Lightning Injury: Occurrence and Medical Treatment

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Abstract Lightning deaths and injuries have greatly been reduced in both number and population-weighted rate in more developed countries in the last few decades. However, this reduction has not taken place in many developing nations. The most important factor affecting lightning casualties is not an excessive occurrence of lightning, although this is often a contributor, but the vulnerability of people in developing nations. In these locations, people continue to rely on subsistence agriculture and have no lightning-safe buildings or vehicles nearby, a poor understanding of lightning, weak medical systems, and no access to lightning data in real time. Although direct strike is often considered the most common mechanism of injury, it is quite rare. Instead, ground current, side flash, upward leader, and direct contact are more common. Injuries are commonly related to cardiac issues and neurologic impacts rather than burns which are usually less consequential. Medical treatment at the time of a mass casualty event should concentrate on those who appear to be dead, and CPR can be lifesaving. Long-term sequelae are often permanent and difficult to manage without substantial intervention which is usually not available in developing areas.

Keywords Isokeraunic level · Kerauna medicine · Injury mechanisms · Barotrauma · Step potential · Ventricular fibrillation

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C. Gomes (ed.), *Lightning*, Lecture Notes in Electrical Engineering 780,
https://doi.org/10.1007/978-981-16-3440-6_8

1 Lightning Injury and Occurrence

A dramatic reduction in lightning casualties has taken place in more developed regions of the world. In contrast, there has not been perceptible progress in many developing countries. Figure 1 shows the latest map of fatality rates by country based on multiple-year publications describing national fatality studies since 1990. Most notable is the concentration of large fatality rates in southern Africa. Note that fatality data are missing in many of the nations in Africa where lightning is frequent (Fig. 2), the countries are densely populated, safe locations from lightning are often not available, and lightning fatality rates are therefore likely to be very large.

Lightning safety can be achieved in well-developed nations due to nearly universal access to well-constructed buildings and fully enclosed metal-topped vehicles that can be reached in very short time periods when lightning becomes a threat. In less developed countries, these refuges from lightning are often not available at all and seldom reachable in a short time. As a result, people are vulnerable to lightning while working in labor-intensive agriculture [1], occupying lightning-unsafe buildings such as schools [3] and dwellings [4], and tending animals and fishing for a livelihood [5]. Compounding this vulnerability is the lack of access to lightning-specific warnings, medical treatment, and the large number of beliefs surrounding lightning due to a lack of knowledge about the scientific nature of lightning as provided in the following chapters of this book. These beliefs and lack of knowledge may actually increase the injury risk by people either not taking action because they believe they are helpless to avert injury or believing they are safe when they are not.

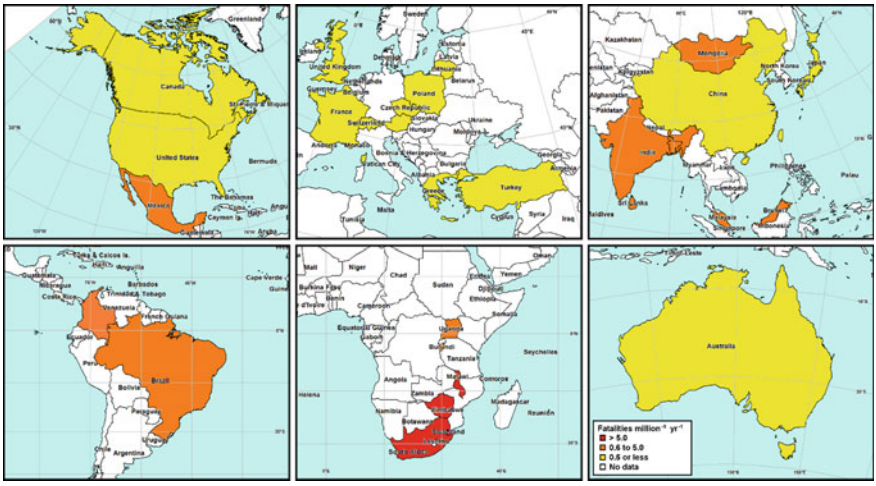

Fig. 1 Lightning fatality rate per million people per year by country. Red shading indicates a rate of more than 5.0 fatalities per million per year, orange is 0.6–5.0, and yellow is 0.5 or less. White indicates no national summaries have been published for datasets ending in 1979 or later (updated from Holle [1])

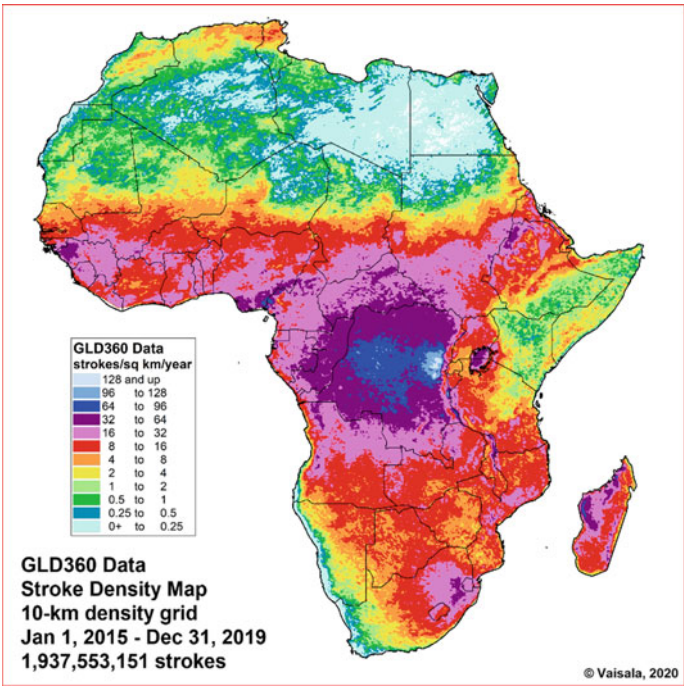

Fig. 2 Lightning stroke density rate per square km per year over Africa, based on 1, 937, 553, 151 detections from 2015 through 2019 by the Global Lightning Dataset GLD360 network [2]

2 Injury Mechanisms and Medical Treatment

i. Mechanisms of injury

Although the pathophysiology of lightning injury could be studied from several approaches, if we want to prevent injury, knowing the mechanisms of injury is the most useful place to start. In this way, we can help construct warnings and lightning safety education that includes the actions individuals can use to avoid injury [5–8].

The five commonly accepted mechanisms of injury have to do with how lightning energy reaches a person [7]. Figure 3 shows the relative distribution of these mechanisms in developed countries. The distribution is not known in developing countries, but ground current is suspected to play an even larger role [5]. A sixth mechanism, blunt or barotraumatic injury from a person being thrown either by concussive force or by induced muscle contraction can be a part of any of the first five as well [9].

1. **Ground current (also called earth potential rise and step voltage)**: The mechanism that kills the most people is ground current, where lightning strikes the surface of the earth and spreads through the earth to injure nearby people. It

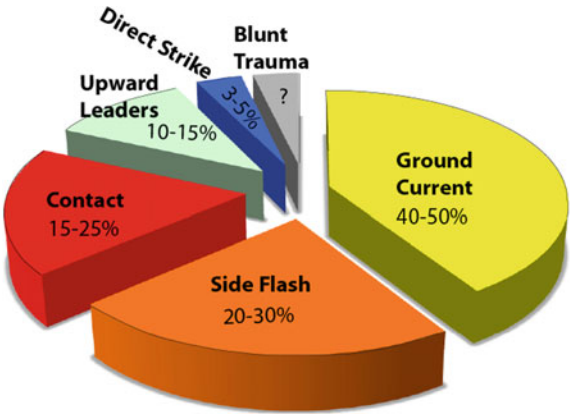

Fig. 3 Relative frequencies of the primary lightning fatality mechanisms [7]

can affect a large number of people, either inside or outside unprotected buildings. Workers in rice paddies, children in classrooms or worshippers at open-air churches are good examples.

2. **Side flash/splash**: This occurs when trees, poles, towers, and many other objects that need not necessarily be very tall are struck and a portion of the lightning jumps to a person nearby. Examples include someone sheltering from the rain under a tree.
3. **Contact**: This occurs when the person is in contact with conducting paths such as plumbing, corded telephones or appliances, headsets, or wiring, either outdoors or inside structures. Contact injury may also occur as animals gather next to long ungrounded wire fences (Fig. 4).
4. **Upward streamer (upward leader)**: Thunderstorms contain strong electrical fields. Whenever a thunderstorm moves across an area, opposite charges are induced on objects on the ground near the cloud including trees, towers, people, and animals. Upward leaders, not usually visible from these objects, will reach up seeking to connect with the downward-moving lightning channel. Even if the lightning attachment (completion of the channel) does not occur, as the upward leader collapses, it contains enough energy to cause injury which has been documented both theoretically and clinically [10–12].
5. **Direct strike**: Contrary to public belief, direct strike is the least common mechanism and causes only perhaps 3–5% of deaths [7]. A direct injury occurs when the lightning stroke attaches directly to the victim and is most likely to occur in the open. While one might intuit that a direct strike is more likely to cause fatalities than the other mechanisms, this has not been shown in any clinical studies.
6. **Blunt trauma (concussive/explosive trauma, barotrauma)**: Blunt trauma has long been suggested as a mechanism in lightning injury. As lightning passes through the air, rapid heating and expansion of the air occurs so that those nearby may experience a concussive force similar to being near an explosion. Blumenthal investigated barotrauma and likened it to being near a blast of 5 kg

Fig. 4 Cows killed by lightning as they gathered by an ungrounded wire fence. This is a common occurrence and can be from contact injury as lightning energy is conducted from a distance or from ground current. Side-flash from the fence is less likely. ©MA Cooper

of TNT [9]. Barotrauma is independent of the other electrical mechanisms of injury but may potentially overlay any of them [5, 7, 8]. Shrapnel from trees or other struck objects exploding can cause injury as well [13]. People who are thrown by lightning experience musculoskeletal injuries, as would be expected [6, 14].

ii. Lightning injury and clinical manifestations

Although nearly 90% of those injured by lightning in developed countries survive, many are left with disabling sequelae [6, 8, 15–19]. The percentage of survivors in developing countries is unknown but may be considerably smaller where people cannot access high quality medical and rehabilitative care [5, 20]. Lightning, despite its extremely high-voltage current, causes substantially different injuries from those caused by high-voltage alternating current electricity as shown in Table 1 [8].

Lightning discharge exerts an electrical effect at the multisystemic level [8]. A wide range of immediate clinical manifestations ranging from minor injuries to serious complications such as cardiorespiratory arrest can occur. Even with early apparently minor injuries, later complications mainly affecting the nervous system are frequent [21, 22]. Although many symptoms occur simultaneously, the clinical manifestations are presented separately in this discussion for academic purposes.

a. Cardiac injuries: The most severe early injury and the most common cause of death is cardiopulmonary arrest [18]. It occurs immediately after the lightning

Table 1 Lightning injuries compared with high-voltage electrical injuries [8]

Factor	Lightning	High voltage
Energy level	30 million volts (V), 50,000 amperes (A)	Usually much lower
Time of exposure	Brief, instantaneous	Seconds
Pathway	Flashover	Deep, internal
Burns	Superficial, minor	Deep, major injury
Renal	Rare myoglobinuria	Myoglobinuric renal failure common
Blunt injury	Explosive concussive effect	Falls, being thrown

discharge and is manifested as absence of cardiac electrical activity (asystole) and respiratory standstill. This primary cardiac arrest may be transient because of the heart's automaticity. This intrinsic property of the heart allows it to restart the cardiac electrical activity and myocardial contraction within a short time. Unfortunately, respiratory arrest may persist, and unless the victim receives immediate ventilatory assistance, attendant hypoxia may induce impaired or irregular heart rhythm (arrhythmia) and secondary hypoxic cardiac arrest [8, 23].

Multiple mechanisms, such as direct thermal damage, coronary artery spasm, increased circulating catecholamine levels, myocardial ischemia secondary to arrhythmia, autonomic nervous system injury and coronary artery ischemia as part of a generalized vascular injury, have been suggested to explain the cardiovascular events following lightning strike [24, 25]. In addition to sudden death, the victim may manifest alterations in the cardiac electrical conduction system (prolonged QTc, dysrhythmias, bundle branch block), myocardial ischemia (chest pain, ST-T segment abnormalities, myocardial infarction without coronary artery disease), cardiogenic shock (Takotsubo-shaped hypokinesis with aneurysmal dilation, abnormal contractility) or hypertension (catecholamine release) [26, 27].

b. Pulmonary injuries: Pulmonary contusion and pulmonary hemorrhage may result from blunt injury or direct lung damage. Other complications include pulmonary edema and aspiration pneumonia secondary to altered mental status [8].

c. Neurologic injuries: Lightning injury is primarily neurologic with damage possible to central, peripheral, and sympathetic nervous systems. Injury to the nervous system causes the greatest number of long-term problems for survivors. The victims can present central nervous system injuries (cerebral edema, intracranial hemorrhages and hematomas, anoxic brain injury, spinal cord injury), peripheral nerve injury and autonomic nervous system injury. Clinical manifestations are altered mental status, coma, agitation, seizures, headache, chronic pain, aphasia, weakness, partial or complete paralysis of one or more extremities, spinal cord dysfunction, and peripheral neuropathy [8, 16, 21].

d. Burns: Less than one-third of lightning survivors have any signs of burns or skin marks. Unfortunately, the lack of burns can result in physician skepticism and legal disputes with workers insurance denial [28–32]. Since the majority of injuries are from mechanisms where the strength of the strike has dissipated due to ground current, contact injury, side flash or upward streamer, and the short duration of the discharge, the flashover phenomenon and lower skin resistance from rain or sweat allow the absence of burns as a reasonable finding [8].
In developed countries, lightning burns tend to be superficial and insignificant compared to the neurologic injuries that are suffered. Burn location provides a prognostic indicator. Cranial and lower-extremity burns are associated with a fourfold and fivefold increase in mortality, respectively, compared to burns in other locations [18]. An occasional, but pathognomonic, finding is the Lichtenberg figure. There are not true burns and usually disappear within hours of the injury [8].
In developing countries, reports often describe lightning victims as "charred" or "burned beyond recognition. In developing countries, where mud brick walls, thatched roofs, and insubstantial buildings are the norm, the possibility of a fire increases (Fig. 5). Keraunoparalysis, a usually temporary paralysis or severe weakness lasting a few minutes to hours, may explain why victims cannot escape from burning buildings [8, 16, 20, 33]. This is present in about one half to two thirds of reported lightning cases [18].

e. Eye and ear injuries: These may be caused by direct thermal or electrical damage, intense light, the shock wave, or combinations of these factors. Clinical manifestations are corneal burns, intraocular hemorrhage or thrombosis,

Fig. 5 Eleven tribal leaders were killed when the thatch building where they were meeting caught fire from a lightning strike (used with tribal permission)

uveitis, macular damage, retinal detachment, optic neuritis, delayed cataract, tympanic membrane rupture, hearing loss, and vertigo [34, 35].

f. Musculoskeletal injuries: Spinal and other injuries may be suffered if the person is thrown by the concussive effect of lightning, by the intense muscle contraction that lightning can induce, or by falls [6, 14].

g. Miscellaneous: Deep muscle damage is rare and may be caused by burns, blunt injury or arterial spasm and secondary ischemia. Compartment syndrome, rhabdomyolysis, myoglobinuria and renal failure are rare. Disseminated intravascular coagulation, sexual dysfunction, menstrual irregularities and other endocrine dysfunction have been reported [8].

h. Psychological and neurocognitive problems: Lightning survivors may suffer temporary or permanent neurological sequalae similar to post-concussive syndrome. Post-traumatic stress disorder, cognitive impairment, severe short-term memory difficulty, attention and concentration deficit, difficulty with learning new information, phobias, emotional lability and irritability, insomnia, decreased exercise tolerance, personality changes and depression are common [8, 36, 37].

iii. Medical treatment

In the event of multiple casualties, victims who appear to be dead should be treated first and aggressively, since these patients may have a good prognosis. Ensuring scene safety is paramount. Rescuers are at risk if thunderstorms are in the area, and, if possible, the victim should be moved to the nearest safe area. Intense vasospasm may prevent discovery of a pulse. If the victim is unresponsive with no pulse or no normal breathing, the victim may have suffered a cardiac arrest and the rescuers should immediately activate the emergency response system and start CPR [23]. CPR may be continued until spontaneous adequate respirations resume, the victim is pronounced dead, the rescuer is exhausted, or there is danger to rescuers' survival [8]. Note that 77% of victims do not respond to CPR [18].

Lightning injury victims should be approached as blunt multiple trauma patients with spinal immobilization and the victim transferred to the nearest health center to perform the medical assessment. Patients with persistent musculoskeletal symptoms, neurologic, cardiac rhythm or vascular abnormalities, or significant burns require admission to a critical care unit. Vital signs are usually stable, but victims may demonstrate acute transient mild hypertension and tachycardia caused by sympathetic activation which usually does not need pharmacological treatment. Hypotension is rare and should prompt investigation for non-visible hemorrhage. Early seizures are probably caused by hypoxia. Any action that improves breathing in addition to administering oxygen can help the victim. If repetitive or recurrent seizures occur or mental status deteriorates, it is necessary to rule out an injury at the brain level [8].

Spinal alignment and immobilization are always required with spinal cord injury-like symptoms such as paraplegia. Keraunoparalysis should be a diagnosis of exclusion. Mottled, pulseless extremities associated with lightning injury often improve over several hours so that fasciotomy is rarely indicated. Lichtenberg figures

commonly disappear spontaneously within hours of the injury. Eye and ear examinations should not be overlooked. Cataracts may develop either immediately or over a prolonged period.

Neurocognitive function and behavior disturbances commonly occur but may not be recognized until a victim returns to work or school. As with other brain-injured people, frustration, impatience, instant rage, and other personality changes may drive away family members, further compromising the survivor's recovery [28, 29, 32]. Unfortunately, there are reports of suicides as survivors become despondent when they cannot find help for their brain injury and other sequelae, may not be able to return to work and lose their homes, or lose the support of their friends and family due to personality changes and other stressors [28, 29, 32]. Some self-medicate with alcohol, drugs, or herbs for their post-injury chronic pain. Family and work dynamics can be difficult.

A further setback to the victim's family, particularly in developing countries such as those in Africa, is a common belief that a family affected by lightning injury is 'cursed' or was punished for bad behavior such as beating their wives or children. The community may shun the entire family so that they have little choice but to leave their community, home and employment to start over in a new community where their tragedy is unknown [38–41].

Even when the family supports the victims, sequelae may exceed their knowledge and ability to cope. This is one of the many reasons the victims often require interdisciplinary assistance services, social, family and community support to avoid isolation and frustration in the face of their new reality.

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