LIGHTNING-CAUSED ACCIDENTS AND INJURIES TO HUMANS

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Abstract - According to the US NOAA, lightning is the second killer among the four major storm-related hazards, just after floods but before tornadoes and hurricanes. About 100 individuals, on average, are killed annually by lightning in the United States, and more than 500 people are injured. Up to 20 % of lightning victims die. Typical accidents are due to lightning through a direct or indirect strike to human being(s). The possible pathways of interactions between the lightning flash and human body are direct strike, side flash, surface arcing, touch voltage, step voltage, subsequent stroke(s), upward leaders and shock waves. These various kinds of mechanisms are described and some evaluated in terms of electrical parameters. The permanent or temporary injuries that a victim suffers depend, among other parameters, on the type of interaction through which the body is exposed to a lightning strike and the path and the strength of the electric current passing through the body. Signs and symptoms of lightning injury may be moderate, strong or severe. If the victim escapes to death, the after-effects are often lifetime lasting. A new branch of medicine has been devoted to such trauma and called keruonopathology. An important issue is the medical care of victims and the management of specialised rescue teams. Personal safety rules have to be dispatched towards any kind of public, mainly those subject to the highest risk in their outdoors activity (recreation, sports, climbing, sailing, fishing, farming ...). Some very basic rules must be known, such like the 30/30 Rule.

1 INTRODUCTION

Lightning-caused accidents are not always fatal. About 80% of lightning victims can survive, with or without after-effects. During summer 2000, in France, several accidents led to death and so were further investigated. Among them, these two accidents occurred under typical circumstances.

On 20 August 2000, in the centre of Paris, in a large public park (Tuileries Gardens), a young man, 24 years of age, was killed by lightning. He was found lying on the ground, twenty meters from the (metal) park gates. The SAMU team arrived within minutes but could not resuscitate the victim. It was assumed that the lightning had first struck the gates and then the young man, who was walking in the garden during the storm. His cellular telephone was found on the ground, not far from his body. We do not know if he was using his telephone at the moment of the shock, but we note that using a cell phone during a storm does not increase the risks of being hit by lightning; the danger comes from standing up in a storm in an open space. Nonetheless, we also note that it is extremely rare for humans to be seriously injured by lightning strikes in big cities such as Paris, for the enormous number of buildings - most equipped with lightning rods - protects the entire city.

On 21 August, a 13 year-old boy was the victim of a fatal lightning strike, while he was playing soccer with friends, on a public playing field near Thonon les Bains (Haute-Savoie, near Lake Geneva and Switzerland). According to the witnesses, the child's body "smoked" after being illuminated by the lightning; it was a direct hit. In this case, the route of the current was between the neck and the feet (according to the burns at the contact points). In addition the blast had a very marked effect (perforated tympana, multiple haemorrhages, clothes destroyed). This case caused great emotion throughout the country. Two of the other children in the group had minor lesions; all were deeply shocked psychologically by this tragic and unanticipated event. The sky was grey, and it was raining a little, but there had been neither lightning nor thunder. It was stormy in the southern part of the area, but in the north, in the precise area of the accident, Météorage recorded only three ground flashes in 24 hours (the day of 21/08/2000), one around 01:30 am, the other two between 04:00 and 06:00 pm; the child was struck by the third. This accident raises the issue of how to detect and/or protect against lightning in playgrounds and playing fields. Besides the forensic investigation, it has been possible to understand how this poor boy has been struck by lightning using the measurement of the ground magnetisation field using magnetometer.
Such accidents are not frequent but questions arise about their probability, the lightning-human interaction mechanisms, the cause of the death and finally if that was possible to avoid them. This is the purpose of this paper to deal with these items in the light of current knowledge.

2 STATISTICS ON LIGHTNING-CAUSED ACCIDENTS

The reference study is that of Ron L Holle, Raul E Lopez, E Brian Curran in 1999 [47];[9];[21];[22];[24]. Annual summaries of weather impacts based on Storm Data have been published since 1990 by NOAA's National Weather Service. Table 1 shows the number of deaths, injuries, and costs of property damage from four types of convective weather during three recent typical years. Lightning caused 44% of the fatalities, 19% of the injuries, and 3% of the damages for all convective-weather reports, according to Storm Data. Absolute values of these numbers must be considered with caution, however, for reasons given in the next section. When all types of weather-related casualties are examined, Table 2 shows that lightning stays near the top of the list; only flash and river floods rank higher than lightning in terms of deaths.

Knowledge of medical issues concerning lightning victims has grown greatly during the 1990s [1];[2];[4];[5];[6];[7];[8];[29];[6]. This improved understanding of the medical profiles and demographic distribution of lightning victims has resulted in a multidisciplinary effort concentrating on lightning safety and education [30]. A significant emphasis is being placed on sports and recreation [3];[31].

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Reports of damaging weather phenomena are compiled monthly at each National Weather Service office. The reports are sent to NOAA’s National Climatic Data Center (NCDC) in Asheville, N.C. where Storm Data is assembled. This publication has been compiled with substantially the same procedures since 1959. For this paper, an electronic version of Storm Data was obtained from NCDC of only lightning reports. From 1959 to 1994, Storm Data had 3,239 deaths, 9,818 injuries, and 19,814 property-damage reports due to lightning. Each report contains:

- Year, month, day.
- Time in Local Standard Time (LST).
- State and county.
- Number, gender, and location of fatalities.
- Number, gender, and location of injuries.
- Amount of damage.

Lightning-caused casualties and damages are often less spectacular and more widely dispersed in time and space than other phenomena such as tornadoes and hurricanes. Therefore, lightning deaths, injuries, and damages are underreported as follows:

* 33% more lightning deaths in Texas than Storm Data [26].
* 28% more fatalities and 42% more injuries requiring hospitalization in Colorado than Storm Data [25].
* The number of Storm Data events was under-reported by 367:1 in a review of insured personal property in 3 western states [17].

The latter paper leads to the conclusion that lightning-caused damages are actually similar to, or exceed costs of other phenomena in Table 1. When other unquantified losses are considered, lightning may be as large a cause of damages, and have as little change from year to year, as any weather type.
Annual averages of casualties and property damage due to convective weather (thunderstorms) during 1992-1994 (from National Weather Service, Office of Meteorology). Order is by number of deaths per year.

<table>
<thead>
<tr>
<th>Convective weather type</th>
<th>Fatalities</th>
<th>Injuries</th>
<th>Damage ($millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning</td>
<td>51</td>
<td>345</td>
<td>32</td>
</tr>
<tr>
<td>Tornadoes</td>
<td>47</td>
<td>1114</td>
<td>551</td>
</tr>
<tr>
<td>Thunderstorm wind</td>
<td>18</td>
<td>352</td>
<td>192</td>
</tr>
<tr>
<td>Hail</td>
<td>0</td>
<td>21</td>
<td>345</td>
</tr>
</tbody>
</table>

Table 1: Annual averages of casualties and property damage due to thunderstorms during 1992-1994

Factors contributing to underreporting include:
- Most casualty events involve one person.
- The National Weather Service relies on newspaper clipping services for many lightning events in Storm Data [25].
- Lightning is sometimes listed as a secondary rather than primary cause of a casualty by the medical system [26],[23].

Nevertheless, Storm Data is the only consistent data source for several decades. In this report, its information was used without modification.

Summary of 1994 weather casualties, and 30-year normals (from National Weather Service, Office of Meteorology). Order is by 30-year death rate, then by 1994 deaths.

<table>
<thead>
<tr>
<th>Weather</th>
<th>1994 deaths</th>
<th>1994 injuries</th>
<th>Deaths per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash flood</td>
<td>59</td>
<td>33</td>
<td>139</td>
</tr>
<tr>
<td>River flood</td>
<td>32</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Lightning</td>
<td>69</td>
<td>484</td>
<td>87</td>
</tr>
<tr>
<td>Tornado</td>
<td>69</td>
<td>1067</td>
<td>82</td>
</tr>
<tr>
<td>Hurricane</td>
<td>9</td>
<td>45</td>
<td>27</td>
</tr>
<tr>
<td>Extreme temperatures</td>
<td>81</td>
<td>298</td>
<td></td>
</tr>
<tr>
<td>Winter weather</td>
<td>31</td>
<td>2690</td>
<td></td>
</tr>
<tr>
<td>Thunderstorm wind</td>
<td>17</td>
<td>315</td>
<td></td>
</tr>
<tr>
<td>Other high wind</td>
<td>12</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Fog</td>
<td>3</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>388</td>
<td>5165</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Weather casualties in 1994
2.1 Deaths

A more international survey of lightning casualties has been presented at ICOLSE in 2003 and 2007 [33];[34]. Both fatality and injury data are underreported in the best datasets, but death totals are more accurate than injuries. Over multiple decades, the population-weighted fatality rates fall since the beginning of records, mainly due to a major population shift from rural to urban areas, a better meteorological forecast, occupation of large buildings, improved medical care, …Figure 1 illustrates this general tendency for the USA, which is also observed in most of the developed countries [10];[11];[12];[13];[14];[15];[16];[18];[19];[20];[27];[28].

Table 3 exhibits the decadal fatality rate per year from 1900 to 2006 in the USA [32];[34] as a good example of the fatality decay in developed countries.

<table>
<thead>
<tr>
<th>Decade</th>
<th>Decadal fatality rate per year</th>
<th>Maximum annual rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1900-1909</td>
<td>4.8</td>
<td>6.3</td>
</tr>
<tr>
<td>1910-1919</td>
<td>4.5</td>
<td>5.2</td>
</tr>
<tr>
<td>1920-1929</td>
<td>4.1</td>
<td>5.3</td>
</tr>
<tr>
<td>1930-1939</td>
<td>3.2</td>
<td>3.7</td>
</tr>
<tr>
<td>1940-1949</td>
<td>2.4</td>
<td>3.1</td>
</tr>
<tr>
<td>1950-1959</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>1960-1969</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>1970-1979</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>1980-1989</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>1990-1999</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>2000-2006</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Table 3 : Decadal fatality rate per year in the USA from 1900 to 2006

Consistent similar data have been found for Australia, Canada, England and Wales, France, but higher values apply to rural agriculturally-dominated countries. An overall toll of 6 deaths per million people seems to be the most appropriate figure at world scale. This would lead to 24,000 deaths and 240,000 injuries worldwide for lightning every year.

Important documentation has been established for specific types of outdoors activities, generally involving groups of people, sports, motorcycles, mountain climbing, water related injuries [35];[36];[37].
2.2 Injuries

The ratio of injuries to deaths is perceived to be 10 to 1 based on an intensive search of medical reports in Colorado [38]. While the largest fatality event was the Maryland airliner crash in 1963 that killed 81 people, for injuries only, 68% of events have one injury. The largest injury event was 90 at a Michigan campground. The distribution of casualty events closely resembles the injury distribution. The same tendency for single victims was noted in the U.S., Singapore and Australia. We will see later what kinds of injuries are lightning-related.

3 LIGHTNING-HUMAN BEINGS INTERACTION MECHANISMS

Seven kinds of mechanisms have been identified to explain interaction of lightning with humans [39]. Let us summarise them according to Cooray et al [39].

3.1 Direct strike

In the case of a direct strike, the lightning channel terminates on the body exposing it to the full lightning current. The channel may terminate usually on the head or the upper part of the body. It is thought that this accounts for the largest number of deaths. The probability of striking is low (about $5 \times 10^{-4}$ per year) [42].

3.2 Side flash

When lightning strikes, for example, a tree, the current injected by the lightning flash into the tree will flow along the trunk of the tree to the ground. If a human stands close to this tree then, due to a potential gradient, a discharge path may be created between the tree and the human. A portion of the lightning current may flow along this discharge path and through the body to ground. Such an event is called a side flash. It is important to note here that, more than 50% of the lightning injuries that take place outdoors are caused by side flashes from trees, while the tree is being used as a shelter from rain. See figure 2.

Figure 2: Example of side flash from [43]
3.3 Touch voltage

When lightning current flows along an object (a tree or a structure), a potential difference is created between the ground and any other point on the object. If a person happens to be holding an object that is struck by lightning, then this potential causes a current to flow through his body from the contact point to the ground causing injuries. This is called injury due to touch voltage.

3.4 Step voltage

During a lightning strike, the current injected into the ground at the point of strike will flow radially outwards. This current flow will result in a potential difference between any two points located in the radial direction. If a person happens to be standing close to a point of lightning strike, this potential difference known as step voltage, appears between his two feet leading to a current surge through the lower body. The current will enter the body through one leg and goes out from the other. In this case, the current does not flow either through the heart or the brain. The resulting injuries are usually not severe. However, if the person happens to be sitting or lying close to the point of strike, the magnitude and the path of the current through the body may depend on the way in which the body contacts the ground. This is even more important for a four-footed animal, where current may flow from front leg to back leg with the heart in the pathway. See figure 3. In this latter, a proposal for a safety position is illustrated when in open area.

![Figure 3: Example of step voltage and safety position from [43]](image)

3.5 Subsequent strokes

In general, a lightning flash consists of several strokes and the point of termination of different strokes may not be the same. That is, the first stroke of the flash may strike the ground or any other object in the vicinity of a human and a subsequent flash may strike the person concerned directly. In this case, the person will be exposed to the step voltage of the first stroke and the subsequent stroke will strike him directly.

3.6 Connecting upward leaders

Another way in which a person can receive injuries from a lightning flash, although only recently identified [40]) in the literature, is through connecting leader current. As a stepped leader reaches within about a few hundred meters of the ground, several connecting leaders may rise from several grounded objects towards the down-coming stepped leader. Only one of these connecting leaders will make the connection between the stepped leader and the ground. For example, in the case of a lightning strike to a nearby object, a connecting leader may arise probably from the head of a person who is located in the vicinity and cause injuries. The currents in these discharges may reach values as high as several hundred amperes and their duration could be several tens of microseconds. This is an injurious current.
3.7 Shock waves

Finally, injuries can also be caused by shock waves created by the lightning channel. During a lightning strike, the channel temperature will be raised to about 25,000 K in a few microseconds and as a result, the pressure in the channel may increase to several atmospheres. The resulting rapid expansion of the air creates a shock wave. This shock wave can injure a human being located in the vicinity of the lightning flash. The pressure associated with the shock wave decreases with the distance rapidly, so that the shock wave can injure a human being located in very close vicinity of the lightning flash only.

In the case of a lightning strike, only a very small fraction of the current may generally flow through the body and the rest will flow over the surface of the body. As the current through the body increases, a potential difference is created across the body due to its resistance and capacitance. This voltage increases as the lightning current increases. As this voltage builds up, a stage will be reached at which, it increases beyond the voltage necessary to create an electric discharge in air along the skin of the body. When this happens, a discharge channel is created along the outer surface of the body to ground. Since the resistance of this breakdown channel is much less than that of the body, most of the lightning current will follow this external path to ground reducing the current flowing through the body to a small value (40). For example, assume that the height of the victim is 1.8 m. In air, the voltage necessary to create a discharge across a 1.8 m gap is about 900 kV. The voltage needed to create a discharge across an insulating surface of similar length is less than the above value. In the case of the human skin smeared with salt from the sweat it would be even less. Assume, therefore, that the voltage needed to create surface breakdown along the human skin is about 450 kV. Now, the resistance of the body is about 1000 Ω. Thus, when the current through the body reaches 450 A, the voltage across the body reaches the surface flashover value thus leading to a surface discharge. The surface discharge is created long before the lightning current reaches its peak value of about 30,000 A. Now let us consider what happens after this event. The resistance of an arc channel in air is about 1 Ω/m. Thus, the resistance of the surface discharge across the body is about 2 Ω. Thus, the lightning current will be divided between the body resistance of 1000 Ω and the external resistance of 2 Ω. Therefore, at peak current, say 30,000 A, only 60 A will flow through the body and the rest will flow outside. If one assumes that the duration of the impulse current of a return stroke is about 100 μs and the shape of the current is of triangular shape, the total electrical energy dissipated inside the body will be about 120 J. For a 60 kg human, the energy dissipation is about 2 J/kg. The lethal electrical energy based on animal models is about 62.6 J/kg [41]. Thus, the effect of the surface discharge is to reduce drastically both the current flowing through the body and the energy dissipation inside the body. The surface discharge may cause burns, however, and will be referred to later.

The lightning current flowing inside the body, though small, can cause various types of injuries by heating of tissue, electrolysis and by upsetting the electrical state of excitable tissue (i.e. depolarization). These effects are controlled by the way in which this current distributes itself inside the body. This in turn depends on the conductivity of body fluids and different types of tissues in the body. The current flowing outside can also cause injuries from heat and shock waves.

It is also important to note that a single lightning flash can injure several humans at the same time.

4 VARIOUS KINDS OF INJURIES

Several kinds of injuries have been reported by physicians in the various aspects of a new medical science, namely the Keraunomedecine. Let us refer to their classical description [39].

4.1 Respiratory and cardiovascular systems

Cardiopulmonary arrest is the major cause of death, following a lightning strike. With appropriate first aid, it is reversible in some cases. However, the mortality from lightning strike remains approximately 20%. A small number of patients can be successfully resuscitated with external cardiac massage and expired air ventilation after cardiac arrest due to lightning injury, demonstrating the importance of this as primary first aid. There is no support for the dogma that individuals are capable of being resuscitated after a longer than normal period of cardiac arrest.

The function of the heart is controlled by the systematic and sequential electrical depolarization and subsequent contraction of different parts of the heart muscles (myocardium) (see figure 4). The current flowing through the body during a lightning strike may depolarize the myocardium, which may result in myocardial dysfunction including arrhythmias (conduction abnormalities that affect the electrical system of the heart muscle, producing abnormal heart
rhythms, which can cause the heart to pump less effectively), cardiac arrest either in complete standstill (asystole), or in an uncontrolled and unsynchronized contraction pattern of the myocardium known as ventricular fibrillation (VF). In both cases, the forward pumping action of the heart is lost and blood does not then perfuse vital organs. Probably, asystole occurs more often than ventricular fibrillation.

The sequence of electrical activity within the heart occurs as follows. First, the electrical impulse leaves the sinus node (SA node) and travels to the right and left atria, causing them to contract together. This takes .04 s. This electrical activity can be recorded from the surface of the body as a “P wave” on the patient's EKG electrocardiogram (ECG). The basics of an EKG are shown in figure 5. The electrical impulse then moves to an area known as the atrioventricular node (AV node). Here, the electrical impulse is held up for a brief period. This delay allows the right and left atria to continue emptying its blood contents into the two ventricles. This delay is recorded as a “PR interval.” The AV node thus, acts as a “relay station” delaying stimulation of the ventricles long enough to allow the two atria to finish emptying. Following the delay, the electrical impulse travels to the Bundle of His, then it divides into the right and left bundle branches, where it rapidly spreads using Purkinje Fibres to the muscles of the right and left ventricle, causing them to contract at the same time. The spread of electrical activity through the ventricular myocardium produces the QRS complex on the ECG. The T wave represents the repolarization of the ventricles. It is known that the heart is more sensitive to electrical shock during the early T wave. This is the time, the “vulnerable window”, when the ventricles are repolarizing randomly after electrical depolarization, and are potentially at their most disorganized and vulnerable state. Any external electrical current that transgresses this portion of the cycle may produce the most deleterious effects. A lightning strike during the vulnerable window may have more serious consequences on the function of the heart more than other times. Sometimes, though much more rarely than with industrial electrical shocks, the heart muscles can be permanently damaged due to a lightning strike and this may appear as a change in the EKG resembling a myocardial infarction or “heart attack”. EKG changes may also develop subsequently being not apparent at the time of injury. These changes however, generally disappear after a long period of time.

Figure 4 : Anatomy of human heart
It is possible to predict how much current is needed in an industrial electric shock to cause VF. This may be done by estimating the current flowing in a given path from the applied voltage and the resistance of the pathway. Our ability to quantify the injuring agent in a pulse as short as a lightning shock is markedly limited. While for long duration shocks, current seems to be the important parameter, for ultra-short duration shocks, it seems to be the charge transferred, which is the important parameter for estimating injury thresholds.

The breathing action in a human is controlled by the respiratory centres in the brain stem, pons and medulla. They control respiration's rhythm, rate and depth. Current flow through this region may lead to a respiratory arrest (central apnea). The blast associated with the lightning flash can also cause injuries to the respiratory system. Usually, the cardiac arrest caused by the depolarization of the myocardium may recover naturally after the cessation of the current flow through the body, as the heart has its own “intrinsic” pacemaker. The respiratory apparatus does not however, act similarly and remains in standstill. The persistence of the respiratory arrest may secondarily deprive the myocardium of oxygen, leading to a second cardiac arrest. The lack of oxygen to the heart may lead to permanent damage of the myocardium, but more importantly, the lack of oxygenated blood reaching the brain, quickly leads to the death of brain tissue.

4.2 Ocular damage

In the case of a lightning strike, both the current passing through the head and the strong radiation produced by the channel may cause a series of medical problems in the eye (see bibliography in [39]). Figure 6 depicts main parts of the human eye. Many eye problems develop over a long period, and so prolonged surveillance of a lightning strike survivor is necessary. The cataract is the most common long-term injury reported in lightning strikes. The first lightning induced cataract was reported in 1722. A cataract is the clouding of the lens in the eye that affects vision. A cataract can occur in either or both eyes. The lens consists mostly of water and proteins. When the proteins clump up, it clouds the lens and reduces the light that reaches the retina. The cause of the cataract could be the heating of the lens fluids due to the current flow or due to exposure of the eye to very strong optical radiation including ultraviolet light during the lightning strike. Indeed, the lightning channel is a very strong source of ultraviolet radiation and recently, it has been shown that it gives rise to strong X-ray and γ-radiation. In the case of lightning injuries, the cataract may occur days or years after the injury. Cataract has been observed not only in the case of lightning strikes outdoors but also in cases of lightning accidents indoors associated with telephones. In addition to cataract, the observed effects of lightning strikes on the ocular region of human beings are numerous. Indeed, lightning is known to have caused a multitude of ocular injuries. Following is a description of some of them.
The retina is the light-sensitive layer of tissue that lines the inside of the eye and sends visual messages through the optic nerve to the brain. The central region of the retina, which contains a high density of photoreceptors, is known as the macula. The macula provides the sharp, central vision we need for seeing fine detail. During lightning strikes, a small break in the macula can occur, acutely causing blurred and distorted central vision. Such an injury is called a macular hole. The lightning injury may lead to a pulling or shifting of the retina from its normal position. Such damage is called retinal detachment. In addition to retinal detachment, lightning can induce wrinkles in the retinal tissue in one or more areas. They cause small blind spots and are called retinal folds.

The vitreous humor is a clear jelly-like substance within the eye, which takes up the space behind the lens and in front of the retina. The vitreous is attached to the retina; more strongly in some places than others. The lightning injury may cause the vitreous to come away from the retina leading to vitreous detachment. Moreover, a lightning flash can also induce haemorrhages into the vitreous.

Lightning can also cause inflammation within the uveal tract (called uveitis) and in the iris (Iritis). Uveitis may cause extreme sensitivity to light (photophobia) with changes of inflammation. During a lightning flash, strong ultraviolet and high-energetic radiation may enter the eye causing eye injuries. The cornea is a layer of protective and light-transparent tissue covering the iris on the front part of the eyeball. Indeed, it is the cornea that takes the main part of the damage when eyes are exposed to energetic radiation. Some of these damages are corneal burns, swelling (oedema), corneal opacities, ulcers and punctuate keratitis. It may lead to changes in vision or complete loss of vision. Lightning can also lead to double vision (diplopia) and this is due to damage to the muscles controlling eye movement or their various nerve supplies. In this case, the eyes do not track conjointly and this is a very troublesome visual disorder. The ability to read, walk and perform common activities is suddenly disrupted. In one reported case (Stig Lundquist—private communication), after receiving a lightning strike, a young girl experienced inversion of the optical image seeing the outside world upside down for some time.

Lightning victims may exhibit fixed or dilated pupils but this does not suggest bad prognosis.

4.3 Auricular damage

The anatomy of the ear can be divided into three parts, namely, the outer, inner and the middle ear. Figure 7 shows the anatomy of the human ear. The outer ear includes the canal, which ends at the eardrum or tympanic membrane. The middle ear consists of a chamber in which there are three tiny bones (Malleus, Incus and Stapes) called ossicles. The ossicles connect the tympanic membrane to the oval window on the opposite side of the middle ear. Their task is to transmit and amplify sound vibration from external to inner ear. The inner ear contains the cochlea housing thousands of hair cells and nerve endings. They mediate the conversion of vibration into nerve impulses thus transmitting an
image of sound to the brain. The inner ear also mediates the balance mechanism. About 20–50% of lightning-injured victims suffer ruptured tympanic membrane in the ear. The cause for this could probably be the shock wave created by the lightning flash. During a direct lightning strike to the upper part of the body, the ears can be located within a few centimetres from the lightning channel. Calculations by Hill shows that the over pressure within a few centimetres of the lightning channel can reach about 10–20 atm. This over pressure is equivalent to a sound impulse of about 200 dB (taking $20 \times 10^{-6} \text{ Pa}$ as the reference level). In the case of human hearing, the pain threshold level is about 120 dB. In some cases, even if the tympanic membrane remains intact, the victims still may suffer from varying degrees of permanent hearing loss and “ringing in the ear” (tinnitus). This is probably caused by the damage to the hair cells and nerves in the cochlea either from the shock wave or by the flow of current through it. The blast can also cause damage to ossicles that will result in conductive deafness, especially at high frequency. Lightning-induced skull fractures can also cause damage in the middle ear.

![Anatomy of the human ear](image)

Figure 7: Anatomy of the human ear

It is important to note that the special sense orifices in the cranium (eye sockets, ear canals, nasal and sinus passages) have been pointed out as entry points for electric current leading easily to body fluids such as cerebrospinal fluid (CSF) and blood.

4.4 Nervous damage

The nervous system of a human can be divided into two parts: the central nervous system and the peripheral nervous system. The central nervous system consists of the brain and the spinal cord. The peripheral nervous system can be divided into two main parts: the somatic nervous system and the autonomic nervous system. The former sends sensory information to the central nervous system and receives instructional output to motor nerve fibres that project to skeletal muscles inducing voluntary movement. The latter controls the unconscious activity of many internal organs, glands, and other structures. The processing of pain, input to the central nervous system is extremely complex and may mediate long-term pain syndromes, often seen after many physical injuries. During a lightning strike, both the central and peripheral nervous systems are often affected. Indeed, the majority of sequels, following a lightning strike are neurological and they are found in 70% of survivors.

In the nervous system, the lightning generated currents may cause acute traumatic injuries, simply due to the trauma of the insult. These include various types of intra-cranial haemorrhages, swelling of the tissues (oedema), and neuronal injury. These can cause prolonged or even permanent neurological symptoms. The nervous system can also be affected due to the lack of oxygen resulting from the cardio-respiratory arrest. Lightning can also cause intense vasospasm and constriction of blood vessels and restriction in blood flow (and thus oxygen) to a part of the body. The lack of oxygen to a tissue is termed tissue ischemia and can cause further injuries to individual parts of the nervous system. A large current flowing through the brain can also lead to neuronal damage, which can lead to permanent brain damage.

In some cases, one may also observe a delayed onset of neurological disturbances such as epileptic seizures, tremor, progressive hemiparasis (paralysis of half the body), malfunction of nerves and neurological defects in the central nervous system.
Of particular importance is the phenomenon of “keraunoparalysis”. It is a flaccid paralysis of an extremity in the path of the current. It is associated with the pulseless and ischemic limbs. It is suggested that the latter may result from the arterial wall constriction as the current flow along them. Facial nerve palsy may also be an expression of this. Keraunoparalysis is thought to be caused by damage to the small blood vessels accompanying the nerves that control the muscles of the extremity involved, along with ischemia of these muscles. It resolves spontaneously and requires no intervention.

The lightning victim may experience loss of consciousness for varying periods. If the spinal cord is damaged, paraplegia may result. The lightning current can also affect the memory of the victim producing “amnesia”. Many do not have any recollection of the event and in some cases, the memory of the events few days to few weeks before and after the event could be affected. Lightning can cause other specific items of brain dysfunction, for example aphasia, an impairment of language expression. This may affect the production or comprehension of speech. The ability to read or write may also be affected.

In addition to keraunoparalysis, lightning victims may experience weakness, numbness and tingling feelings in muscles and tissues (paresthesias) that may last for several weeks to years.

One case report illustrates the case of growth arrest after a lightning strike. The victim suffered a lightning strike and presented with asymmetric growth arrest 2 years after the accident. During the strike, there was swelling and venous congestion below both knees, multiple blisters on all toes, third-degree burns over right upper arm and first-degree burns over the flank and abdomen. On arrival at the hospital, the victim was conscious and oriented and examination showed no bony deformities.

4.5 Mechanical injuries and burns

It is a hallmark of lightning injury that burns are usually minor and require little treatment. This is in severe contrast with other electrical injuries. Lightning can cause burn injuries ranging between superficial burns to full-thickness burns. Location of burns can be anywhere from head, neck, trunk, upper extremity, hands, lower extremity and legs. There are several ways in which lightning can cause burn injuries. When an electric discharge in air terminates on a solid body, a voltage difference of about 10 V is created across a thin layer of gas and vaporized solid matter. In the case of metal objects, this is called a cathode fall and has a thickness of less than a millimetre. A similar ‘electrode layer’ may arise at the gas to solid interface of the entrance and exit points of the lightning current into and out of the body. The heat generated in this gas layer is proportional to the total charge passing through this layer. This heat can cause full-thickness burns in the body tissue in contact with it. In lightning-burn victims, it is often observed a characteristic burn pattern in the form of small, circular, full-thickness burns involving the sides of the soles of the feet and the tips of the toes. These are probably caused as the lightning current exits from the body by creating an electric discharge between the feet and the ground.

As mentioned previously, as the lightning current passes through the body, it builds up a potential difference between the point of strike and the ground leading to a surface discharge. This surface discharge may follow the surface of the skin. Any discharge in air may heat the discharge channel to several thousand degrees and this heat may cause burn injuries on the skin. Most probably, these will be superficial due to the fact that this discharge channel may be isolated from full contact with the skin through a layer of vaporized moisture on the skin. On the other hand, if the victim is wearing any metal objects such as necklaces, then the surface discharge may intercept the metal object and the full current may flow through it causing it to melt. This molten metal can cause deep burns on the skin.

Many lightning-struck victims also develop a skin discoloration, which looks like red-brown feathery skin markings. These marks, sometimes known as keraunographic marks or arborisation, are probably caused by the streamer-like electrical discharges, connected to the main discharge channel propagating over the surface of the skin. This may be an inflammatory reaction that usually disappears within a day or two. Indeed, the pattern of discharge is very similar to the one that, one can observe when electrical discharges are directed onto insulating photographic paper i.e. Lichtenberg figures (see figure 8).
One has to keep in mind that the nature of lightning injuries depends not only on the parameters of the lightning flash but also on the physiology of the body and on the location of the victim during lightning strikes. For example, there is a case of a soldier who suffered full-thickness burns of the scalp and cranial bones extending down to the dura mater. He, together with four other soldiers, took cover from rain using a thick nylon cover. The burn injuries were probably caused by the heating and vaporization of the water on the nylon cover, which was in contact with the head. Mechanical injuries are mainly due to the fall of the injured victim to ground.

4.6 Psychological damage

It is usual that although physical injury can be marked, it is the psychological components of the injury that cause the most ongoing distress. In addition to physical damage, lightning victims may experience a range of psychological problems. These include the fear of thunderstorms, anxiety, depression, disturbances in the sleeping rhythm, panic attacks (a sudden rush of uncomfortable physical symptoms such as increased heart rate, dizziness or light-headedness, shortness of breath, inability to concentrate, and confusion), and disorders of memory, learning, concentration, and higher mental facility. There was at least one reported case in which, the patient had to be transferred to a mental hospital. Some lightning victims repeatedly re-experience the ordeal in the form of flashback episodes, memories, nightmares, or frightening thoughts, especially when they are exposed to events or objects reminiscent of the trauma, for example thunderstorms or sudden bright lights. This may, in some, be part of a post-traumatic stress disorder. These problems may lead to altered bowel habits, constipation and gastric dilation in which, the stomach becomes excessively dilated with gas, causing it to expand.

4.7 Blast

During the lightning flash, the channel temperature may increase to about 25,000 K within a few microseconds. This rapid heating leads to the creation of a shock wave in the vicinity of the channel. As mentioned previously, the shock wave associated with the lightning flash may reach over pressures of 10–20 atm in the vicinity of the channel. In addition to causing damage in the ear and eyes, this shock wave can also cause damage to other internal organs such as the spleen, liver, the lungs, and the bowel tract. Moreover, it may displace the victim suddenly from one place to another causing head and other traumatic injuries. Indeed, as well as appraising a victim for specific lightning caused injuries, one must always have in mind, associated trauma. In one situation, the victim received fractures of the facial bones during a lightning strike. At the time of strike, he was wearing a helmet and the damage may have been caused
by the intense pressure created by a discharge that resulted during the passage of the lightning current from the helmet to the head across the layer of gas lying between the head and the helmet.

One can also receive blunt injuries from material ejected from the object that is being struck. For example, when lightning strikes trees, the trunk of the tree can explode sometimes and the splinters can cause injuries in those standing in the vicinity. One can also receive blunt injuries from flying objects, also inside buildings. During a lightning strike to an unprotected building, the central power distribution switches, television sets and antenna cables may explode causing injuries. Trauma may also be associated with falls from a region (e.g. a cliff) in which a victim finds himself.

5 LONG-TERM AFTER-EFFECTS [44], [48]

5.1 How Do Lightning Injuries Affect People?

While any death is a blow to a family, eventually the family readjusts and goes on. However, for those who have a relative who suffers significant disability from lightning, life changes forever and the dreams of that family and the survivor may be markedly altered. The family income may be tremendously decreased if the survivor was one of the breadwinners, or the spouse or another family member may have to quit work to care for the survivor if the disability is great enough.

While about one third of all injuries occur during work, workers compensation companies are often reluctant to acknowledge the injury or pay their medical expenses. About another third of injuries occur during recreational or sports activities. The last third occurs in diverse situations, including injuries to those inside buildings. Many injuries in each of these groups can be prevented with proper education, well conceived lightning protection systems that protect the people as well as the equipment being used or ‘shelters’ where the survivor may seek safety, and lightning safety plans for coaches, parents, and referees at sporting events. While lightning safety and injury prevention is an individual responsibility and decision for adults, adults are always responsible for the children in their care, particularly if it is an outdoor sports activity such as soccer, camping, …

Unlike high voltage electrical injuries where massive internal tissue damage may occur, lightning seldom causes substantial burns. In fact, most of the burns are caused by other objects (rainwater, sweat, metal coins and necklaces, etc) being heated up and causing the burn rather than caused by the lightning itself.

Lightning tends to be a nervous system injury and may affect any or all parts of the nervous system: the brain, the autonomic nervous system, and the peripheral nervous system. When the brain is affected, the person often has difficulty with short-term memory, coding new information and accessing old information, multitasking, distractibility, irritability and personality change. A great quote sums it up perfectly: "Patients have difficulty in all areas that require them to analyze more items of information than they can handle simultaneously. They present (appear) as slow because it takes longer for smaller than normal chunks of information to be processed. They present as distractible because they do not have the spare capacity to monitor irrelevant stimuli at the same time as they are attending to the relevant stimulus. They present as forgetful because while they are concentrating on point A, they do not have the processing space to think about point B simultaneously. They present as inattentive because when the amount of information that they are given exceeds their capacities, they cannot take it all in."

Early on, survivors may complain of intense headaches, tinnitus (ringing in the ears), dizziness, nausea, vomiting and other ‘post-concussion’ types of symptoms. Survivors may also experience difficulty sleeping, sometimes sleeping excessively acutely after the injury but changing during the next few weeks to inability to sleep more than two or three hours at a time. A few may develop persistent seizure-like activity several weeks to months after the injury. Unfortunately, standard EEG’s do not always pick up injury in the areas that lightning most often affects leading to a diagnosis of ‘pseudo seizures’.

5.2 Personality Changes / Self-Isolation

Many may suffer personality changes because of frontal lobe damage and become quite irritable and easy to anger. The person who ‘wakes up’ after the injury often does not have the ability to express what is wrong with them, may not recognize much of it or deny it, becomes embarrassed when they cannot carry on a conversation, work at their previous job, or do the same activities that they used to handle. As a result, many self-isolate, withdrawing from church, friends, family and other activities. Friends, family and co-workers who see the same external person,
may not understand why the survivor is so different. Friends soon stop coming by or asking them to participate in activities. Families who are not committed to each other break up.

Obviously, depression becomes a big problem for people who have changed so much and lost so much. Suicide is something that almost all severely injured people have thought about at one time or another. Occasionally, those who do not have access to medical care or who do not understand what is happening may self-medicate with alcohol and other drugs, particularly those who have previously sought solace with these compounds. It is very important that the family and friends of the survivor maintain supportive contact even though it requires an adjustment in their relationship with the survivor. An injury such as this is an injury to the family, not just to the person hit.

5.3 Fatigue

Survivors often complain of easy fatigability, becoming exhausted after only a few hours of work. This may be because every task that they used to automatically do without thinking now requires intense concentration to accomplish. Many return to work but find that they cannot multitask and do all of the activities that are required at their job.

5.4 Medical Testing

There are two kinds of medical tests:

- Anatomic ones that take a simple picture (X-ray) or measurement (blood count)
- Functional ones that show how something is working (PET, neuropsychological testing, intelligence testing)

Sometimes function can be ascribed to the anatomic tests but often it cannot so that it is often fallacious on the basis of a normal static picture to ascribe normal function. The mental changes that the lightning survivor has are functional (how the brain works) changes, not anatomic ones so that anatomic tests such as the CT scan and MRI are usually normal. More functional scans such as PET and SPECT may show changes but are hard to obtain due to their relative infrequency in medical centers. To use an analogy: if an electric shock were sent through a computer, the outside case would probably look ok (similar to a photo or X-rays of the person), the computer boards on the inside would probably look ok and not be fused nor melted (CT, MRI for the person), but when you boot up the computer it would have difficulty accessing files, making calculations, printing, etc. similar to a person with brain injury who has short term memory problems, difficulty accessing and coding information, difficulty organizing output, ...

A functional test of how a person’s brain is working that is seldom thought of by most non-neurologists is called neurocognitive or neuropsychological testing. These tests are administered by a qualified neuropsychologist familiar with the literature in this area, not by a psychiatrist, and consist of a 6-8 hour battery of pen and paper tests including memory, IQ, organizational ability, and other ‘how the parts of the brain are working’ kinds of tests. Survivors of lightning and electrical injury usually have a characteristic pattern of deficits. This type of testing is expensive and not necessary for most but can sometimes be helpful when litigation is involved and there is a doubt about the cause of a person’s injury.

5.5 Delayed Problems

Another common, often delayed problem for some survivors is pain, also a difficult problem to quantify and manage and one that does not always present initially in the full-blown pattern that it may have later. The pain may not only present as the chronic intense headaches mentioned above but may be in the back (perhaps from compression and disc injury from the intense muscle contractions which may throw a person several yards at the time of the injury), or in an extremity. Many may have nerve entrapment syndromes. A small number may eventually develop classic RSD. (Reflex Sympathetic Dystrophy, Sympathetically Mediated Pain Syndrome, causalgia)

Sometimes the functional tests that are ordered are testing the wrong thing an electromyogram (EMG) measures only the largest nerve fibers, the motor fibers, which are seldom affected by lightning injury. Smaller pain-
carrying nerve fibers are not tested by EMG so that a ‘normal EMG’ means little when ordered for someone with pain. Likewise, the standard EEG does primarily surface readings of the brain and misses seizure activity in several deeper regions. EEG’s may not pick up only 50% of temporal lobe seizures (some personality, organizing ability) and miss 120% of hypothalamic seizures.

Lack of libido and impotence are often reported. Other common and not so common complaints involve the digestive system, the endocrine (hormonal) system, and the immune system, some of which are currently being studied. It is not clear if these are directly due to lightning injury, to medication side effects, or to other incidental causes unrelated to lightning.

The four most important factors in overcoming disability from lightning injury (or from any illness or major injury for that matter) are:

a. A supportive family/friends network.
b. The person or family becoming their own best advocate and learning as much as they can about their disability.
c. A physician (regardless of specialty) who is willing to listen, read, learn and work with the survivor and their family.
d. A sense of humor.

Far more important than treating survivors is preventing lightning injury.

6 PERSONAL LIGHTNING SAFETY RULES

There are considerable safety tips concerning either individuals or groups facing danger to be struck by lightning. It is not possible to list all but we wish to start our safety tips designing, as proposed in the USA by the Lightning Safety Group, a kind of checklist with six different levels of prevention and action, in an increasing order of danger.

At level 1, if you are planning outdoors activities, obtain the weather forecast beforehand. Schedule outdoor activities around the weather to avoid exposure to the lightning hazard.

At level 2, if you are planning to be outdoors, identify and stay within travelling range of a proper shelter. The use of the “30-30 Rule” is recommended to know when to seek for a safer location. The “30-30 Rule” means that when you see lightning, count the time until you hear thunder. When less than 30 s, go immediately to a safer place. After the storm has apparently dissipated or moved on, wait 30 mn after hearing the last thunder before leaving the safer location.

At level 3, when lightning threatens, go to a safer location. Additional measures should be taken to avoid hazards even inside the shelter. A second choice for the shelter would be enclosed vehicle fully metallic.

At level 4, in case of failure of the previous tips, minimise the threat to be struck, staying away from locations of higher risk, such like trees and open areas.

At level 5, use the lightning crouch. Put your feet together, squat down, tuck your head and cover your ears.

At level 6, if the worst happens, there are key Lightning First Aid guidelines. CPR and mouth-to-mouth-resuscitation are recommended to victims. Move them to a safer location when possible.

Specific recommendations apply when being trapped outdoors or indoors. Any contact with services able to conduct electricity has to be avoided. It is better for a group to spread. Hereunder are typical recommendations, not exhaustive by far (see figure 9).
Some of the well-known tips are dubious. For example, it is often advised to run to find a shelter (because it might reduce the step voltage hazard). A recent study [45] has shown that this is not safe at all. But, in emergency situation, running to a safe building or metal-topped vehicle will shorten the exposure to the threat of lightning.

7 CONCLUSIONS

The various types of injuries described in this paper are not limited to outdoor lightning victims. A person staying indoors can also receive injuries either through side flashes or by lightning surges travelling along telephone or electrical distribution lines. Indeed, about 52% of lightning accidents happen indoor. Even though the magnitude of the current to which the body is exposed here could be less than those of outdoor lightning injuries, almost all the injuries mentioned above can also happen indoor. Andrews and Darveniza analyzed over 300 cases of telephone-mediated lightning injuries and found that about 10% of the victims were severely injured. This is less, however, in comparison to 40–60% for direct strike victims.

The information given here, shows that an interaction with lightning strikes can have severe immediate as well as long-term consequences, both to victims and their families. The best means to prevent being injured by lightning and resulting consequences is to take proper precautions during thunderstorms and to offer immediate medical assistance to those struck by lightning.

Education of people, especially to the young, is essential to prevent lightning accidents. No lightning safety guidelines will provide 100% guaranteed total safety, but respecting the rules will greatly minimise the lightning hazard to humans. In the USA, considerable efforts have been continuously brought to educate people from teaching in schools and delivering lectures and information to adults. We wish that similar active behaviour will be done in other countries, especially for those experiencing the highest risks such like in the tropics.

Especially, I would like to quote some distinguished physicists and physicians who acted to promote such a public education, namely Dr Mary Ann Cooper, Dr Chris Andrews, Dr Michael Cherington, Dr Ron Holle, Pr Vernon Cooray.
This lecture at SIPDA 2007 has been dedicated to the memory of my regretted friend Dr Elisabeth Gourbière, pioneer in keraunopathology, who passed away prematurely in 2006.

8 REFERENCES
