

10.3.5 Lightning and electrical injuries 1696

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SECTION 10 Environmental medicine, occupational medicine, and poisoning 1696 FURTHER READING Bierens J, et al. (eds) (2006). The handbook on drowning. Springer, Berlin. Hasibeder WR (2003). Drowning. Curr Opin Anaesthesiol, 16, 139–45. Idris AH, et al. (2003). Recommended guidelines for uniform re- porting of data from drowning: the ‘Utstein style’. Resuscitation, 59, 45–57. Papa L, Hoelle R, Idris A (2005). Systematic review of definitions for drowning incidents. Resuscitation, 65, 255–64. Piette MH, De Letter EA (2006). Drowning: still a difficult autopsy diagnosis. Forensic Sci Int, 163, 1–9. Salomez F, Vincent JL (2004). Drowning: a review of epidemiology, pathophysiology, treatment and prevention. Resuscitation, 63, 261–8. van Beeck EF, et al. (2005). A new definition of drowning: towards documentation and prevention of a global public health problem. Bull World Health Organ, 83, 853–6.

10.3.5 Lightning and electrical injuries Chris Andrews ESSENTIALS Lightning Lightning strikes are rare accidents but carry a 10% case fatality, killing 0.1–0.3 per million population each year. During thunderstorms, the risk is increased by sheltering under trees or by being on open water, on tractors, or in open fields or in outdoor activity. Lightning is considered to cause instant asystole. It is suspected clinically if someone is found collapsed in the open with linear or feathered burns (see next), exploded clothing, and ruptured ear- drums. Victims are safe to handle, with most victims showing keraunoparalysis (cold, pulseless, mottled extremities, not unlike compartment syndromes). Immediate cardiopulmonary resuscita- tion is mandatory. Survivors might develop complications including pain syndromes and psychological sequelae. Burns are generally of minor consequence, unlike electrical injury. The most disabling con- sequences of the injury are generally the psychological sequelae. Electric shock The term electrocution implies death from electric shock. Survivors are said to have been exposed to or received an electric shock. Electrocution is the fifth most common cause of workplace death, mainly affecting utilities, mining, and construction labourers. Domestic electrical accidents are common, where contact with over- head power lines, faulty power tools, and particularly using extension cords, are the most common causes, with metal ladders and an- tennae being particularly dangerous. Prevention is by implementing codes of safe practice. Victims of electric shock might suffer prolonged attachment to the source of electric current and must be disconnected from the source before resuscitation. A victim still attached to a

source of current is dangerous to touch. The most expedient method of disconnection is to turn the offending power off. Consequences of the shock include: (1) Immediate scale—ventricular fibrillation, which is the mechanism of fatality, sometimes leading to persistent cardiac dysfunction in survivors; (2) Neurological and muscular manifestations, both early and late, including paraesthesiae, and pareses. In the early stages, generalized convulsions, respiratory embarrassment, due to tetanic spasm, and rhabdomyolysis may occur; (3) Burns, which might be severe and require expert surgical attention. Electroporation (a special form of cell membrane disruption by electric fields) contributes to cell death; delineation using polaxamers can direct the extent of surgical debridement. (4) In the longer term, persistent paraesthesiae and pareses occur, with a particular fatiguability of the musculature, evidenced as loss of stamina. Visual and auditory dysfunction may occur. The most disabling consequence is the psychological syndrome, which has its own unique character. Introduction Lightning is a powerful force; it provides spectacular displays and has evoked an extensive mythology. It is poorly understood in medical terms and it is only recently that its characterization, physically and psychologically, has been made more plain. The comparatively recent discovery and distribution of electricity have had an equally profound effect, and provide truth to the adage that 'electricity is a good servant and a bad master'. Generation of electricity occurs in several ways, but in the final analysis electrons are imbued with energy by a generator of electric current. From any given generator notionally one conductor emanates to be a source of current in the form of electrons, and this current is delivered by the conductor to a location where electrical work can be done. This conductor is generally termed the 'active' conductor. A second conductor is required to return the electrons in a less energetic state to the generator for re-energization. This is the return path, or the neutral conductor. The electrical system is referenced to earth, and the second conductor might indeed be earth. Alternatively, a common method of injury occurs when an individual contacts the active conductor and earth simultaneously. While it could be argued that earth reference creates danger on the one hand, on the other technical considerations show that system stability and predictability is enhanced by earth reference. Epidemiology Lightning injury It is not appreciated that only a small fraction of lightning strike to individuals lead to fatality. The latest accepted case fatality of

10.3.5 Lightning and electrical injuries 1697 lightning shock is 10% and is around 0.3 per million population in the United States of America each year, but fewer than 0.1 per million in the United Kingdom. In the early part of the 20th century, most people struck by lightning were outdoor workers (67%) and outdoor recreationalists (28%). Nowadays, the breakdown is 45% and 50%, respectively, explained by changes in social and work habits. Indoor strikes (e.g. by current conducted through communication or power apparatus) continue to account for about 5% of these accidents, but few fatalities. Men are more often injured than women (1.67 males to 0.33 females); the age group most at risk is 20–29 years. Risky situations include sheltering under trees (particularly), on open water, on tractors, in open fields, and playing outdoor sports, like golf. Regional differences correlate well with storm activity and population density in that area. Electrical injury Electrocution ranks fifth in the causes of workplace death, accounting for the death of 10 000 workers each year in the United States, with a further 10 million being injured. Most of the victims work for utility companies, followed by mining and construction workers. Contact with power lines causes 53% of fatal shocks, and contact with power tools accounts for a further 22%. The most dangerous times of day seem to be between 10.00 a.m. and 3.00 p.m. on Mondays, Tuesdays, and Thursdays. Most of the victims are trade and labouring staff; sales,

clerical, and professional categories are at least risk. Metal ladders and antennae are particularly dangerous and can easily be hoisted into overhead power lines. Codes of safe practice are written accordingly. In domestic situations, contact with overhead lines by ladders and poles is again important. Faulty, including amateur, repair of equipment, and faulty apparatus, wiring, and especially power and extension cords account for large numbers of deaths and injuries. Children are at particular risk. Death from domestic electric shock has shown a marked decrease with the introduction of residual current devices. These are items of good practice, and sense if current is diverted from the active supply to earth rather than neutral, and then interrupt the supply in a matter of milliseconds. These will not ameliorate every accident, but are considered to act in 80% of cases, notably active conductor to earth shocks. While they ameliorate the fatal effects in these cases, victims still can have several of the stated consequences. Mechanisms of injury

Lightning injury Lightning injury may be sustained in five separate ways:

1. A person might be struck directly. This might represent the most common cause of fatality.
2. A nearby object, such as a tree or a building, might be struck, and someone in direct contact with it might receive a shock.
3. Without direct contact an arc might 'jump' to a nearby person from the struck object, thereby generating a 'side flash'. This is particularly dangerous in the unwise event of sheltering under a tree.
4. As current disperses away from the base of a strike to ground, an individual might divert current flowing in the ground through themselves. This is termed 'shock due to increase in earth potential', or simply 'earth potential rise'.
5. A recently documented mechanism is the transient flow of current due to corona and streamer formation around the upper parts of an individual. The current to provide these streamers flows from ground through the individual to project upwards to reach a descending stroke from a cloud. It has been found that both cardiac and respiratory function cease instantaneously under lightning strike, the cardiac arrest being asystolic. Cardiac function restarts under local pacemaker control, but respiratory function does not recommence, and secondary hypoxic cardiac arrest supervenes. The major cranial orifices are portals of entry for lightning current, and from there the pathways to the brainstem are short. Respiratory function is thought to be affected in the brainstem. Fluid channels (cerebrospinal fluid and blood) might be channels to the myocardium. The QT prolongation resulting from lightning injury can predispose to episodic arrhythmias. There is no evidence at all for one dictum, viz., that lightning inhibits body metabolism. Resuscitation is as urgent as with any other injury. There is no evidence for the notion sometimes quoted that resuscitation can be delayed in a lightning victim. There is similarly no evidence that metal on the head, or the presence of a mobile telephone (cellphone), predisposes to being struck. Electrical injury With electric shock, it is important to assess the points of entry and exit and the pathway of current through the body. Once the pathway has been determined, a locus for expected injury can be established, and the flow of current can be estimated from the applied voltage divided by the impedance of the proposed pathway. Most impedance is in the skin barriers, and is nonlinear. There is initial (contact) impedance, which decreases as current flow continues. Impedance also varies with time since application, contact surface area, and frequency. Contacts can be with the active and neutral (return) conductor, or with the active

conductor and earth, with earth providing the return path to the generator. Indeed, these considerations become blurred as most countries operate an MEN distribution system (Multiple Earthed Neutral). In this system, the earth referencing comes about as the neutral conductor is connected to earth regularly along its route back to the generator. Return paths are then shared between earth and neutral. For currents with a frequency of 15–100 Hz, externally applied from hand to hand, or hand to foot, relevant variables characterizing the current are the threshold of perception (0.5 mA) and 'let go' current (10 mA). The threshold of fibrillation (where threat to life can occur) is a higher threshold again. For example, there is a 50% chance of fibrillation when 2000 mA is conducted for 10 ms, or at the other extreme 100 mA conducted for 10 s, in a hand to foot path. Direct internal application of less than 200 μ A to the heart muscle can induce fibrillation. Dangerous current levels as well as impedance parameters are documented in standards.

SECTION 10 Environmental medicine, occupational medicine, and poisoning 1698 Joule heating might account for tissue damage in the path of the current. It can be calculated from the power dissipation in the tissue—the square of the tissue current (often hard to estimate) times its impedance. The complex phenomenon of electroporation, where cell membranes are breached by the electrical induction of unstable pores in the membrane, can also lead to cell death. The complex nature of internal electric fields leads to internal field damage which is difficult to quantify and predict. Presentation of the injured person The presentations and physical consequences of electrical and lightning injury are different, and hence the application of principles from one to the other is invalid, physically. On the other hand, the psychological consequences are similar, and they may be considered together. Lightning injury A witnessed strike offers the best chance of resuscitation. The victim is not dangerous to touch, and does not constitute a risk to the rescuer. Immediate cardiopulmonary resuscitation is paramount. It has been stated that: Any person found with linear burns and clothing exploded off should be treated as the victim of a lightning strike. Feathering burns are pathognomonic of lightning injury and occur in no other type of injury. . . . Another complex diagnostic of lightning injury includes linear or punctate burns, tympanic membrane rupture, confusion, and outdoor location In assessing a lightning victim, the following features must be sought. Cardiovascular and pulmonary consequences Asystolic arrest is the main cardiac event in lightning injury. Electrocardiographic (ECG) findings can take many forms, with ischaemic and infarct forms. They almost invariably resolve completely over time. Alterations in QT interval and arrhythmias of many kinds are seen. ECG changes might not occur until late in the course, and so are poor diagnostic tools. Respiratory arrest is common. A person not suffering cardiopulmonary arrest is highly unlikely to die from lightning strike. Neurological consequences Direct neural injury can occur both centrally and peripherally. All forms of intracranial bleeding have been reported. Direct cerebral damage particularly affects the basal ganglia, cerebellum, and brainstem. Dural tears, scalp haematomata, and fractures are also seen. Seizures occur as a result of anoxia and injury. Peripheral nerve injury, including autonomic injury, can give prolonged and long-lasting disability, which often develops late. Other late features include spinal cord atrophic paralysis, cerebellar ataxia, incoordination, paraesthesiae, and aphasia. Continuing complex regional pain syndromes may be seen. Keraunoparalysis and burns More than 70% of victims demonstrate keraunoparalysis. This is a syndrome of cold, pulseless, mottled, and asensory extremities. The syndrome resembles a compartment syndrome and occurs in the line of passage of the strike current. It resolves spontaneously within 24 h with no

sequelae, and requires no surgical intervention. Burns are of minor consequence in lightning injury, and again require little intervention. Entry and exit burns might be full thickness, though small. Arborescent (feathering) burns resemble fern-like patterns on the skin (Fig. 10.3.5.1). Their aetiology has been convincingly shown to be due to an inflammatory response following field arcing across the skin. They fade within 24 h. Linear burns are due to the passage of hot plasma tongues over the skin. Eschar is simply allowed to separate without further treatment. Flash might be seen, like sunburn or welder's flash, from the profound radiation of the strike. Sheet burns resulting from efflux of hot plasma can be a variant of linear burning, since both seem to follow moisture and sweat lines. There might be contact burns from metal such as buckles and coins. It is said that these are thermal, but doubt has been cast on this. Eye, ear, and explosive injuries The explosive force of the lightning insult blasts clothing apart (Fig. 10.3.5.2), and may cause percussive injury to the lungs and abdominal viscera. Tympanic membranes are usually ruptured, perhaps from the explosive force of the strike. Percussive eye injury, particularly retinal, has been reported. Cataracts can develop much later. Other injuries Renal and haematological damage have occasionally been reported. Several writers examining lightning strike during pregnancy suggest that outcome for a fetus is poor, independent of Fig. 10.3.5.1 Example of keraunographic marking. Courtesy Dr Ajay Mahajan (Mahajan AL, Rajan R, et al. (2007). Lichtenberg figures: cutaneous manifestation of phone electrocution from lightning. *J Plast Reconstr Aesthet Surg*, 61(1),111-13). Reprinted with permission from Elsevier.

10.3.5 Lightning and electrical injuries 1699 that for the mother. Menstrual and sexual difficulties have been reported, though the latter could be more of a psychological nature. Electrical injury In contrast with lightning injury, victims might suffer prolonged attachment to the source of electrical current, making them dangerous to touch. Before resuscitation, they must be separated from the current source, and this usually means interrupting the current flow at the supply point. Burns are far more serious, and might merit intense surgical treatment. The likelihood of internal burning (remembering the possibility of electroporation) might require further surgical intervention. Cardiac and respiratory burns can also occur. Cardiovascular consequences Ventricular fibrillation is the most common fatal cardiac arrhythmia following electrical injury. Cardiopulmonary resuscitation is urgently required. Electricity suppliers have standard first aid/resuscitation procedures. Cardiac dysfunction can persist for long periods, and ECG changes may not resolve. Recent studies indicate the importance of vascular channels for the passage of current. Alterations in vascular function have been documented, and further, similar alterations in vessels remote from the current passage have been demonstrated at the same time. These findings point to humoral factors in mediating electrical injury. The findings also cause us to question whether most of the damage is mediated by current passage through fluid channels, rather than previously claimed nerve conduction. Neurological and muscular consequences Neural injury can be categorized into early and late syndromes, at cerebral, cord, and peripheral levels. Early tetanic muscular contraction locks the victim on to the electrical conductors. This tetany can compromise respiratory function. Neurological injury might be hard to distinguish from hypoxic and vasospastic injury. Similarly, neural injury is often hard to separate from ischaemic injury due to vessel spasm. Early and late generalized convulsions can occur. Pareses and paraesthesiae might develop, both early and late. There is a characteristic easy fatiguing of the musculature, which resembles a profound loss of stamina. In the long term, complex regional pain syndromes and other chronic pain syndromes must be considered. Burns Burns are often severe in electrical injury and merit much treatment effort. Arc and flame burns and contact burns from current entry and exit are seen. For

example, tetanic gripping of the electrical conductor causes grasp burns to the hand. Severe internal thermal or electroporation damage can occur. The management is largely surgical. Joints, ligaments, and tendons might be severely damaged by the heat generated, and osteonecrosis might be seen. Amputations are relatively common. Other aspects Widespread muscle damage generates myoglobin that must be cleared by the kidney with a severe risk of renal damage. Other metabolic and biochemical disturbances secondary to hypoxia might develop. Massive hyperkalaemia has implications for the use of depolarizing muscle relaxants. Eye damage includes retinal damage, with punctation and detachment, and thermal damage to other media. During follow-up the possibility of ocular pareses and cataracts must be recognized. After shock during pregnancy, the prognosis for the fetus is poor. Nonfocal injury is more likely in survivors.

Psychological consequences of electrical

and lightning injuries Although electrical and lightning injuries are fundamentally different in nature and management, their psychological sequelae are similar. Sequelae ('remote symptoms', so-called as they occur with no evidence of current passage through the brain) can be profoundly disabling. They most often come to attention via Worker's Compensation and litigation, and if ignored, do a great disservice to a victim. They can persist for many years and might never resolve. The changes have the features of organic psychological consequences. This is the overall picture, though it might be suggested that a psychological reaction to the loss of function and continuing pain might be functionally generated, although many believe that findings from neuropsychological testing strongly suggest an organic basis. Indeed, recent research in depression indicates that the hippocampus is found to diminish in volume, implicating that such volume changes, together with changes in cortisol and (a) (b) Fig. 10.3.5.2 Reconstruction of external result of a lightning strike. Courtesy Professor Mary Ann Cooper, University of Illinois, Chicago.

SECTION 10 Environmental medicine, occupational medicine, and poisoning 1700 brain-derived neurotrophic factor, are important in causing depressive syndromes. Research in the sequelae of electric shock also shows reduction in hippocampal volume as a direct consequence of peripheral shock. Several of these symptoms develop over time postinjury, and might not be present for some weeks after the initial examination where the emphasis is more on the physical symptoms. The state of the victim, in totality, deteriorates for 12–18 months following the injury, then improves to achieve stability 18 months to 3 years from the injury though falling short of original premorbid function. The remote symptoms follow two major categories—emotional, personality, and behavioural consequences on the one hand, versus cognitive and higher function consequences on the other, with effects on cognitive agility and speed. Table 10.3.5.1 is a summary of psychological findings. An important part of evaluating a victim is to submit them to neuropsychological testing. The aim of such testing, in part, is to objectify the dysfunctions that are seen, and if possible, subdivide them more specifically. It is unfortunate that in evaluating an electric shock victim or a lightning victim, too many examiners regard the psychological syndrome as either representing malingering, or of no consequence, to the victim's severe detriment. It has been documented that assessment by those unfamiliar with the injury overlooks or wrongly diagnoses over 90% of the resulting syndrome features. Treatment of the injuries First, urgent and life-saving treatment must be administered. Secondly, there must be surveillance for delayed sequelae, and thirdly, long-term monitoring for morbidity, including cataract formation and psychological problems. Lightning injury First, the casualty is resuscitated and evacuated. Cardiopulmonary resuscitation is continued until medical emergency help is obtained. Ventilation and cardiac support might be required. ECG monitoring must be used to detect subtle effects like

QT prolongation. Associated trauma is treated. In the long term, patients are observed for development of pain syndromes. Ocular and auditory functions are monitored. Sensitivity to the psychological sequelae is required, and preventive interviewing might be useful. Carbamazepine, gabapentin, clonazepam, flecainide, and mexilitine are useful to control neurally derived pain and resulting weakness. An antidepressant is a useful adjunct to this. Electrical injury Urgent life support is indicated. Ventilatory and inotropic support and correction of arrhythmias may be required together with correction of biochemical abnormalities, and attention to any myoglobinuria. For burns, progressive debridement and/or amputation might be needed. Specialized rehabilitation may be required. Associated trauma is treated. Ocular and auditory functions are monitored, and psychological disturbances are reviewed. In the long term, surveillance is similar to lightning injury. Psychological elements In all cases, the management of the psychological syndrome is paramount and might be the greatest determinant of long-term functional capability. Awareness of the impact of the injury on employment and relationships and social networks is fundamental. Cognitive and computer aids are being developed, and cognitive support is important. Personality change, social withdrawal, sexual dysfunction, with loss of earning capacity, places a large strain on marital partnerships, and this requires special support. An antidepressant such as an SSRI/SNRI (selective serotonin reuptake inhibitor/serotonin and norepinephrine reuptake inhibitor), or a tricyclic such as clomipramine, may be useful. Agomelatine is showing some promise in this application. Early and continuing neuropsychological assessment and support is desirable. Controversy The place of polaxamers in discovering the extent of electroporation and in delineating debridement levels is of great interest. A polaxamer is a polymer with a central hydrophobic chain flanked by two hydrophilic chains. There are multiple variants of each of these elements. In this structure, however, they

Table 10.3.5.1 Proportions and enumeration of remote injuries	
Memory disturbance	71%
Concentration disturbance	63%
Aggression and irritation	67%
Wariness and phobia	58%
Loss of mental powers	50%
Social isolation	38%
Sleep disorder	38%
and others including confusion, word finding disability, anxiety, depression, and learning disorders.	
Subdivisions of remote injuries	
Memory and learning deficits	Globally more
specifically	
Visual	19%
Visuospatial	35%
Auditory	38%
Verbal learning deficit	62%
Verbal fluency deficit	54%
Concentration and attention deficit	46%/42%
Executive function deficit	38%
Reduced executive speed	62%
and others including general and verbal IQ decrease, dynamic coordination decrease, slowed information processing, deficit in fine motor skills, phobia, and anxiety and depression.	

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