Accidents Resulting from Lightning

Pathophysiology, Pre-Clinical Emergency Medicine, Acute and Long-Term Effect

This pamphlet is aimed at medical personnel and laypersons with some level of medical expertise. It summarizes present knowledge on the effects of accidents involving lightning from various medical points of view, as well as from the perspective of veterinary medicine. The knowledge and recommendations presented are intended to aid in assessing the situation after an accident involving lightning. Recognized medical standards and the guidelines of medical organizations apply for therapy, follow-up care, and evaluation.

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1 Lightning: A Natural Phenomenon.

Lightning is generated by the separation of electrically charged particles in storm clouds. In the process, electrical charges of many tens of millions of volts can occur from cloud to cloud or cloud to earth [7][38]. If this electricity is discharged, it can result in electrical currents of up to 200,000 amperes. During this process, the lightning current immediately heats the air to tens of thousands of degrees Celsius, leading to an explosion of the channel containing the spark [39].

An extremely short but powerful exchange of current is often followed by further electrical discharges within the same channel of lightning: subsequent bolts of lightning with electrical currents of multiple thousands of amperes [40]. Moreover, long stroke currents also occur. These have a comparatively low electrical current (a few hundred amperes), but they can last for up

2 The Dangers of Lightning.

Immediate danger to people (and animals)[1] will always result from: [75]

- A direct lightning flash (Figure 1),
- Arc lightning (Figure 2) that might, for example, strike trees or wooden pylons,

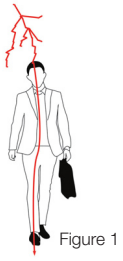
Figure 1

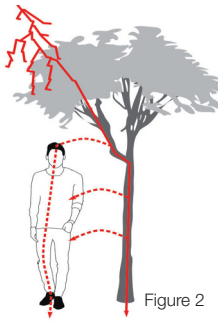
Figure 2

- Contact voltage: When a person touches metal objects such as flood light poles, flagpoles, lightning rods, etc.,

[1] With the exception of section 7, all information that follows applies to people.

part of the lightning current flows through the person (Figure 3),

- Step voltage: The lightning current diffuses across the ground, starting from the point where it struck. A person's legs then create a bridge that allows some of the resulting "step" voltage to travel through the person's body (Figure 4),
- Explosions or fire when the objects struck by lightning explode or ignite.

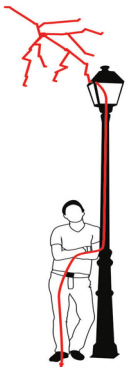

Figure 3

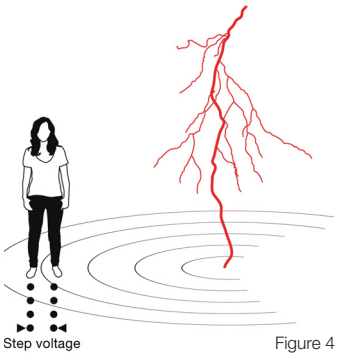

Figure 4

How often these effects of lightning strikes occur is explained in the following table [76].

Table: Effects in Order of Priority
Fire/explosion ("hot" lightning)
Explosive effect (without fire)
Electrical surge (generated in an electrical installation)
Direct lightning flash (to an object or a person)
Arc lightning (that strikes an object or a person)
Step voltage (generated by the voltage funnel that forms)
Contact voltage (when the person touches a conductive object)
Electromagnetic pulse (electronic components may be destroyed)

People should seek shelter as soon as they hear thunder [27][44][60]. As soon as thunder is audible, the storm is less than 10 km away (time interval between lightning and thunder: approx. 30 s). If there has been no thunder for at least half an hour, it is safe to assume that the storm has passed. People may then leave their sheltered areas.

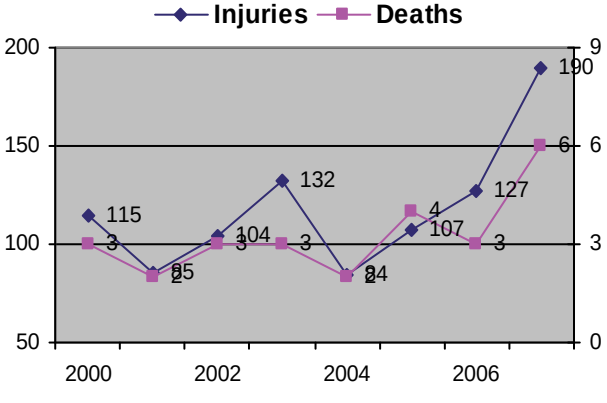

Figure 5: Injuries and Deaths in Germany, 2000 - 2007 [76]

Deaths caused by lightning have become less common in Germany (Figure 5). Unlike open spaces, bodies of water, or forests, closed vehicles or buildings with lightning protection systems provide secure protection. If these are not available, the best strategy is to head for the following areas:

- Buildings without lightning protection systems,
- Large tents with metal frames and grounding stakes,
- Areas surrounded by buildings or metal pylons.

In these situations, people should maintain a distance of at least 3 m from walls and metal components, if possible.

3 Pathophysiology

When lightning strikes the human body, energy is transferred into the body in a number of different ways. [8][55][67]-[69][82]. "Lightning current" is responsible for irritating and heating up bodily tissues. Important factors include:

- The strength of the current flowing through the body (in the case of lightning's impulse current, the electrical charge must also be considered),
- The length of time that the current flowed through the body, and
- The path of the current and the specific resistance presented by various tissues within this path (e.g., bones, skin, muscles, nerves, and blood, or the surface of the body-clothing, skin) [10][11][54][56].

Figure 6 [12]

The arc of light connected to a lightning strike in the immediate vicinity or an area nearby transfer's external radiation energy onto the body's surface in the form of radiated heat and intense light radiation. The skin, eyes, and flammable clothing are most vulnerable to this radiation.

Ultimately, mechanical energy can cause acute trauma via the sudden development of differences in pressure (acoustic shock >145 db) or via secondary explosions [2].

4 Death

Death as the result of a lightning strike is rare, as long as proper aid is rendered quickly at the site of the strike [43][66][81]-[84]. However, when death does occur, it can either happen immediately or after a certain period of time. It should be emphasized that in some cases, an autopsy does not provide concrete proof of the cause of death. This is not surprising, as cardiac arrhythmias, which are named as the main cause of death in the prevailing literature on the subject, cannot be proven by means of morphological examination [82]. In such cases, thermal lesions on clothing or objects that the victim carried on his/her person can provide proof that lightning was the cause of death.

The most recognizable morphological evidence is the Lichtenberg figure on the skin, which can be observed in 20-30% of cases (Figure 6, [12]), but the longer the corpse lies, the fainter this pattern becomes; it may even disappear [12][82][84]. In addition to this lightning pattern, burns on the skin, singed hairs, a certain grouping of tears in clothing, [69] and melted metal components that were close to the skin (e.g., necklace, belt buckle) may help lead to a diagnosis during the necropsy (Figures 7 & 8[2]).

Figure 7

Figure 8

Because torn clothing and concomitant mechanical injuries can create the appearance of a homicide [82], a lightning information system [76] should be used to confirm that the lightning strike occurred at the same time and place as the fatal injuries.

5 Pre-Clinical Emergency Medicine

5.1 Cardiopulmonary Resuscitation

After a person is struck by lightning, unaffected individuals and emergency personnel must recognize the urgency of the situation and implement life-saving measures immediately [59]. Mortality rates for victims are generally estimated at around 10 – 30 % [16][21][68], but comprehensive data for Germany is unavailable.

Case studies indicate that immediately performing CPR on the victim of a lightning flash is often successful and even demonstrates higher success rates than CPR performed on victims of cardiac arrest caused by something other than a lightning flash [32][42][53][59][62]-[64][73]. Even resuscitation measures that are not implemented immediately after the accident are occasionally successful when resuscitation is attempted for prolonged periods of time.

Basic and enhanced resuscitation measures are generally carried out according to international resuscitation guidelines [13][18][51].

5.2 Protecting Yourself

Unlike an accident involving electricity at a low- or high-voltage facility, there is no risk of electrical shock directly after the lightning flash. In that sense, contrary to what might occur after accidents involving technical systems fed by current, it is not possible that the victim's body will contain a residual charge that might harm him/her or potential helpers. The victim may be touched immediately following the accident.

During all life-saving measures carried out in the open, the safety of rescue personnel should take top priority. If there is still a risk of storms, rescue personnel should immediately seek shelter in an emergency vehicle or a building in order to continue resuscitation measures on the patient in safety. If the circumstances prevent adequate therapy from being carried out on a possibly unconscious patient in difficult terrain, only basic resuscitation measures should be attempted. In cases of cardiac arrest, for instance, only chest compressions are indicated [51][85].

5.3 Mass Casualty Incident

Unlike a mass casualty incident involving pure trauma (e.g., a traffic accident), treating unconscious individuals should take priority after a mass casualty incident involving a lightning flash [1][14][17][21][31][62]. This is primarily due to the overall better prognosis if the lightning flash caused cardiac arrest.

6 Acute and Long-Term Effects

Lightning patterns or characteristic marks left by electricity are reliable indicators of a lightning strike [82]. Exposure to electrical, thermal, and/or mechanical energy can primarily lead to unconsciousness, acute paralysis, cardiac arrhyth-

[2] Provided by Dr. Schwark, Institute for Forensic Medicine at Schleswig-Holstein University Hospital, Kiel campus

mia, burns, visual and auditory impairment, direct damage to organs, hemorrhages, a state of shock, or other trauma [26][82]. Particular attention should be paid to the effects on the central and peripheral nervous system. These are addressed in greater detail in section 6.3.

If a medical examination turns up a complex pathophysiological pattern of injury, a range of different medical disciplines must be brought to bear.

6.1 Indications for In-Patient Treatment and Intensive Therapy

It is relatively common for patients to have multiple injuries. Indications for in-patient monitoring include [20][45][50] [52][59]:

- Unconsciousness, disorientation, or seizures,
- Cardiac arrhythmia,
- Injuries (fractures, dislocations, luxations, open wounds, etc.),
- External burns due to arc lightning and/or characteristic marks left by electricity, which raise suspicion of deeper tissue damage, and
- Subjective symptoms such as dizziness, shortness of breath, chest pain, or amnesia.

If there is reason to suspect extensive damage to the skeletal muscles that is not visible from superficial examination, crush syndrome with secondary renal failure may develop. Although burns are not likely to be as severe and extensive as they would be in an accident involving high voltage, the thermal effects of lightning on the skin and inner organs should not be underestimated. Close monitoring should be conducted in order to detect possible aftereffects.

If the lightning flash has also caused explosions or fires, the inhalation of toxic gasses and vapors is a potential risk. Indicators such as singed hair and/or eyelashes, burn marks on the face, or even burns on the skin can serve as red flags.

6.2 Effects on the Heart

Myocardial trauma (which can indicate everything from a functional disruption to rare thermal damage) can result from a lightning flash. For this reason, an EKG should be conducted as soon as possible. While the chance of resuscitation is good, it is safe to assume that the following acute dysfunctions have occurred:

- Respiratory paralysis causes apnea/anoxia, which leads to cardiac arrest in a matter of minutes. However, ventricular asystolia can also be caused by temporary blockage of nerve structures due to the electrical current (depolarization of cell membranes) [24][25].
- Ventricular fibrillation is triggered when surge current occurs during the vulnerable phase of cardiac activity (T wave on an EKG) or the subsequent direct current component (which lasts up to approx 500 ms) triggers ventricular fibrillation via a threshold reduction during the ensuing relative refractory phases [4][57][58].

The following cardiac dysfunctions are consistently reported after EKG monitoring [4][11][55][56][61] [69][71]:

- Arrhythmias (complex ventricular ectopic beats, atrial flutters and fibrillation),
- Issues ranging from nonspecific QT/ST changes to infarctionlike EKG images.

Monitoring/follow-up care for dysfunctions of this nature is required. The changes that initially become evident during the EKG (including infarction-like current waveforms) will disappear within one week to a few months. Further cardiac monitoring is not indicated for patients with a normal EKG, no symptoms, and who did not require CPR [55].

6.3 Effects on the Central and Peripheral Nervous System

The central, peripheral, and autonomic nervous systems can also be temporarily or permanently damaged by high waveform current. Depending on the amount of energy introduced, initially acute neurological damage cannot be ruled out. In the past, this type of damage has been underdiagnosed, largely in view of the fact that its precise pathogenesis remains unknown [48][49]. The most formidable effects include keraunoparalysis (lightning paralysis), unconsciousness of varying duration, disorientation, sensory dysfunctions, cortical blindness, or even circulatory arrest caused by damage to the autonomic nerve system.

Lightning flashes sustained directly to the skull are associated with a particularly high mortality rate. In such cases, contusion spots, hemorrhages, or subarachnoid hemorrhages may occur [2]. Long-lasting myelon damage can occur if the primary flow of the electrical charge travels through the spinal cord. It appears that electricity prefers the preformed conductive paths offered by the central nervous system, myelon, peripheral nerves, and even the vascular system. This is certainly also due in part to the body's subcutaneous adipose tissue, which provides good insulation [80].

If the victim of a lightning flash survives, disorientation can last anywhere from a few minutes to hours; it improves

slowly. Often, the patient will suffer from amnesia regarding events both before and after the lightning flash. Some patients report hearing a boom before everything goes white. They are then unable to see, and they remember nothing else about the event [48]. After the acute phase, they complain of a loss of memory and concentration. These (often unspecific) symptoms should be taken seriously, particularly as they are often perceived differently by caretakers, evaluators, or other people in the victim's surroundings. CT and MRI results generally come back normal [15].

Proper diagnosis of long-term neuropsychological damage requires differential diagnostics. A mini mental test, for example, is by no means sufficient. In the majority of cases, temporal and frontal functions are affected. The severity of the neuropsychological defects is often underestimated; they can potentially cause a 100% reduction in the victim's ability to work. Rapid detection of these defects can ensure astoundingly successful, targeted, and early rehabilitation.

It should be noted that the diagnosis can often overlap with pronounced posttraumatic stress reactions and/or depression. In such cases, it is not always clear whether the depression is a direct, physical result of the lightning flash, or whether it is a depressive reaction to the event and/or the resulting deficits. However, these conditions must be distinguished from understandable anxiety disorders such as keraunophobia or a generalized fear of electric shocks. Behavioral therapy is required in such cases and must be implemented as soon as possible [29].

In the area of the peripheral nervous system, some patients complain at an early stage of non-specific sensory disturbances that are difficult to describe. With the exception of severe localized injuries, tests of motor and sensory nerve conduction, evoked sensory responses, and evoked motor responses will return normal results and thus cannot contribute much to diagnosis or treatment. Because normal nerve conduction and latencies are recorded, the examiner will first establish a normal diagnosis and then assume a psychological component. In such cases, the possibility that thin, unnoticed fibers may have been damaged should not be ruled out. These fibers are also responsible for temperature and pain sensitivity, for example, and damage of this nature can only be detected by means of differential neurophysiological diagnostics (e.g., quantitative sensory testing, microneurography).

In summary, doctors or psychologists who have extensive experience dealing with lightning-flash victims should carry out neurological/psychiatric diagnostics. They will be unlikely to miss significant damage and will be able to prevent the patient from feeling like he/she is imagining symptoms after what was almost certainly a traumatic experience.

6.4 Effects on Hearing and Balance

Lesions on the organs responsible for hearing and/or balance occur in more than half of the victims of lightning flashes [3][74]. The shock wave that develops when a person's head is near a lightning flash is often responsible for these lesions.

These otological injuries are the result of barotrauma, burns, or vasomotor effects [36][47]. In nearly all patients, they are combined with further lesions (e.g., burns on the skin) [74]. The most commonly described injuries are ruptured eardrums in combination with subsequent complications such as hearing loss [74][78][79].

Accidents involving non-wireless telephones typically cause burns to the outer ear canal, perforations of the eardrum, persistent tinnitus, bilateral numbness, vertigo, and/or nystagmus [46].

6.5 Effects on the Eyes

Nearly all injuries to the eyes share significant reduction in vision as a primary symptom. Photochemical reactions generally lead to irreparable damage to all of the frontal segments of the eye, vitreous humor, and retina. Retinal bleeding, macular foramina, arterial/venous central closures, and retinal detachment as a result of hole formation have also been described [5][9][23][28]. Minor lesions can heal without lasting effects; more significant damage may be improved through an ophthalmologist's intervention. The cornea and lens are most frequently affected [33]-[35].

Possible damage includes:

- Lids: Arborescent erythema, torn muscles, burns, ankyloblepharon, contusion spots, pigment disorders [23].
- Eye muscles: Disruptions of binocular vision, nystagmus, acute strabismus with permanent diplopia.
- Keratoconjunctivitis: Photokeratitis with irritation of the conjunctiva and keratitis superficialis, painful damage to the corneal epithelium, scarring of the cornea [34][37][54].
- Eye contusion: The shock wave can cause bruising of the eye with associated anterior chamber and retinal bleeding, dysfunction of the pupil, and deep tears in the tissue. Contusion cataracts, secondary glaucoma, hemorrhaging in the vitreous humor, and retinal detachment as a result of hole formation have been described as immediate or long-term effects [28][35][54][65][74].

- Electric cataract: This opacification, which often occurs with a certain latency, generally affects all segments of both eyes, particularly the rear cortex and capsule [23][33][65].

7 Comparative Insights from Veterinary Medicine

Accidents involving individual animals are relatively rare. Generally, lightning flashes cause mass casualties among animals in a pasture. Cows, horses, and sheep seek safety by huddling under trees or next to pasture fences. Large animals are at particular risk, as they have four feet on the ground and are exposed to higher step voltage than a standing human would be. Characteristic marks left by lightning only occur rarely, but when they do, they are primarily located on the coronary band (the upper limit between the leg and the insulated hoof). Contact voltage is primarily responsible for fatal accidents in stables (pigs, cows).

If an animal is directly struck by lightning, powerful muscle reactions are an expected result, as is the direct flow of electricity through the heart and nerve structures. Additionally, as a result of step voltage, electricity will flow through the animal's body both horizontally and vertically. Consequently, animals such as cows will immediately topple over. Paralysis of the extremities, respiratory failure, and dysfunctions of the cardiac and central nervous systems generally lead to immediate death. Lesions of the myocardium have not been positively identified during autopsy. However, reports have indicated marked tympanites (gas), in some cases associated with bloody foam leaking from bodily orifices, as well as rectal prolapse. Subcutaneous vessels and all organs (including the brain) are often filled with poorly coagulated blood. Additionally, these areas are often interspersed with hemorrhages. The trachea may contain foam and blood. In some cases, broken bones (skull or limbs) are also present [6].

With only a few exceptions, animals tend to recover from minor dysfunctions. The dysfunctions they suffer may be temporary or permanent. Clinical manifestations primarily include dizziness, sensitivity to touch, nystagmus, impaired vision, facial asymmetry (facial nerve paralysis), abnormal posture of the head or neck (accessory nerve paralysis), ataxia, or complete paralysis of the limbs. Cows will appear to "go mad," demonstrating sudden and intense agitation, bellowing, trembling, tossing of the head, wild kicking, rearing or jumping, sudden release of urine, or abruptly lying down and stretching their limbs. It has been reported that their hearts experience a total AV block, failure of the sinoatrial node with subsequent ventricular automaticity, ST elevation, bundle branch block-like widening of the QRS complexes, extra multi-focal ventricular heartbeats with extreme bradycardia and ventricular flutter, and Wenkebach periodicity [22].

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