Annals of Internal Medicine | Review

Narrative Review: Electrocution and Life-Threatening Electrical Injuries

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The authors reviewed the mechanisms and pathophysiology of typically encountered electrical injuries by searching English-language publications listed in MEDLINE and reference lists from identified articles. They included relevant retrospective studies, case reports, and review articles published between 1966 and 2005. The authors also searched the Internet for information related to electrocution and life-threatening electrical injuries. They found that familiarity with basic principles of physics elucidates the typical injuries sustained by patients who experience electrical shock. Death due to electrocution occurs frequently. However, patients successfully resuscitated after cardiopulmonary arrest often have a favorable prognosis. Approximately 3000 patients who survive electrical shock are admitted to specialized burn units annually. Patients with serious electrical burns admitted to the intensive care unit are trauma patients and should be treated accordingly. Initial prediction of outcome for patients who have experienced electrical shock is difficult, as the full degree of injury is often not apparent.

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Patients who experience electrical shock, including being struck by lightning, sustain a wide spectrum of injuries with unique pathophysiologic characteristics that require special management. We review the physics and mechanisms of tissue damage, typically encountered injuries, and the prognosis of patients with severe injuries.

Epidemiology

It is estimated that approximately 1000 people die of exposure to electricity annually in the United States (1, 2). The age distribution of patients who are electrocuted is bimodal; the first peak occurring in children younger than 6 years of age, and the second occurs in persons in young adulthood (3, 4). Electrocution in children usually occurs at home. Most deaths in adults due to electrocution are work related, and electrocution is a frequent cause of occupation-related death. Miners and construction workers account for most of these cases, with rates of 1.8 to 2.0 deaths per 100 000 workers (5). Patients surviving electrical shock represent 3% of approximately 100 000 patients admitted to specialized burn units annually (6).

Physics

Electricity is defined as the flow of electrons across a potential gradient from high to low concentration. This potential difference, expressed in voltage (V), represents the force driving the electrons. The amount or volume of electrons that flow along this gradient is called current and is measured in amperes (I). The impedance to flow is described as resistance (R). Ohm's law expresses the relationship among these factors as $I = V/R$ (**Figure 1**). Using this equation, it is easy to see that current is directly proportional to voltage and inversely proportional to resistance. In alternating current, the direction of electron flow changes rapidly in a cyclic fashion, for example, standard household current of 110 V flows at 60 cycles per second (60 Hertz [Hz]). Direct current, on the other hand, flows constantly in 1 direction across the potential. Examples of entities that produce or carry direct current include batteries, automobile electrical systems, high-tension power lines, and lightning.

The primary determinant of damage caused by direct effects of electricity is the amount of current flowing through the body, which can potentially lead to fatal arrhythmias or apnea. Additional factors that determine damage include voltage, resistance, type of current, current pathway, and duration of contact with an electrical source (7). Joule's law describes the relationship of 3 of the aforementioned factors, with thermal energy generated as follows: Energy (thermal) $= I^2 \times R \times T$, with T representing the time of current flow. This equation demonstrates the relationship of the squared function of current and time and resistance to the amount of thermal energy delivered, which leads to tissue damage.

Tissues that have a higher resistance to electricity, such as skin, bone, and fat, tend to increase in temperature and coagulate. Nerves and blood vessels that have low resistance to electricity ($I = V/R$) conduct electricity readily. The skin has a wide range of resistance to electricity and plays the crucial role of "gatekeeper" when the body is exposed to electricity. Dry skin, which has a higher resistance to electricity than moist skin, may have extensive superficial tissue damage but may limit conduction of potentially harmful current to deeper structures (8). Moist skin receives less superficial thermal injury but allows more current to pass to deeper structures, resulting in more extensive injury to internal organs.

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Figure 1. **Ohm's and Joule's laws.**

Ohm's law states that the amount of current (I) through a material with a given resistance (R) is directly proportional to the voltage across the material:

$$V = R \times I$$

Rearranging the terms, Ohm's law appears as:

$$I = \frac{V}{R}$$

Joule's law expresses the relationship between the thermal energy (heat [E]) generated by the current (I) through material with resistance (R) for the time (T):

$$E = \frac{V^2}{R} \times T$$

Incorporating Ohm's law ($V = R \times I \rightarrow V^2 = R^2 \times I^2$):

$$E = \frac{I^2 \times R^2}{R} \times T$$

$$E = I^2 \times R \times T$$

MECHANISM OF INJURY

Electrical shocks of 1000 V or more are classified as high voltage (9). Thus, low-voltage electrical shocks are less than 1000 V. Although this classification appears to be somewhat arbitrary, voltage is often the only variable known with certainty after exposure to electricity and therefore is the most reasonable marker for categorizing electrical shocks. High-voltage electrical shocks are expected to result in more severe injury per time of exposure. Typical household electricity has 110 to 230 V, and high-tension power lines have voltages of more than 100 000 V. Lightning strikes are can produce 10 million V or more (8).

There are 4 causes of electrocution: 1) direct effect of current on body tissues, leading to asystole, ventricular fibrillation, or apnea; 2) blunt mechanical injury from lightning strikes, resulting in muscle contraction or falling; 3) conversion of electrical energy to thermal energy, resulting in burns; and 4) electroporation, defined as the creation of pores in cell membranes by means of electrical current (10). Unlike thermal burns, which cause tissue damage by protein denaturation and coagulation, electroporation disrupts cell membranes and leads to cell death without clinically significant heating. This form of injury occurs when high electrical field strengths (defined as volts per meter) are applied (11).

Direct current causes a single muscle contraction, often throwing the person receiving the electrical shock away from the source of electricity. Alternating current is considered more dangerous than direct current because it can lead to repetitive, tetanic muscle contraction. In the case of contact between the palm and an electrical source, alternating current can cause a hand to grip the source of electricity (because of a stronger flexor than extensor tone) and lead to longer electrical exposure. The amount of alternating current needed to cause injury varies with the frequency of the current. Skeletal muscles become tetanic at lower frequencies, ranging from 15 to 150 Hz (8, 12). Household electricity (60 Hz) is particularly arrhythmogenic and may lead to fatal ventricular arrhythmias. Alternating current is the most frequent cause of electrocution.

TYPICAL INJURIES

Skin

Burn injuries are categorized into 4 groups: electrothermal burns, arc burns, flame burns, and lightning injuries. We discuss the last in greater detail in the section titled Special Circumstances. Electrothermal burns are the classic injury pattern and create a skin entrance and exit wound. Regardless of the mechanism involved, wounds due to exposure to electricity can be classified as partial-thickness, full-thickness, or skin burns involving deeper subcutaneous tissue. High-voltage injuries commonly produce greater damage to deeper tissues, largely sparing the skin surface. Thus, using estimation of surface burns to guide therapy may lead to critical errors because minor superficial injury may be associated with massive coagulation necrosis of deeper tissue (13, 14).

Respiratory

Respiratory arrest immediately following electrical shock may result from inhibition of the central nervous system respiratory drive, prolonged paralysis of respiratory muscles, tetanic contraction of respiratory muscles, or a combined cardiorespiratory arrest secondary to ventricular fibrillation or asystole. In the last case, respiratory arrest may persist after restoration of spontaneous circulation, presumably because of the inherent automaticity of cardiomyocytes, which cause quicker recovery of cardiac function. If respiratory arrest is not corrected promptly by ventilation, secondary hypoxic ventricular fibrillation may occur (15). Parenchymal lung damage is rarely seen in patients who have experienced electrocution or received an electrical injury.

Cardiovascular

Cardiac effects of electrical shock can be divided into arrhythmias, conduction abnormalities, and myocardial damage. The last category can be further separated into injury due to direct electricity exposure and secondary myocardial injury due to induced ischemia. These effects are not mutually exclusive.

Arrhythmias

Sudden cardiac death due to ventricular fibrillation is more common with low-voltage alternating current, whereas asystole is more frequent with electric shocks from direct current or high-voltage alternating current (16, 17). Experimental studies show alternating current to be more hazardous than direct current applied at the same voltage. In a dog model, ventricular fibrillation occurred 9 times

more often with alternating current than with direct current shocks. Of interest, at voltages ranging between 50 to 500 V, the incidence of ventricular fibrillation was inversely proportional to voltage and the occurrence of ventricular tachycardia and atrial fibrillation were directly proportional to voltage (16). Potentially fatal arrhythmias are more likely to be caused by horizontal current flow (hand to hand); current passing in a vertical fashion (from head to foot) more commonly causes myocardial tissue damage (18–20). Survivors of electrical shock frequently experience some form of subsequent arrhythmia (10% to 46%) (17, 21, 22). The most common arrhythmias are sinus tachycardia and premature ventricular contractions, but ventricular tachycardia and atrial fibrillation have been reported (17, 21–23). Most arrhythmias occur soon after the electrical shock, but delayed ventricular arrhythmias (noted up to 12 hours following an incident) may occur (24). Most patients not experiencing sudden cardiac death have nonspecific ST–T-wave abnormalities on 12-lead electrocardiography (ECG) that usually resolve spontaneously (25, 26). Patients without ECG changes on presentation are unlikely to experience life-threatening arrhythmias (22).

Conduction Abnormalities

Sinus bradycardia and high-degree atrioventricular block have been reported following electrical shocks. Electrical injury caused by alternating current seems to have a predilection for the sinoatrial and atrioventricular nodes (27). The reason for this vulnerability is unclear. It has been hypothesized that the sinoatrial- and atrioventricular-node ion channels are the easiest to disrupt and that ischemia and infarction in the right coronary artery distribution (running closest to the chest surface and supplying both nodes) make the nodes more vulnerable to electrical current. Some of these conduction abnormalities may persist as long-term consequences of electrical injury, and thus sinoatrial and atrioventricular node function should be monitored carefully in patients surviving electrical shock.

Myocardial Injury

Damage to the myocardium may occur after exposure to high- and low-voltage current. Injury is caused directly by electrothermal conversion and electroporation or secondarily by contusion following a lightning strike. Other described mechanisms include coronary spasm leading to ischemia and arrhythmias inducing hypotension and secondary coronary hypoperfusion (28, 29). The diagnosis of myocardial injury can be difficult (mostly because of the diffuse nature of myocardial necrosis), as evidenced by absence of typical symptoms, lack of specific ECG changes, and normal myocardial pyrophosphate scans (30). Creatine kinase–MB subfraction elevations are frequent in patients following electrical shock, but their significance in this context is unknown (30–32). Troponins have not been evaluated sufficiently in this setting. Rare vascular complications include arterial spasm or rupture, as well as venous and arterial thrombosis (33, 34).

Musculoskeletal

Bone has the highest electrical resistance and experiences the most severe electrothermal injuries, including periosteal burns, destruction of bone matrix, and osteonecrosis (8). Forceful tetanic contractions or falls can cause fractures and large-joint dislocation (35). Electrothermal injury of the musculature may manifest as edema formation and tissue necrosis and may lead to the compartment syndrome and rhabdomyolysis (36, 37). The extent of muscle tissue damage can be assessed with serum measurements of creatine kinase. In a series of 42 patients with electrical burns, the average creatine kinase level was severely elevated at 18 903 U/L on the day of admission (38). The degree of elevation of creatine kinase levels correlated with the amount of burned total surface area, and investigators postulated that it might be used as a decision aid for early surgical decompression.

Neurologic

Electrical shock can damage the central and peripheral nervous system. Loss of consciousness, generalized weakness, autonomic dysfunction, respiratory depression, and memory problems are frequent manifestations. *Keraunoparalysis* is a specific form of reversible, transient paralysis that is associated with sensory disturbances and peripheral vasoconstriction and is seen in some patients following lightning injury (39). Such patients may have fixed and dilated pupils (due to reversible autonomic dysfunction), characteristics that should not lead to termination of resuscitation efforts. Central nervous system complications also include hypoxic encephalopathy, intracerebral hemorrhage, and cerebral infarction (40). Although sensorineural hearing loss has been reported, hypoacusis is mostly due to rupture of the eardrums, which is common in patients struck by lightning (41).

Special Circumstances

Lightning

Lightning strikes are an unusual form of trauma, accounting for approximately 150 to 300 deaths annually in the United States (42, 43). Lightning strike is unique because it causes cardiac and respiratory arrest, resulting in a 25% to 30% mortality rate (44). Several differences between lightning strikes and other high-voltage exposures have been summarized in excellent reviews specifically addressing the topic (40, 45, 46). Lightning delivers a large amount of direct-current electricity (up to hundreds of millions of volts and 200 I) during a very short period (milliseconds). Thus, according to Joule's law, the actual amount of energy delivered may be less than with other high-voltage electrical injuries because of the short exposure time (**Figure 1**). Unlike patients who have experienced

Figure 2. **Lichtenberg figures caused by lightning strike in a 54-year-old man.**

The fern-like pattern vanished within 2 days. (Adapted with permission from the *New England Journal of Medicine* [49]).

electrical shock, those struck by lightning rarely sustain extensive tissue destruction or large cutaneous burns; thus, the principle of aggressive fluid resuscitation for those who have been electrocuted does not apply in patients struck by lightning. The mode of cardiac arrest in patients struck by lighting is asystole, with frequent spontaneous restoration of an organized cardiac rhythm (47). However, concomitant respiratory arrest is often prolonged, and without ventilatory support, apnea results in hypoxia-induced ventricular fibrillation. Thus, the duration of apnea, rather than the duration of initial asystole, has been considered the critical factor in survival of patients who have been struck by lightning (48).

Although rarely seen, Lichtenberg figures are pathognomonic skin manifestations in persons struck by lightning (**Figure 2**) (49). Lichtenberg figures are transient in nature and do not cause apparent damage to the epidermis or underlying tissues (50). They are typically formed by rapid dispersion of charge from the surface of poorly conducting tissues.

Cardiopulmonary Resuscitation

Aggressive and prolonged cardiopulmonary resuscitation (CPR) of patients who have experienced electrical shock is indicated for several reasons (18). First, cardiac arrhythmias and prolonged respiratory arrest may be the only clinical problem, especially in patients struck by lightning. Second, as mentioned, patients who experience electrical shock are commonly young and have few or no comorbid conditions. These young patients may survive prolonged CPR with no or minor sequelae. It is important to remember that keraunoparalysis leading to autonomic dysfunction may masquerade as irreversible neurologic injury in patients who have been electrocuted. For practical purposes, guidelines for CPR as issued by the American Heart Association (51) still apply. The algorithm for asystole acknowledges that "atypical clinical features" need to be considered in deciding whether CPR should be continued after initial unsuccessful attempts.

If more than 1 person who has been electrocuted is found at a scene of injury, standard triage practices need to be modified, especially in those struck by lightning. Most patients who do not experience cardiac or respiratory arrest will survive (44). Thus, the usual triage principles should be reversed: First responders should focus initially on patients who appear clinically dead before patients who show signs of life are medically managed (48, 52).

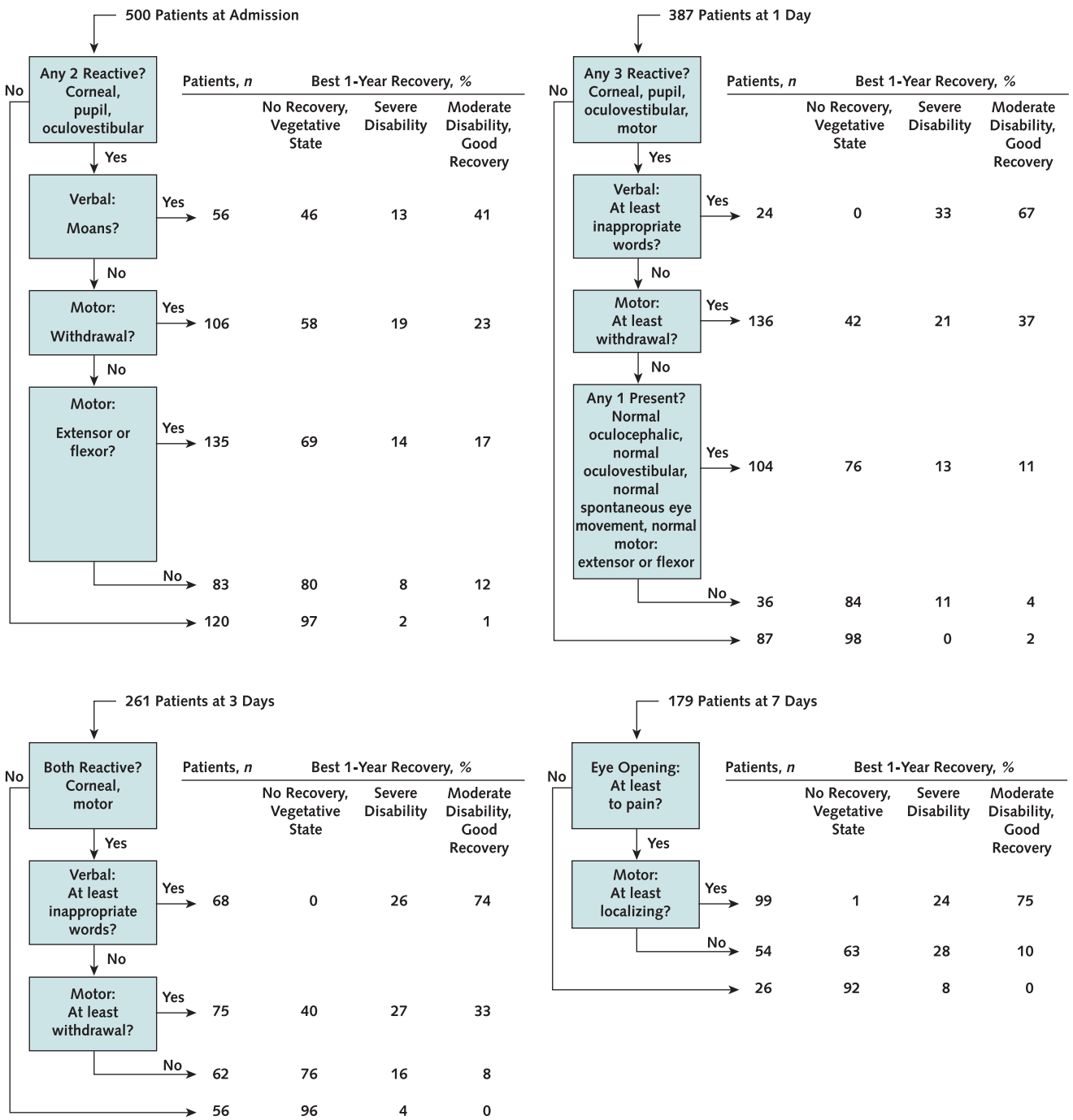
Pregnant Women and Children

Fetal injury and death have been described following minor electrical injuries to pregnant women; the causal relationship, however, has been questioned. The estimated prevalence of fetal death following accidental electrical injury ranges from 6% to 73% (53, 54). Younger children commonly have oral injuries caused by primary contact with household electrical cords (3). Older children frequently experience high-voltage injuries from power lines while climbing balconies, trees, or utility poles (8, 55). Following hospital admission, pediatric patients rarely experience cardiac arrhythmias; their only described ECG abnormalities are nonspecific ST–T-wave changes and premature ventricular and junctional complexes (55, 56).

Forensic Cases

Cases of electrocution are relatively infrequent in the field of forensic medicine and involve suicidal electrocution or accidental electrocution during autoeroticism. Suicidal electrocution is usually performed by intentional placement of electrical devices, such as lamps or hair dryers, in a water-filled bathtub. Specific construction of homemade electrocution machines has also been described (57–59). Autoerotic deaths due to electrocution are classified as atypical because suffocation is not the primary mode of death (60). Although a wide range of case presentations has been described, a general set of circumstances can be identified. Those affected are predominantly young to middle-aged men, and cross-dressing and pornographic materials are frequently found at the accident scene (60, 61). These

Figure 3. **Prediction of outcome in nontraumatic patients with coma.**



Adapted with permission from *Annals of Internal Medicine* (63).

features, together with the absence of previous depression and suicidal ideation, help distinguish autoerotic accidents from suicide (62).

Prognosis

It is difficult to predict the outcome of patients admitted to the intensive care unit for electrical shock because the full degree of their injury is often not apparent. However, most patients are young and otherwise healthy, and this suggests a favorable prognosis. Fatal arrhythmias usually occur immediately following the electrical shock. Thus, death in patients admitted to the intensive care unit following electrical injury is, for the most part, not a result of damage to the cardiovascular system. Most patients sur-

viving cardiopulmonary arrest resume spontaneous breathing within 1 hour. Nevertheless, complete recovery has been described after prolonged respiratory arrest. Ventilatory support for patients who have experienced electrical shock should be continued for a reasonable time until cerebral function can be fully assessed (15).

Prediction of neurologic outcome following resuscitation from electrical shock is usually based on the presence or absence of findings compatible with anoxic encephalopathy. However, the most commonly used algorithm for outcome prediction in hypoxic–ischemic coma, as described by Levy and colleagues (63), may not initially apply to patients who survive electrocution (**Figure 3**). Brainstem reflexes and motor responses may be absent because of keraunoparalysis. Therefore, in patients resuscitated following an electrical shock, prognosis should be assessed with great caution and may only be reliable several days after the event, when the direct effects of electrical shock are no longer present. In a retrospective analysis of 59 patients with high-voltage electrical injuries (those resulting from an electrical shock of ≥1000 V), Ferreiro and colleagues (64) did not find the amount of voltage exposure to be associated with greater severity or more frequent occurrence of sequelae.

The extent and depth of burn injuries affect prognosis. Deeper and more extensive burns may require emergent fasciotomy, debridement, and wound exploration. Rehabilitation of patients with burns due to electrical trauma is also a fundamental part of management. The rehabilitation phase begins when wound coverage is near completion (wounds may require autologous skin grafting) and represents an extension of the acute-phase therapy, which includes pain management, wound coverage, positioning, and exercises. Hypertrophic scars are a concern in patients with electrical burns. Young age, prolonged healing times, deep initial wound, and pigmented skin are factors that increase the risk for hypertrophic scars. Various treatments, including pressure therapy, pharmacologic therapy, radiation, laser therapy, cryotherapy and massage therapy, have been used with variable success rates. Selvaggi and colleagues (65) address these issues in greater detail.

Electrical injuries are often avoidable, and preventive measures should be emphasized. In the setting of home accidents, specifically with children, parents should implement such preventive measures as plugs for electrical outlets. In the case of occupational injury, efforts to improve protection of workers at high risk for electrical injury seem prudent. Governmental intervention may be necessary to lead industries in the right direction.

CONCLUSIONS

Electrical trauma causes a wide range of injuries. Knowledge of the basic principles of physics helps explain the typical injuries sustained by patients who have experienced electrical shock. Treating physicians need to be aware of the specific features of each patient's injuries, as well as appropriate treatment options. Individuals treated successfully seem to have a favorable overall prognosis.

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