used for major trauma patients. As with standard trauma resuscitations, the emphasis is on airway, breathing, and circulation. History taking should focus on the events surrounding the injury, with attention to voltage, duration of exposure, and whether the patient was thrown from the source. As with all trauma patients, a thorough physical exam should be performed. The head, neck, chest, abdomen, and pelvis should be closely examined. If current has passed through the pharynx, significant upper airway edema can occur, possibly necessitating prophylactic intubation. Careful examination of the spinal column should be performed. A neurologic exam evaluating for motor

Case 3

A 3-year-old girl presents to the emergency department after sustaining an electrical injury while chewing on a household electrical cord. The mother says the child cried immediately after, but she is now consolable and without obvious other injuries or complaints. Clinical evaluation shows only a mildly swollen left upper lip with a 1-cm black eschar and no bleeding. Gentle wound cleansing is performed by the emergency physician. The child is appropriately discharged without further monitoring or diagnostics. Discharge instructions include daily saline oral rinses and topical antibiotics to promote healing. The parents are counseled to be aware of potential bleeding complications. They are instructed to apply direct pressure if this occurs and to return to the emergency department. They are referred to a plastic surgeon for follow-up consultation in 24 to 48 hours to monitor wound healing and assess the need for wound debridement.

and sensory dysfunction is important, as peripheral neurologic deficits can be delayed. Pulses should be palpated in all extremities. Joints should be palpated with range of motion to evaluate for dislocation or fracture.

Laboratory testing should be directed by the history, exam findings, and condition of the patient. Asymptomatic patients who have only small burns and were involved in minor events do not require laboratory evaluation (CK, urinalysis).[7] Patients with obvious serious injury or concerning factors in the history should have a thorough workup that includes basic blood work and standard imaging to evaluate for traumatic injury. CT of the head should be obtained in the setting of altered level of consciousness. Imaging of the cervical spine should be considered and is especially important in the setting of altered level of consciousness and associated blunt trauma. Additionally, ECG should be performed in symptomatic patients.

Severe electrical burns should be treated more like crush injuries, owing to the inability to quantify the degree of damage based on outward appearance. The Parkland formula underestimates required intravenous fluids.[7] A Foley catheter should be placed to monitor urine output. Fluid resuscitation with isotonic fluids should be directed at maintaining a urine output of 1 to 1.5 mL/kg/h.[8] Urinary alkalinization using sodium bicarbonate to promote heme excretion may be considered. It should be noted, however, that some authors suggest maintaining an arterial pH greater than 7.45 to guide therapy, given the inaccuracy of urine pH.[7,8] Mannitol can be a useful adjunct to augment urine output. Some authors recommend 25 g as an IV bolus, followed by 12.5 g/h if the initial bolus does not clear the myoglobinuria.[14,18]

Local burn care with silver sulfadiazine or mafenide acetate should be performed. Mafenide acetate is associated with better eschar penetration, but in large doses it causes electrolyte and pH abnormalities, given its inhibition of carbonic anhydrase.[12] Tetanus vaccination should be updated. In high-voltage injuries, stress ulcer prophylaxis with a proton pump inhibitor or H_2 blocker should also be initiated.

Early fasciotomy or surgical debridement of necrotic muscle may be warranted when severe acidosis and myoglobinuria do not rapidly improve with aggressive resuscitation; management in a burn center in which these injuries can be monitored closely by a burn surgeon is optimal.[18] Although routine fasciotomy has been advocated, a review of national trends in management of patients with electrical burns supports selective decompression.[19]

Pregnant Patients

Pregnant women with electrical injury are a unique patient population. In a review of the literature regarding pregnant patients with electrical injury, Fish found studies showing both high and low incidence of fetal demise after minor electrical contact.[20] Placental abruption, the most common cause of fetal demise after blunt injury, has been observed following electrical injury. Evaluation for placental abruption should be undertaken in pregnant patients with a fetal gestational age greater than 20 weeks. This should occur even in the setting of minor blunt trauma. A common misconception is that ultrasonography is adequate to screen for placental abruption. In fact, cardiotocographic monitoring of fetal heartbeat and uterine contractions is the most appropriate tool.[21] Fetal distress as documented by cardiotocographic monitoring provides indirect evidence of placental abruption.

DISPOSITION

Transfer to a regional burn center should be strongly considered in all high-voltage exposures. High-voltage electrocution victims, those with concerning signs or symptoms, and those with abnormal laboratory results should be admitted for further evaluation and monitoring.[7]

Traditionally, management guidelines for persons who have been exposed to transthoracic current or experienced tetany have included admission for cardiac monitoring. A recent prospective study by Bailey et al refutes this recommendation.[22] These authors concluded that asymptomatic patients with transthoracic current exposure and/or tetany and a normal initial ECG do not require cardiac monitoring after an electrical injury with voltage less than 1,000 V and no loss of consciousness.[22]

Most of the medical literature, however, is in agreement that adults and children with low-voltage (110 to 220 V) exposure and no other significant injury can safely be discharged to home.[7,20-24] These patients have been found to have a negligible risk of developing a subsequent cardiac dysrhythmia.[7,20-24] The requirement that asymptomatic patients undergo an initial screening ECG has more recently come into question. Upon review of existing literature, Chen and Sareen concluded that children exposed to common household current, if asymptomatic at presentation and without cardiac arrest in the field, have an extremely low risk for arrhythmia.[25] These authors support an evaluation and treatment pathway that not only excludes cardiac monitoring but also dismisses the need for an initial screening ECG.[25]

There is not much debate that patients with worrisome signs or symptoms should be admitted for a more prolonged evaluation. Inpatient monitoring and evaluation may be warranted for patients with a dysrhythmia, abnormal mental status or physical exam, or extensive tissue damage.[20] Admission may also be advisable when the duration of electrical exposure cannot be ascertained. Pregnant patients without significant injuries can be discharged to home after a period of cardiotocographic monitoring.

Pediatric Patients

Asymptomatic children or children with only minimal burns who were involved in minor events associated with household voltages do not need to undergo ECG or laboratory evaluation (CK, urinalysis); nor do they require admission.[7,17,25,26] As previously noted, children with labial burns can also be discharged to home with proper parent/caregiver discharge instructions, including instruction to apply direct pressure over a hemorrhaging labial artery. Parents should be cautioned that bleeding can occur up to 2 weeks after the injury. Patients with labial burns should be discharged with saline or hydrogen peroxide oral rinses and topical antibiotics to soothe and promote healing.[7,14]

CONCLUSION

Knowledge of the physics and pathophysiology of electrical injuries is essential for the emergency physician. Electrical injuries range from minor to severe, and their depth and severity may be deceiving. Proper risk stratification is essential, and the ability to interpret clinical findings and determine appropriate treatment is crucial. **EM**

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