

REVIEW ARTICLE

Lightning Strike-Mechanisms of Energy Transfer, Cause of Death, Types of Injury

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SUMMARY

Introduction: Lightning can injure via a direct hit, a contact effect, a side splash, a ground strike or a telephone/wire-mediated strike. The flash-over phenomenon is not an independent energy transfer mechanism. It is observed in all energy transfer modes described, and accounts for the fact that many humans survive a lightning strike. **Methods:** Selective literature review.

Results and Discussion: The majority of people hit by lightning strike survive. Lightning victims can die immediately after the lightning strike or after a latency period. Death immediately following the event is usually due to a lethal cardiac arrhythmia with ventricular fibrillation and subsequent or immediate asystole. If the lightning strike is survived initially, ensuing myocardial infarction, shock following burns, secondary renal failure and trauma-related cerebral haemorrhage may occur. A lightning strike can cause numerous different lesions in survivors. Injuries to skin, the heart, the nervous system, ears and eyes are most commonly seen. The management of lightning victims is usually interdisciplinary, due to the complexity of potential injuries. Emergency management of apparently lifeless persons should take priority in a mass accident involving lightning, because of the relatively good chances of success in cardiopulmonary resuscitation of lightning victims.

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Key words: lightning strike, energy transfer, resuscitation, cause of death, emergency

Lightning strikes – in contrast to other high-voltage accidents – are characterized by an extremely strong current and an extremely short exposure period. Injuries result from either the electrical energy, the high temperature, and/or the explosive power of the blast (1, 2). Lightning strikes rarely result in death. Whereas 50 years ago, 50 to 100 people died due to lightning strike in Germany every year, the number of fatalities has fallen continuously, to about 3 to 7 cases per year since 2000 (3). In view of recent events, however – for example, the lightning strikes with numerous injured people during an air show in Hangelar near Bonn in August 2006 and on football pitches in Gelsenkirchen in August 2006 and in Hamburg-Bahrenfeld in June 2007 – this article presents a short overview of the different energy transmission pathways in lightning strikes, of the causes of death, and of frequently observed injuries in people who have survived a lightning strike, on the basis of a selective literature review.

Physical parameters

In a stormy climate, voltages of more than 100 000 000 volt may occur between clouds and earth surface. The lightning discharge takes about 0.02 seconds and is associated with currents of several 100 000 ampere. The air in the lightning channel reaches temperatures of 25 000 to 30 000 °C. The result is an explosive expansion of air, which causes the well known acoustic effects of thunder (4).

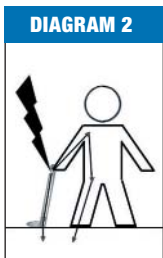
Energy transfer in lightning strike

5 (or 6) mechanisms of energy transfer to humans have been described (5, 6):

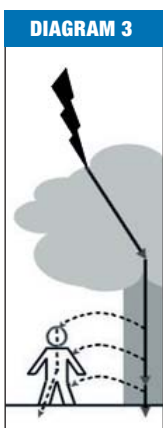
- In a direct strike or direct hit – the type of strike with the greatest potential for serious harm – the main proportion of the current passes through the body. Often, entry wounds are found on head or shoulders, and small, deep holes on the feet or shoes (*diagram 1*).



Direct strike with the current passing through the body



Contact voltage-lightning strikes into an object that is touched by the victim (for example, a golf club)



Side splash, flashing through the air resistance – lightning strikes a nearby object (for example, a tree)

- Contact voltage occurs if lightning strikes an object that is in direct contact with the victim – for example, a golf club. The current passes through the victim's body if this presents the path of least resistance (7) (*diagram 2*).
- A side splash or side flash occurs when lightning strikes another object – for example, a tree – and part of the energy is transferred to a person physically close to the event (8, 9) (*diagram 3*).
- In a ground strike (also known as stride potential, step voltage, grounding, or ground current effect), the person is walking, running, or standing with his/her legs apart up to 200 meters from the lightning strike. A difference in potential develops between the feet so that the current enters the body through one leg and exits via the other (2, 5) (*diagram 4*).
- In a telephone- or wire-mediated strike, lightning may strike a telephone wire directly and as a result the current will pass the telephone set directly, reach the person on the telephone and reach earth via different electrical conductors. But the current in the telephone connection can also be caused by a lightning strike in the electrical cable. The energy passed on to the person is lower than in a direct hit but is particularly directed at the ear (10). Inside buildings, people may be struck by lightning not only when using the fixed telephone line but also while using electrical equipment (1) (*diagram 5*).
- Cooper (5) reports a transfer mechanism that has thus far not been mentioned in connection with lightning strikes. The victim had been working outdoors on a raised platform and had been killed by a discharge in the opposite direction, from the earth upwards to the clouds ("weak upward streamer"). If this case study is confirmed then such upward streamers will need to be classified as the sixth energy transfer mechanism.

The skin effect (flash-over phenomenon) can obviously occur in all of the mechanisms described in this review. The assumption is that the main proportion of a lightning current is conducted alongside the body's surface. The postulated cause is the drop in voltage as a result of the skin's resistance during a brief exposure time. The skin effect explains why people may survive lightning strikes (5, 8, 11).

Postmortem findings

The best known morphological finding in lightning victims is the dendritic lightning figure, which is observed in 20% to 30% of cases and pales or even vanishes the longer the body has been dead (12, 13). Further to the lightning figure, skin burns, singed hair, torn clothes (mostly grouped), and molten metal items worn close to body (for example, chains or belt buckles) may aid diagnosis.

As not all lightning victims have externally visible lesions or conspicuous findings, the risk is that fatalities due to lightning strike may be overlooked in postmortem examinations (14). In Central Europe, all thunderstorms are registered via weather satellites and can be precisely located to within a few meters. Such records can be used in questionable cases of possible lightning fatalities (15).

Torn garments and accompanying mechanical injuries sometimes during postmortem examination lead to incorrect assumption of a killing offense having been committed (13).

Lightning related causes of death

Death can occur immediately after the lightning strike or after a time interval.

Where death has been immediate cardiac arrhythmias are the main cause (9, 16, 17). Karobath et al. (17) have shown that after experimental lightning discharges in animal models, shape changes of the ventricular complexes and cardiac repolarization abnormalities are common, as are sinus bradycardia, Wenckebach's periodicity, extra systoles, ventricular fibrillation, and asystole. In the literature, central respiratory paralysis with secondary circulatory arrest is usually held responsible for death occurring (2, 18). Further, mechanical tears of internal organs have been described as the cause of death (17).

In people who have initially survived a lightning strike, the spectrum of possible causes of death is wider. Myocardial infarction and lesions after lightning strike are observed quite often. Lightning victims also die as a result of their burns injuries, as a result of renal failure in crush syndrome – that is, as a result of damage to the distal renal tubuli parts owing to raised hemoglobin, myoglobin, and protein in the blood after trauma to the skeletal musculature – or as a result of secondary trauma (16, 19–23).

In some cases, postmortem examinations of lightning victims do not yield any cause of death. Cardiac arrhythmias, for example, cannot be seen in morphological investigations. In such cases, thermal lesions on the dead person's clothes or on items carried on the body can help confirm lightning related death (1, 24).

Medical consequences of lightning strike

Many clinical disciplines may be involved in treating the consequences of lightning strike. The hypothesis that the health of survivors of lightning strikes has been completely restored (25) has been disproved by many case reports.

Although Muehlberger et al. (e1) found that 12 patients with lightning related injuries did not have any late sequelae after 6 to 7 years, the annual world congress of lightning survivors in the United States usually sees victims reporting thought disorders, paresthesias, and atrophying muscles, which persist for many years after the incident (e2).

We present the most common medical sequelae related to lightning strike, without any claim to completeness.

Skin

Burns and scalds of all degrees of severity may be caused by the direct effect of the current, overheating of the air, metal objects worn close to the body, and clothes that have caught fire. First or second degree skin burns are most common (11, e3). The extent of body surface affected may vary widely according to the case constellation (e4). High temperatures at the entry point of the current may lead to vaporization of metal (metallization, evaporation).

A typical skin change after lightning strike is the fern shaped Lichtenberg figure, which pales after several hours to days or vanishes altogether (1, 11). Of note: Lichtenberg figures may be found not only on the skin of lightning victims but also on their shoes (e5) or on the soil (23).

In addition to the skin, its appendages, especially hair, may contract thermal damage as a result of lightning energy.

Heart

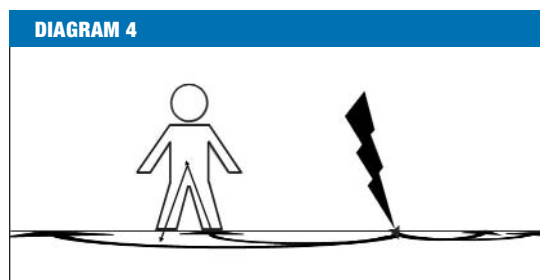
On many lightning strikes, cardiac injuries are found. Especially different arrhythmias and/or conduction disorders, angina pectoris related complaints, acute myocardial infarction, pericardial effusion, and conspicuous heart sounds have been described. Ventricular fibrillation and asystole are the main life threatening conditions related to lightning strike.

Most pacemakers stop working after lightning strike (e6).

In each lightning victim, an electrocardiogram should be taken and in patients who have been resuscitated or who have ongoing cardiac symptoms, long term cardiac monitoring is required (22).

Kidneys

While directly lightning related renal damage is rare, secondary renal failure is one of the most commonly observed complications and may occur with a delay of 3 to 8 days. In most cases, myoglobinuria is the cause, which can result from necroses of the skeletal muscles or trauma (crush syndrome). In severe cases, hyperkalemia with resultant cardiac arrest may develop (22).



Ground strike, where lightning strikes into the ground near the person

Neurological effects

The main neurological sequelae are impaired consciousness, which may vary between disorientation with retrograde amnesia and loss of consciousness. These have either cerebral or cardiac causes (e7).

The neurological deficits affect the cerebral nerves and the remaining peripheral nervous system. Damage to the cerebral nerves may manifest as visual and/or acoustic impairments, pareses of the facial muscles, aphonia and/or swallowing difficulties. In cases where the peripheral nervous system is affected, motor, sensory, and vegetative impairments have been described, as have impaired reflexes, with most of these complaints subsiding in the hours immediately after the lightning strike. Some case reports, however, have documented symptoms occurring only after days or even weeks (e8). Motor deficits can manifest as pareses and paralyses, sensory deficits as paresthesias, hypesthesias, or anaesthesias; the main quality of the pain sensation is reported to be burning. Vegetative deficits include cyanosis, hyperhidrosis, hypertension, loss of bladder tonus, and/or malfunctions of the intestinal motility. The described reflex disorders include hyperreflexia, hyporeflexia, and areflexia (18).

Psychological/mental health effects

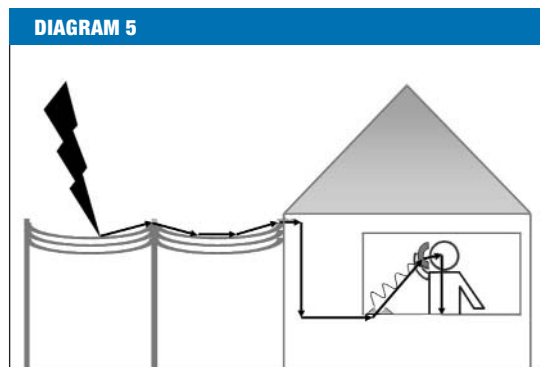
In children, mood changes, excited states, forgetfulness, loss of concentrations, and depressive states have been described, which may be interrupted by periods of emotional lability and fear of death (e9). Adults may also develop depression, which can persist for months. Hysterical behavior as an expression of extreme fear and emotion has been observed in slightly injured patients as well as in witnesses to a lightning strike (8). Further possible psychological sequelae include fatigue, cognitive disorders, photophobia, and post-traumatic stress disorder (e10).

Eyes

The most common lightning related intraocular lesion is the electrical cataract. Such cataracts usually develop 2 to 4 months after the incident, but they may occur instantly or with a delay of many years (11, e11). More rarely, retinal lesions – including chorioretinal atrophy, papilledema, hemorrhage, retinal ablation, macular edema, and hole shaped macular lesions – and lesions to the other visual organs have been reported (11). Occasionally, transient or permanent loss of vision may occur (e12, e13).

Ears

In more than 50% of lightning strikes, lesions to the auditory and/or balancing organs occur (11). The otological injuries are caused by barotraumas, burns, or vasomotor effects (e13). Mostly, ruptured eardrums with resultant complications – for example, hearing difficulty – have been described (7, 11, 23).



Telephone mediated or wire mediated lightning injury – lightning strikes into a conductor and energy is transmitted to the victim (diagrams 1–5 reproduced from: Zack F, Schniers E, Wegener R: Blitzunfall – Vorschlag einer Klassifizierung der verschiedenen Energieübertragungen auf den Menschen. Rechtsmedizin 2004; 14: 396–401; with permission from Springer Medizin Verlag, Heidelberg)

Telephone mediated lightning strikes typically cause burns to the outer ear canal, perforated eardrums, persistent tinnitus, bilateral deafness, vertigo, and/or nystagmus (e14).

In nearly all victims of lightning strike, otological injuries were combined with other lesions – for example, skin burns (11).

Traumatic effects

Traumatic injuries may be due to the direct effects of the lightning strike and to secondary effects – for example, if the victim is thrown against a hard surface or suffers a fall. In addition to the myocardium, the skeletal musculature is vulnerable to electricity related lesions (e15). Since extended necroses of the skeletal muscles may occur without damage to the skin, they are often overlooked in the initial examination of lightning victims and are diagnosed only after notable excretion of myoglobin (21, e4). Lightning related muscle contractions are often so severe that they may lead to bone fractures. In cases where lightning has struck the head, deep seated thermal necroses, skull fractures, and epidural, subdural, subarachnoid, and/or intracerebral hemorrhages have been described (23). The lightning related blast can lead to ruptured internal organs – for example, the bladder – or to vascular ruptures – for example, aortic rupture (e16, e17).

Gynecological and obstetric effects

After lightning strike, disruptions of the menstrual cycle at the level of the hypothalamus have been observed (e18). According to several case reports, the fetus is more at risk from lightning injury than the pregnant woman herself. In 8 case reports, all the women survived, but 4 fetuses died as a result of the lightning strike (e19–e21).

What to remember during resuscitation after lightning strike

People who have been struck by lightning and present with cardiac and respiratory arrest can be resuscitated. Even dilated, unreactive pupils should under no circumstances be interpreted as a sign of death (e6). Where resuscitation was started immediately and continued for a prolonged time period if required, patients have survived without lasting impairments even after an occasionally lengthy time interval between the lightning strike and the start of resuscitation (e22, e23).

Resuscitation of lightning strike victims is more promising than in victims of circulatory arrests due to another cause (1). Karobath et al. (17) assume as the main reason the frequent presence of bradycardic arrhythmias after lightning strike – in parallel to their animal studies – which may temporarily sustain minimal circulation. In contrast, Taussig (e12) assumes that the circulation arrests in the moment the lightning strikes but that the subsequent cellular degeneration proceeds relatively slowly.

The fact that the resuscitation of lightning strike victims has a good chance of success is of particular clinical and legal relevance. Whereas in other mass catastrophes, the primary attention should go to injured parties emitting signs of life, the initial aid measures in a group of lightning victims should focus on the seemingly lifeless victims with circulatory arrest (1, e12, e24).

Conflict of Interest Statement

The authors declare that no conflict of interest exists according to the guidelines of the International Committee of Medical Journal Editors.

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