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TECHNICAL REPORT

Effects of current on human beings and livestock –
Part 4: Effects of lightning strokes

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Effects of current on human beings and livestock – Part 4: Effects of lightning strokes

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a Technical Report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC TR 60479-4, which is a Technical Report, has been prepared by IEC technical committee 64: Electrical installations and protection against electric shock.

This third edition cancels and replaces the second edition published in 2011. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) lightning occurence and climatory effects around the world are depicted;
b) direct strike description is extended;
c) step voltage effects are expanded;
d) upward streamer explanation is enhanced;

e) other direct or indirect related effects to lightning injuries to the human body are specified;

f) various safety procedures and related possibilities with respect to the personal danger of lightning are presented.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
64/2369/DTR	64/2398/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60479 series, published under the general title *Effects of current on human beings and livestock*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

IEC 60479-1 and IEC 60479-2 deal with the effect of electric shock derived from electrical systems on the bodies of human beings and livestock. This document describes the influence and effect of electricity in the form of lightning strikes. Lightning current can consist of several uni-polar and/or bi-polar impulses with different peak values and durations; IEC 60479-2:2019, Clause 6 does not cover these effects.

The interaction of a lightning stroke with the body is often different from that of electric shock derived from electrical systems. If the head is struck, the electrical path may include the brain stem, which includes the respiratory centre.

IEC 60479-2 includes information related to the effects of short duration impulses which extend to the magnitude and duration of lightning impulses.

It is accepted that more than 70 % of lightning accidents involving humans are not fatal [36], [47][1]. Corresponding reliable data for livestock is not known. There is a large variation in outcome due to different environments, different activities of people and knowledge of first aid and quality of medical care [40],[47].

It has been necessary, therefore, to create a separate document concerning the special effects of lightning strokes. The physical behaviour of lightning is shown as a basis. The interaction with a living body is then described, followed by the ongoing life consequences.

1 Numbers in square brackets refer to the bibliography.

EFFECTS OF CURRENT ON HUMAN BEINGS AND LIVESTOCK –

Part 4: Effects of lightning strokes

1 Scope

This part of IEC 60479 summarizes the basic parameters for lightning and its variability insofar as they apply to human beings and livestock.

The possible direct and indirect interactions of strikes with bodies of living beings are indicated.

The resulting effects caused by lightning currents for the organism are described.

This document shows the differences of effects on human beings and livestock due to lightning strokes versus those effects of electric shocks derived from electrical systems.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60479-1, *Effects of current on human beings and livestock – Part 1: General aspects*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60479-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1 Definitions of technical terms

3.1.1
lightning flash
<to earth> electrical discharge of atmospheric origin between cloud and earth consisting of one or more lightning strokes

3.1.2
lightning stroke
lightning impulse
single electrical discharge in a lightning flash to earth

3.1.3
lightning channel
conducting path of the lightning current

3.1.4
stepped leader
faintly luminous channel of generally less than 10 C of charge with associated branches that develops in virgin air and progresses towards the earth in discrete steps

3.1.5
return stroke
bright highly visible channel carrying the impulse current of the stroke, which is initiated when the stepped leader and upward connecting streamers meet to form the channel

3.1.6
upward flash
lightning flash initiated by an upward leader from earth to cloud

3.1.7
continuing current
current with a magnitude of tens to hundreds of amperes and a duration up to hundreds of milliseconds often following a return stroke

Note 1 to entry Continuing currents with duration in excess of 40 ms are traditionally termed "long continuing currents".

3.1.8
lightning current
current flowing at the point of strike

3.1.9
current peak value
maximum value of the lightning current

3.1.10
upward streamer
pre-discharge phenomena induced by the stepped leader, one of which will connect with the stepped leader opening a lightning channel which becomes a lightning stroke

3.1.11
average steepness of impulse current
average rate of change of lightning current within a time interval bounded by the 10 % and 90 % values of the peak impulse current front

3.1.12
stroke duration
time in microseconds between the time the return stroke exceeds 2 kA and the time to half peak value on the tail of the current pulse

3.1.13
flash duration
time for which the lightning current flows at the point(s) of attachment

3.1.14
point(s) of attachment
point(s) at which the successful upward streamer was launched

EXAMPLE Object, human or otherwise.

3.1.15
remote earth
ideal earth of zero resistance and zero potential

3.1.16
physical earth
earth as contact by objects

Note 1 to entry The difference between remote earth and physical earth allows the modelling of an earth resistance between the two, creating ground potential.

3.1.17
lightning ground flash density
measurement of the number of lightning strikes to ground, over a period of one year, per km^2

3.2 Definitions of interactions

3.2.1
direct strike
interaction whereby the lightning attaches directly to an object (including a living object)

3.2.2
contact voltage
potential difference between contacted points on an object, on which currents generated by a lightning event are present, or between an accessible point and an independent object (including earth) which could result in current flow through a living being

Note 1 to entry In some texts this has been referred to as "contact potential" or "touch voltage".

3.2.3
side flash
electric arc between two objects (including living objects), at least one of which is subject to partial lightning current

3.2.4
step voltage
step potential
potential difference between two points on the earth's surface due to a lightning stroke current being conducted through the earth

3.2.5
flashover
electric arc over the surface of an object carrying a significant proportion of the stroke current

3.2.6
streamer current
current, passing through an object, to establish an upward streamer, but which ultimately will not become a point of attachment

4 Basic physics of lightning

4.1 General

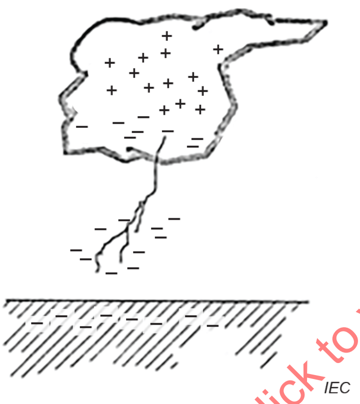
The explanation of the basic physical mechanisms for the onset and the dynamics of lightning is very complicated. Within a cloud, three layers are recognized, each with identifiable charges (see Figure 1). They are generated by microscopic charge transfer between soft hail particles (also called graupel) and ice crystals. The basal layer is normally negatively charged, with the layers successively positively and negatively charged in ascending order.

Lightning is a transient, high-current discharge whose path length is measured in kilometres. A lightning flash is a current phenomenon, and not a voltage phenomenon. More correctly, it is a "charge dumping" phenomenon, which occurs when the increasing electric field between two statically charged points exceeds a threshold.

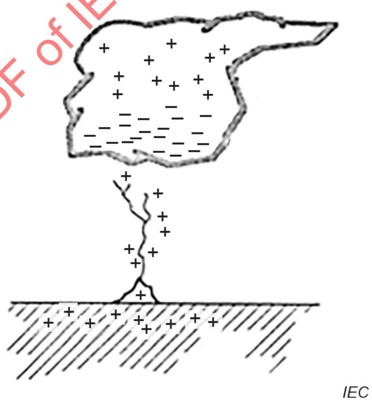
Well over half of all flashes occur wholly within the cloud and are called intra-cloud (IC) discharges. Cloud-to-ground (CG) lightning has been studied more extensively than other forms of lightning because of its practical importance (for instance, as a cause for injuries and death, disturbances in power and communication systems, damage to structures and installed equipment, and the ignition of forest fires). Cloud-to-cloud and cloud-to-air discharges have begun to be quantified more easily as a result of space and high altitude experimentation. Upward flashes from a cloud to the ionosphere have also been identified. All discharges other than those between cloud and ground (CG), are often combined under the general term cloud discharges.

Four different types of discharges between cloud and earth have been identified (Figure 1). Negative CG flashes probably account for about 90 % of the CG discharges world-wide, and less than 10 % of lightning discharges are initiated by a downward-moving positive leader [57]. Ground-to-cloud discharges are initiated by leaders that move upward from the earth. These upward-initiated flashes are relatively rare and usually occur from mountain peaks and tall man-made structures [56], [59].

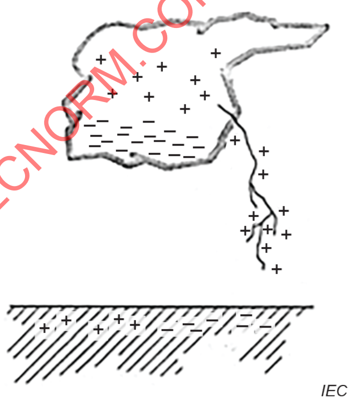
Other important physical parameters of the lightning environment have been characterized. Examples are the peak current per return stroke, the charge transferred in a return stroke, the average steepness of impulse current rise, as well as the stroke duration and total flash duration where there is more than one stroke in a flash.



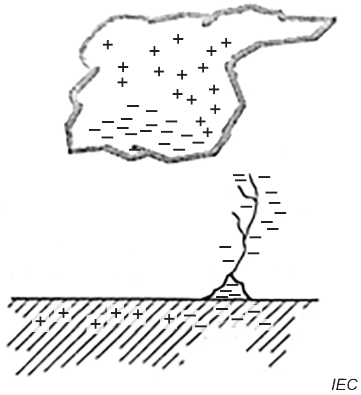
a) Downward negative lightning



b) Upward negative lightning



c) Downward positive lightning



d) Upward positive lightning

Figure 1 – Categorization of lightning types [4]

Thunder accompanies lightning and is generated by superheated air at the channel, which causes air pressure waves.

4.2 Lightning occurrence

Lightning ground flash density data is now available for most world locations. Lightning location system networks meeting the requirements of IEC 62858 [64] can provide lightning density information with a median location accuracy for cloud-to-ground strokes better than 500 m within the interior of the network. It is acknowledged that the data provided by lightning location networks could underestimate the actual flash density due to multiple earth attachment points for one-third to one-half of all cloud-to-ground flashes. IEC 62858 has introduced the term N_{SG} to identify the number of ground-strike points to represent the effect of the multiple earth attachment points. It is generally agreed that ground strike density is the most important parameter in assessing the number of dangerous events per year when conducting a lightning risk assessment. It is accepted by the scientific community that the location networks more accurately estimate the occurrence of cloud-to-ground lightning density than empirical occurrence estimates.

Where lightning location network data is not available, the use of satellite data may be used. These data represent the most accurate estimations available at the present time. In the past, empirical relations were derived from an observation of thunderdays, as follows:

$$N_G = 0{,}023\ T_D^{1{,}3} \quad \text{km}^{-2} \quad \text{yr}^{-1}$$

found best in South Africa but with wide variation [4];

$$N_G = 0{,}01\ T_D^{1{,}4} \quad \text{km}^{-2} \quad \text{yr}^{-1}$$

found in a survey of 26 countries with N_G varying from 0,2 km^{-2}yr^{-1} to 3,0 km^{-2}yr^{-1} and T_D varying from 10 days yr^{-1} to 100 days yr^{-1} [42];

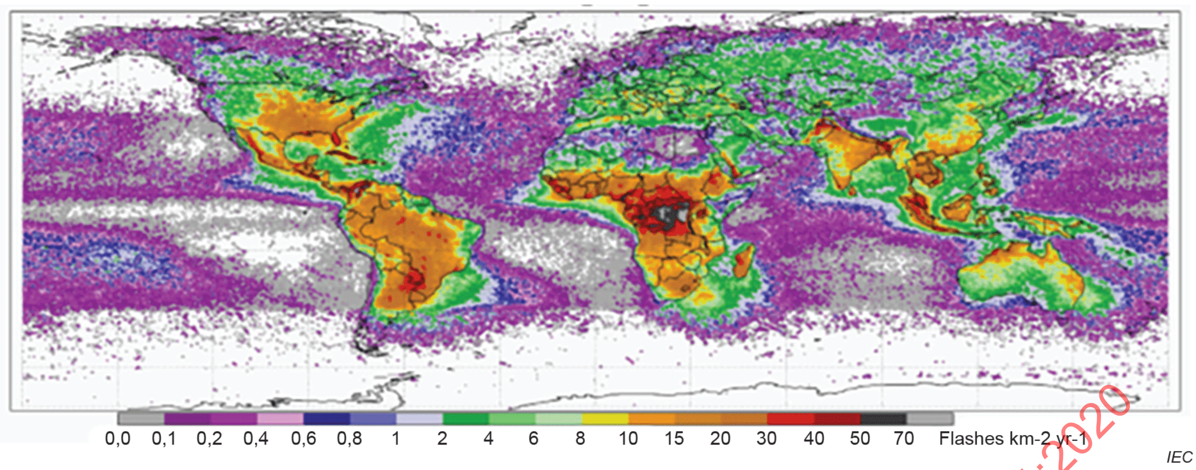
Prentice [46] recognized that the general form of these empirical equations was

$$N_G = a\ T_D^{b} \quad \text{km}^{-2} \quad \text{yr}^{-1}$$

It seems empirically justifiable that $b \geq 1$, since it is intuitive that the higher the number of thunderdays, the longer one might expect a storm to last at a given location.

While the use of the thunderday has had substantial currency in the manner shown, the use of this parameter is no longer current and should not be used in favour of LLS or satellite data.

A thunderday world map is shown in Figure 2.



SOURCE: https://ghrc.nsstc.nasa.gov/pub/lis/climatology/LIS-OTD/HRFC/browse/HRFC_COM_FR_V2.3.2015.png

Figure 2 – High resolution full climatology (HRFC)

NOTE In most areas of the world, an indication of lightning activity can be obtained from observations of lightning optical transients. Satellite-based sensors respond to all types of lightning with relatively uniform coverage. With sufficient averaging, optical transient density data provide better estimates of ground flash density than thunder observations, which have a wide range of relations between ground flash density and thunderstorm hours or thunderstorm days. There are also regional variations in the ratio of ground flashes (CG) to total flashes (CG + IC).

The ratio of cloud flashes (N_c) and ground flashes (N_G) has been further estimated, and is a function of latitude. The measurement has been enhanced by the ability to differentiate cloud and ground flashes electronically [42].

The relationship is found to be:

$$\frac{N_c}{N_G} = 4{,}16 + 2{,}16\cos(3\lambda)$$

where λ is the latitude (in degrees). The maximum occurs at the equator and decreases with distance from the equator.

4.3 Lightning flash characteristics

Numerous studies have determined typical values for lightning parameters. Uman and Krider [57], and Cooray [31] provide one summary of these. The studies are also summarized in the lightning environment defined in IEC 62305-1:2010, Tables 3 to 5, Table A.1, and Table A.3 [63]. CIGRE Technical Bulletin 549 [65] has conducted a review of recent studies and confirmed the lightning environment of IEC 62305-1.

4.4 Primary and secondary injuries

The focus of this document is on death and injury to humans and livestock from the various effects of lightning. Clause 5 will indicate the mechanisms by which lightning derived current can impinge on a victim, and Clause 6 will indicate a number of the likely symptoms of injury seen as a consequence. These are purely due to the electric current and may be thought of as primary lightning injuries.

Another group of injuries may however be seen and are regarded as secondary to a lightning strike. This occurs when a lightning strike damages a nearby inanimate object, and the damage inflicted on these then causes consequent injury to a human being. Protection of structures from examples of possible secondary injury follows. The means of protection of inanimate objects, including electronic equipment, is a wide science and is examined in detail in IEC 62305 (all parts) [62].

Rocket triggered lightning experiments provide an experimental vehicle for examining these. Their experiments are represented in the following:

- Overhead power distribution line damage, where overhead power lines become conduits for impulses to be transmitted inside a building. Fires may result, and equipment damage may be seen. Secondary burns and trauma may result.
- Direct strike damage: Mechanical destruction of inanimate objects may cause trauma from fragmentation and “missiles” thrown toward nearby individuals.
- Underground cables: Surges into a dwelling may result causing similar damage to the first case above.

Similarly, communication cable entry to dwellings may cause shock damage to individuals using communication apparatus like telephones. Andrews et al., [14] describes the mechanisms of personal danger from telephone apparatus.

Internal mechanical damage within residential buildings threatens individuals within an otherwise safe dwelling.

Electric current causing muscle contraction may also propel a victim into an object, or induce a fall.

Overhead cables entering a building can also carry dangerous currents to the interior. Some amelioration of this danger can be provided by earth shielding wires.

These are a few examples of primary and secondary injury which can affect humans and livestock.

Additional information of primary and secondary injury are given in the documents from Rakov [50], [51].

4.5 Summary

There are multiple paths of entry and impingement for lightning current onto an individual via power and communication cabling.

This risk is an addition to the ways in which lightning impulses can impinge on an individual "directly", that is, without the external agencies enumerated in examples above.

5 Interaction of strokes with human beings and livestock

5.1 General

The possible interaction of lightning current directly with living beings can take one of five forms [30], and effects depend on the pathway of the current in the body and on its surface. As the temporal and spatial current distribution of strokes varies, so the effects on living organisms are different. The five types of interaction are described below.

The body is essentially capacitive in nature. When a lightning impulse attaches to a body, current is conducted internally to the body. The body’s capacitances charge and the electric field over the surface of the body reaches a value where breakdown occurs. The value depends on the nature of the surface, the nature of skin, the nature of surface hair, the state of wetness and so on. While metal worn on the body has no effect on attracting a lightning impulse, it may affect the flashover path and breakdown phenomenon.

Once flashover occurs, internal current decreases quickly, and the majority of current is transmitted in the external flashover.

Nonetheless the flashover duration is still very small in absolute terms, and the internal conduction time is even smaller, perhaps accounting for the fact that burns in lightning injury are a very small feature.

It has been noted that body orifices, such as eyes, ears, mouth, and nose, provide re-entry portals for current, and the path from these to sensitive parts of the brain (e.g. eyes, otic apparatus, temporal lobes, respiratory centres, brainstem) is short and direct. Coupled with the ready conducting ability of the cerebrospinal fluid (CSF), the possibility for damage to central nervous system structures is high.

5.2 Strike mechanisms

5.2.1 Description of direct strike

When the tip of the downward stepped leader has reached a height of some tens of metres above ground level, the resulting field strength attains a critical value so that an upward streamer, influenced by the downward stepped leader, can be initiated from prominent items such as structures, trees, or possibly victims. When one of the upward streamers connects with the stepped leader, a lightning channel is formed [6], [30] making an attachment directly with the stricken object which may be a living being (see Figure 3). A return stroke then flows via the channel.

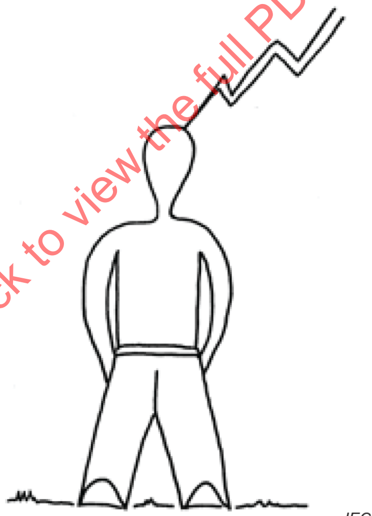


Figure 3 – Direct strike

The current flowing in this circumstance has been estimated.

There is no data on exact currents, partly because of difficulty in obtaining research subjects. A further reason is that the lightning attachment process is so variable that consistent repeatable measurements are not possible. Thus the data following is intended to provide representative values only.

A 5 kA 8/20 µs stroke is illustrative. This is a small stroke.

The sequence of events is shown in Figure 4. An artificial situation with no flashover establishes that foot flashover and body flashover occur well before the 1 µs.

The flash is postulated to attach to the cranium of a person 2 m tall. Using representative capacitance, the field over the body reaches 4 000 V/cm at approximately 550 ns from attachment. Flashover occurs over the surface at this value, by which time the internal current has risen to approximately 1 280 A. At that point the internal current drops dramatically, and in the 8 μs that the applied current continues to build, it is conducted externally.

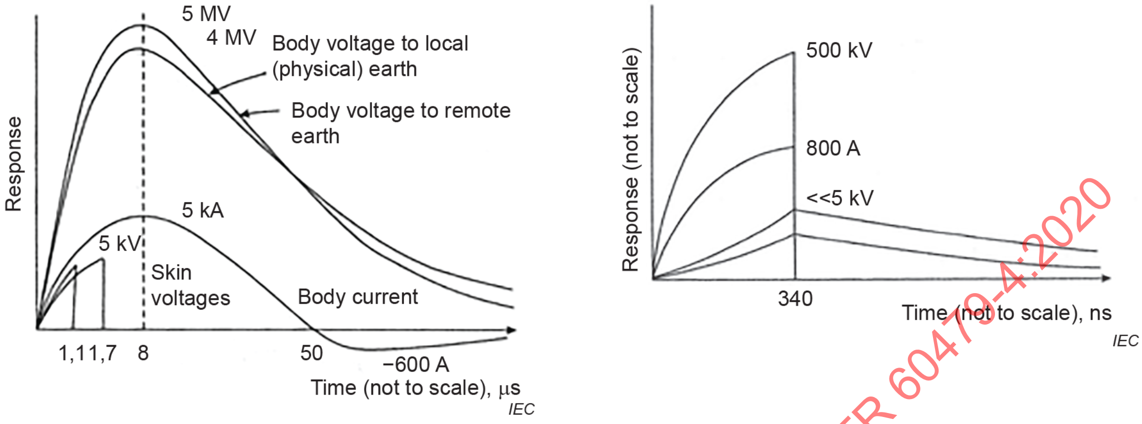


Figure 4 – Direct strike with no flashover and then with flashover

The internal charge transfer is therefore approximately 1 mC.

5.2.2 Description of contact voltage

When an object, not necessarily metallic, is struck by lightning, points on its surface are raised in potential. When a living being contacts one of these points and another, possibly earth, to complete a circuit, lightning current will flow through the victim [6], [30]. This contact voltage is determined by a resistive and an inductive component [1] (Figure 5).

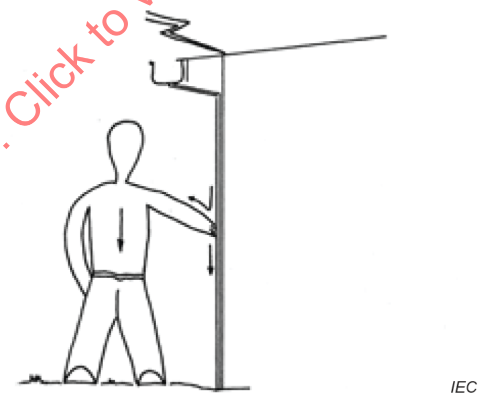


Figure 5 – Contact potential

The voltage at the contact point is given by:

$$u = i_L R + L di_L/dt$$

where

u is the resulting contact voltage, i_L is the current through a vertical structure, and R and L are the resistance and inductance between the points of contact.

The consequences for internal and external current conduction are similar to that for direct flash.

5.2.3 Description of side flash

When a person is near, but not touching, a vertical structure which conducts lightning current, potential is distributed over the object in the same way as with contact voltage. The resulting potential difference may exceed the electrical breakdown strength of the gap between the object and a person standing nearby. Then a side flash occurs [6], [30] (Figure 6) from the object to the victim. Figure 8b) shows the case where the vertical structure is another human being.

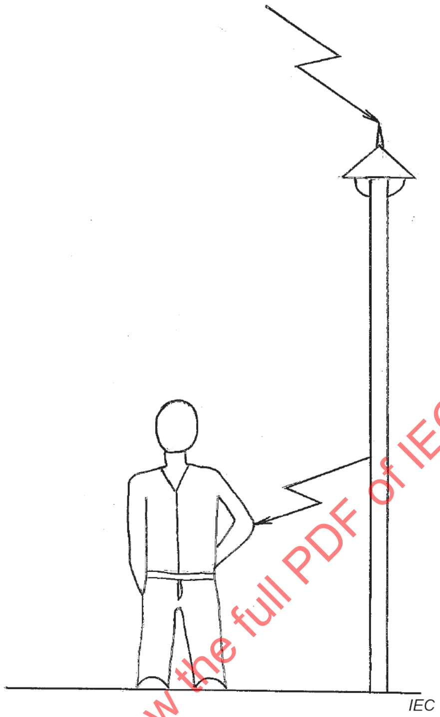


Figure 6 – Side flash

5.2.4 Description of step voltage

The common means by which a step voltage is generated occurs when a lightning impulse is injected into the earth [6], [30]. Passing through the earth resistance, a potential gradient is set up. Two points of contact of a victim establishes a potential difference between those points, and current flows through the victim.

The potential is given by

$$U_{\text{step}} = \frac{\rho I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

where the step voltage is U_{step} and I is the current injected into ground of resistivity ρ, and r_1 and r_2 are the distances from the base of the strike of the two contact points.

Suppose a lightning stroke of 10.000 A is injected into the ground of resistivity of 100 Ωm, with two points at 20 m and 21 m distant. The step voltage is then approximately 378 V.

For these values, the voltage profile is shown in Figure 7:

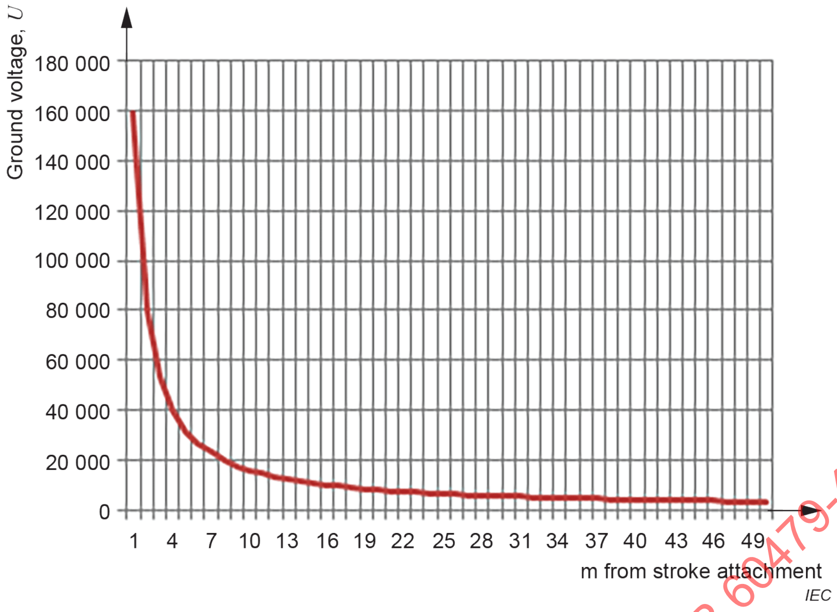


Figure 7 – Earth potential versus distance from the stroke base – 10 kA stroke, with earth resistivity 100 Ωm

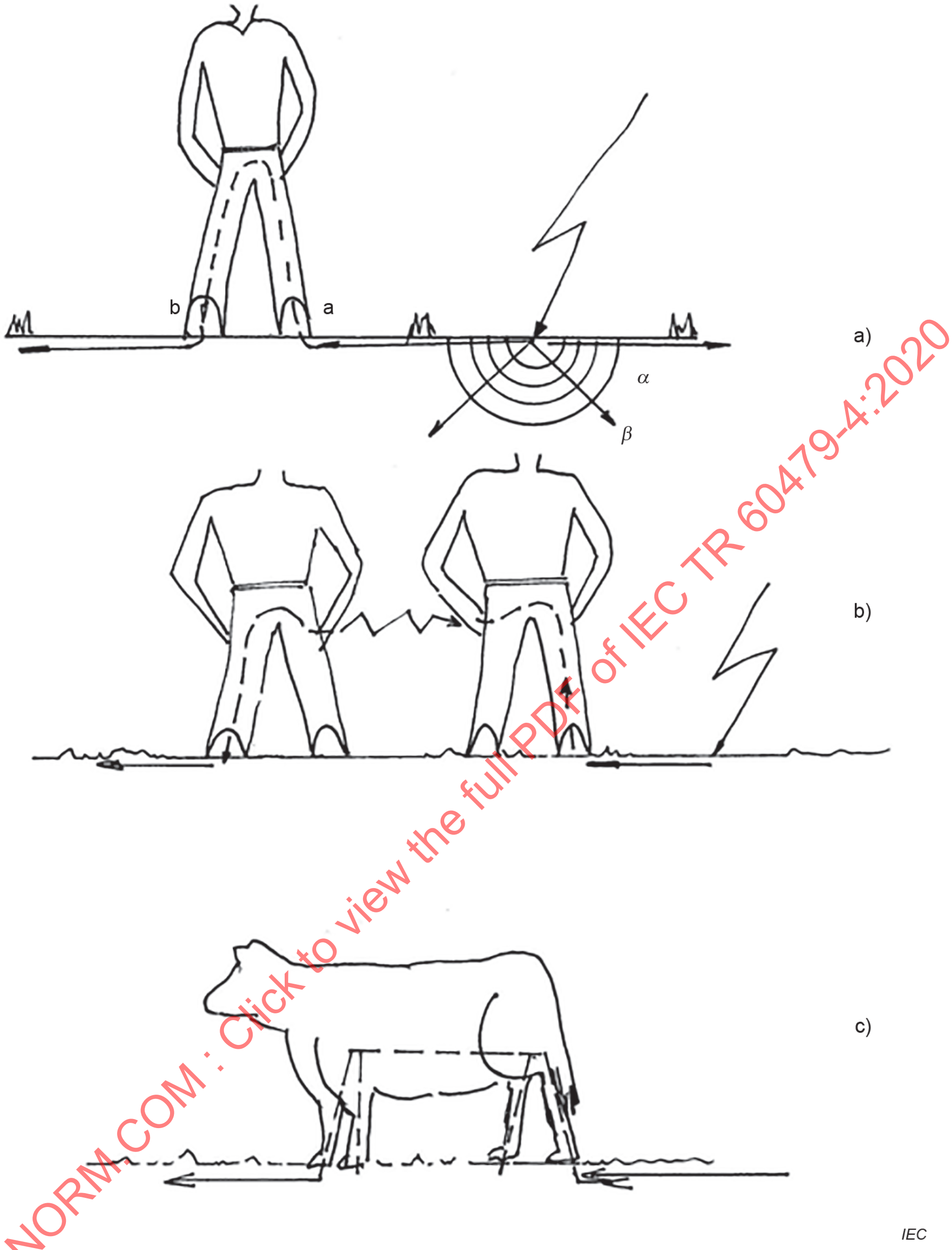
This voltage between two human feet is unlikely to be harmful.

However, in a quadruped, with 2 to 3 times the step distance, the step voltage becomes approximately 1 000 V. The pathway of the currents in quadrupeds may include the heart (Figure 8c)). Another reason that quadrupeds are much more likely to be killed is that they often stand in muddy ground so that their legs are in particularly good contact with the ground.

Often, if the pathway of step voltages for humans does not include the heart, for example if the victim is standing vertically with feet in contact with the ground, the victim is often temporarily paralysed in the extremity involved in the current passage (keraunoparalysis). Keraunoparalysis can occur with any lightning conduction involving an extremity.

5.2.4 Description of streamer current

If an upward streamer emanates from a living being, the associated charge will travel current through the victim from earth. It emanates in answer to the descending stepped leader, and may be said to be induced by the stepped leader. The current that flows in this way may produce injuries in the victim (Figure 9) [2], [3], [25], [26].



a) For a human being: current travels out radially from the base of the strike (β). The current travelling through the earth resistance sets up isopotentials (α) of decreasing magnitude from the base of the strike. For the human, foot "a" is at a higher potential than foot "b", and current flows internally in the body from foot to foot.

b) For two humans: combined with side flash.

c) For a quadruped: noting the vulnerability of the chest, and therefore heart.

Figure 8 – Examples of step voltages, assuming a uniform earth of constant resistivity, and no surface flashover

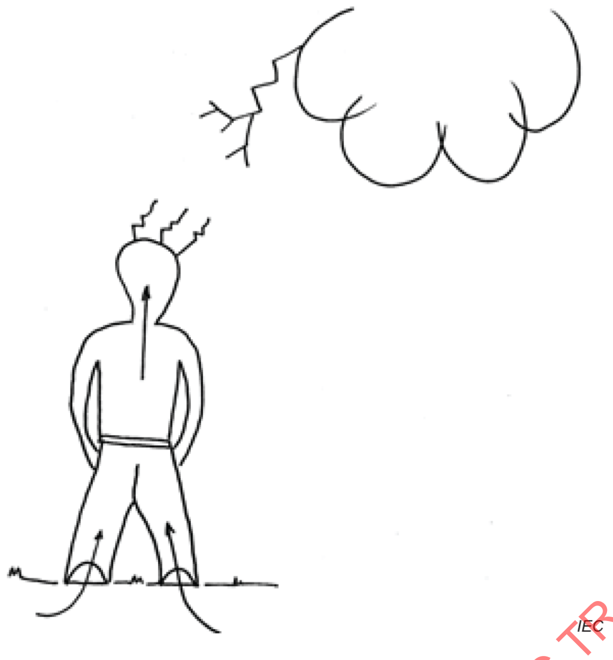
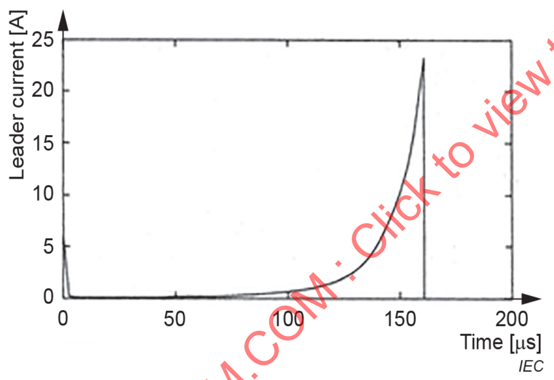
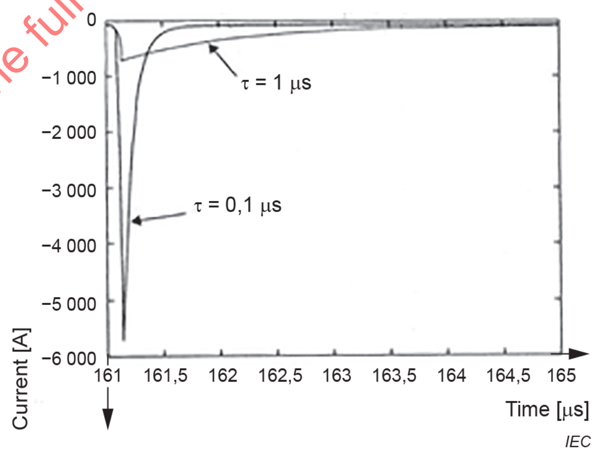


Figure 9 – Upward streamer

Becerra and Cooray [16] examine the currents flowing. They are shown in Figure 10 a) and Figure 10 b).



a) Current in establishment of upward streamer



b) Current in collapse of upward streamer

SOURCE: Becerra and Cooray [16], reproduced with permission from the authors.

Figure 10 – Current in establishment and in collapse of upward streamer

Two phases of current passage are identified. The first is during the phase of establishment of the upward streamer. The second is during the collapse of the streamer. Figure 10 a) and Figure 10 b) show these phases. The time constants applicable are a complex interplay of earth resistance, individual resistance, and individual capacitance, and environmental capacitance.

5.3 Specific matters regarding body response

Attachments close to the head of victims initiate current which has been found to enter the body at cranial orifices as portals of entry, including the ear canals, the eye apparatus, the mouth and the nose. These portals provide easy access to body fluids, especially blood and CSF. Conduction paths to the brainstem and the heart are plain, and thus cardiac and respiratory dysfunction is likely, and has been demonstrated.

Investigation shows that the heart enters asystole, and then re-establishes its own automatic rhythm. Respiratory cessation is seen, and no automatic rhythm re-establishes, leading to a secondary hypoxic cardiac arrest [7].

The establishment of asystole rather than ventricular fibrillation (VF) may be a function of the size of the cardiac insult. The establishment of VF often occurs due to an isolated focus of ventricular depolarization with irregularities in ventricular conduction. Various theories of VF exist including a) the consequent establishment of circus rhythms on the one hand, or alternatively b) the multiple wavelet theory resulting from multiple areas of stimulation.

With lightning injury however, the stimulus is almost certainly above the upper limit of vulnerability (ULV) for defibrillation, and thus induces complete myocardial depolarization without the VF possibilities above. Asystole is the result.

There is no evidence to support the once stated contention that body metabolism ceases after a lightning strike, and time available for external resuscitation is prolonged [55]. It is a prime principle of first aid for lightning victims (vide infra) that cardiopulmonary resuscitation (CPR) should be commenced early and kept up for a prolonged period, as various neural signs of decease may be unreliable.

Current paths through the body are thought to follow most easily the paths of low resistance i.e. fluids like blood and CSF. However there are multiple parallel paths through which current will flow, in proportion to their conductivity [54]. No tissue may be considered exempt from the passage of current and its effects, and current passage will be through all pathways in inverse proportion to their resistances.

6 Effects of lightning strokes on the body of living beings

6.1 General comments on effects on the body

A tabulation of the majority of injuries is given below. General comments are made first.

If electric current flows through the body of living beings, damage and/or malfunction can occur. Lightning current is an example of such injuring current. Unlike technical electric shock, a lightning impulse generally injects current into the body, whereas an applied technical voltage causes current to flow through body impedance. The exception is exposure to step potential.

Direct strike obviously gives rise to the greatest harm, and probably the most mortality, whereas step potential is possibly the least harmful. Interaction due to contact voltage and side-flash may be thought of as variants of direct strike, but of lesser magnitude [6]. In assigning a causative mechanism, it is not generally possible to differentiate potential from streamer current, and this may be the reason that victim injury assigned to step potential in the past, may actually have been due to streamer current.

Cardiac arrest occurs, predominately in asystole and rarely in fibrillation [28]. Respiratory arrest leading to hypoxia also occurs and lasts much longer than cardiac arrest. While the heart may restart, a secondary cardiac arrest will occur, unless ventilation is given. This emphasizes the importance of emergency cardio-pulmonary resuscitation, which should not be withheld due to any concern of risk of shock to the rescuer – unlike technical electricity to which a victim may remain attached.

Involuntary skeletal muscle contraction may occur, which can lead to body propulsion and fractures. Seizures may result from brain involvement and the mechanical effect on the cranium may induce intracranial bleeding.

Membrane rupture is possible, and ear drum perforation is the norm. Secondary effects may have serious consequences.

While many effects of neurological abnormality may be seen, it should not be immediately concluded that neural structures are more sensitive to lightning (or electrical) current passage. Indeed, the importance of vascular passages is emphasized, and post injury signs may not be visible in these prime conduction pathways (being "self-sealing"). Effects showing as neural dysfunction may be seen secondarily to this passage.

In addition to physical effects, profound neuropsychiatric effects may be seen.

The latter, and to some extent the former, may be delayed in onset from months to years.

The neurological effects of lightning strike have been classified [21] as:

- immediate and transient;
- immediate and prolonged (e.g. hypoxic encephalopathy, intracranial bleeding, cerebral infarction (particularly parieto-occipital), basal ganglion syndromes, cerebellar syndromes, spinal cord injury (also some permanent), chronic epilepsy, peripheral nerve lesions (including neuropathy, myopathy, NMJ, and polyneuropathy);
- delayed neurological syndromes (e.g. motor neuron disease, amyotrophic lateral sclerosis);
- secondary injury due to pressure waves (impulsive pressure phenomena due to air compression and rarefaction akin to blast waves. Within the body, trauma due to pressure phenomena is often referred to as barotrauma).

Table 1 tabulates the range of injuries seen. Details of the specific nature of lightning injuries are given in [5], [9], [10], [11], [12], [13], [15], [19], [20], [22], [24], [28], [29], [39].

While not fully exhaustive, this is an indicative tabulation.

Table 1 – Lightning injury and physical symptoms [8], [9], [10], [11], [12], [13], [17]

Lightning death	Mostly in asystole, with occasionally some ventricular fibrillation, and subsequent cardiorespiratory progression Secondary multisystem failure
Cardiopulmonary injury	Arrhythmiae Sympathetic, and cardiac induced, arterial pressure changes Electrocardiographic changes, usually transient Cardiac failure Pulmonary contusion and oedema
Immediate neurological effects	Hypoxic encephalopathy Loss of consciousness Brain stem dysfunction especially respiratory dysfunction Cerebellar and basal ganglion haemorrhage Peripheral neurovascular spasm – keraunoparalysis Intracerabral haemorrhage Seizures Neuromuscular junction damage Cerebral infarction
Long term neurological effects	Cerebral states, including motor neurone disease Paraesthesiae Neuromuscular weakness, including articulation disorders Pain syndromes Neuropathy, mononeuropathy and polyneuropathy Parkinsonism Spinal cord change – amyotrophic lateral sclerosis, paraplegia, quadriplegia
Immediate psychiatric effects	Confusion Amnesia Anxiety and agitation Aphasia, and hysterical changes Dystonia
Long term psychiatric effects [8], [10], [11], [23], [27], [33], [36], [37], [38], [43], [44], [45], [47], [48], [49], [52], [58]	Depression, possibly organic Anxiety states Phobias Memory disorder, especially auditory memory Sleep disorder Loss of cognitive ability, and learning, especially verbal learning Asthenia and fatigue Post-traumatic stress disorder Sexual and relationship dysfunction

Burns and cutaneous markings	Six types of burns are identified: 1 Entry and exit burns (often deep but closely circumscribed) 2 Flash 3 Linear burn 4 Arborescent burn (Lichtenberg figure, ferning) 5 Punctate flower like burn (possibly a variant of the arborescent burn) 6 Contact burn, though some doubt this is due to thermal burning
Contusive blast injury	Exploded, torn and shredded clothing Body contusion (skin, brain, lung, bowel, etc.) Ruptured tympanic membrane Lung contusion Bowel contusion and perforation
Trauma	Blow, bruise, laceration Fractures These may be primary to the strike, or secondary due to induced motion
Special senses	Tympanic membrane rupture Deafness Tinnitus and vertigo Loss of ocular movement and ocular reflexes Blindness Retinitis Retinal detachment and macular and retinal punctation Cataract Uveal inflammation
Others	Endocrine, including cerebral salt wasting syndromes In electrical injury: Low voltage – Myoglobinuria known High voltage – Myoglobinuria common In lightning injury – Myoglobinuria rare

6.2 Comments on specific syndromes

6.2.1 Keraunoparalysis

Keraunoparalysis is a transient paralysis and loss of perfusion of an extremity in the path of the lightning current. The limb becomes cold, swollen, and pulseless, with absence of feeling. It might be considered to resemble a compartment syndrome, however resolves without sequelae in a short period of hours. The consideration of the performance of fasciotomy should be resisted.

Present thinking is that vascular spasm is at the root of its causation.

6.2.2 Burns

Burns are a relatively minor part of lightning injury. The six main types are:

Keraunographic marking (Lichtenberg figure, arborescent burn): This is a branching tree like burn whose origin is thought to be due to inflammation following and underneath the arborization of current streamers. Attention has been drawn to its fractal shape. It is thought to be pathognomonic of lightning injury, though may rarely be seen in high voltage injury. It requires no treatment and resolves. It is particularly seen with negative flashes to the body.

Punctate burns*:* The progression of punctate burning is similar to the Lichtenberg figure, and may be a variant of it. It is seen with positive flash to the body.

Linear burn: This is thought to be a true superficial burn due to current passage along lines of moisture and/or sweat. They generally form eschar and scale off.

Entry and exit burns: These are full thickness but closely circumscribed true burns at major points of current attachment and exit. They may be treated conservatively, but occasionally require grafting.

Flash burn: Radiation from a lightning flash may produce a burn similar to sunburn or welding flash.

Contact burns: Heating of metal objects in the path of surface lightning currents have been thought to produce imprints of hot objects like necklaces, belt buckles, and coins. Analysis does not always bear out the heating necessary for this to occur, and these burns may be due to complex field interactions with metal in a current path and the skin beneath.

Unlike technical electrical burns, burns due to lightning are minor and rarely require specific treatment. This may be due to the small amount of time available for heating to occur during current passage.

6.2.3 Comparison between effects of electric shock derived from electrical systems and lightning

It has been emphasized that injury from lightning stroke is markedly different from that due to either low voltage or high voltage electricity derived from electrical systems, whether domestic or industrial. Details of the specific nature of lightning injuries are covered in [5], [9], [10], [11], [12], [13], [15], [19], [20], [22], [24], [28], [29], [39]. See Table 2.

There is, however, no basis to the dogma that recovery after 'longer than normal' cardiac arrest can occur or that all body metabolism cease with a lightning shock [55].

Table 2 – Comparison of electrical and lightning injury [30], [34], [35], [40]

	Low voltage	High voltage	Lightning
Voltage	<1 000 V AC or <1 500 V DC	>1 000 V AC or >1 500 V DC	Complex and impulsive, with or without flashover A current rather than a voltage phenomenon
Location	Domestic and industrial, including workplace Rural Children represented	Industrial – mostly electrical workers	Outdoors, more often during recreation, cf past outdoor occupations Indoors, telephone – or other – line mediated
Common mechanisms	Interference with appliances and other electrical equipment Inadequate safety precautions Faulty appliances Inadequate insulation practices, e.g. – misuse of extension cords – unintended contact with live parts	Installation service and repair Inadequate safety practice or procedures	Direct strike Side flash Contact potential Step potential Streamer initiation
Type of current	50/60 Hz AC Some direct current	50/60 Hz AC	Impulse discharge, often multiple, and possible continuing component
Source	Domestic and workplace outlets wiring and appliances	Reticulation, installations, supply and control mechanisms	Natural atmospheric discharge
Duration of contact	Maybe prolonged if let-go exceeded. Being thrown may terminate contact.	Maybe prolonged if let-go exceeded. Being thrown may terminate contact.	Impulsive and ultrashort, though continuing current may occur
Mode of death	Ventricular fibrillation (VF)	Ventricular fibrillation (VF) more likely than asystole	Asystole much more likely than ventricular fibrillation (VF), coupled with respiratory paralysis
Burns	Often severe, deep, and extensive necessitating amputation and/or fasciotomy	May be similarly severe	Minor
Lichtenberg figures	Absent	Can be present rarely	Common
Electroporation **(direct damage to the cell under the influence of high electric fields).**	Demonstrated	Demonstrated	Yet to be determined
Muscle damage	Common	May be present	Rare
Renal consequences	Myoglobinuria known	Myoglobinuria common	Rare
Direct traumatic tissue damage (by current)	Common	Common	Known though rarer

	Low voltage	High voltage	Lightning
Secondary traumatic tissue damage **(by being thrown)**	Common	Common	May occur
Prevention	Protective devices and design Personal practice	Protective devices and design Safety codes	Codes of personal behaviour Structure, personal, and crowd protection
First aid	Avoidance of injury to rescuer when separating victim from source. Preferably switch current off. Cardio pulmonary resuscitation (CPR) as per known protocol when safe. Obtain medical help.	Avoidance of injury to rescuer when separating victim from source. Preferably switch current off. Cardio pulmonary resuscitation (CPR) as per known protocol when safe. Obtain medical help.	Immediate and prolonged cardio pulmonary resuscitation (CPR) Summon medical help
Psychological effects	Common	Common	Common

7 Present considerations of causation

7.1 Under investigation

Causation of injury in lightning strike remains a matter of investigation. The following is a summary of present theories.

7.2 Electrical effects

The passage of electric current provides the means for the induction of dysfunction in excitable organs, for example, cardiac arrhythmias, generation of seizures, respiratory disturbance.

Structures by which electricity is conducted in the body is in order of conductivity of individual tissues, with blood, CSF, and other fluids being most conductive, nerve and muscle intermediate, and bone least conductive.

7.3 Thermal, field and radiation effects

The burns of direct strike can be explained by:

- direct thermal effects in the case of entry and exit burns and liner burns;
- surface radiation and field effects in the case of punctate and arborescent burns [32];
- radiation effects in the case of radiation burns, akin to sunburn.

Contact burns, the causation of "burns" due to imprinting of metal objects onto underlying skin is debated. Not all metal objects attain a temperature sufficient to burn. There may be complex field interplay between a metal object and the underlying skin, giving this "burn".

7.4 Traumatic injury

Secondary effects, such as muscle contraction, may lead to secondary traumatic injury, such as falls, fractures, and the like.

7.5 Barotrauma

Impulsive pressure phenomena due to air compression and rarefaction akin to blast waves occurs especially with the generation of thunder. Within the body, trauma due to pressure phenomena is often referred to as barotrauma. Pressure waves may lead to rupture of tympanic membranes, and contusion injury of compressible organs, such as the lung and intestine [17], [18].

7.6 Release of hormones

The cause of psychological injury is under active research [15], [52], [53].

A proposed theory is that excess physiological hormone release occurs, and this has an effect on particular parts of the brain, directly by its own toxicity, and indirectly via the inhibition of brain derived neurotropic factor (BDNF) and also the release of oxidative radicals, responsible for the symptoms seen. The major area affected is postulated to be the hippocampus. This accounts for the quite specific symptoms seen (see Table 2), and also the delay in onset of such symptoms.

The theory is supported by the observation that electric current causes direct hippocampal atrophy, and also that vascular active compounds are released which can have action at sites distant from their release.

8 Individual and crowd safety procedures

8.1 General – "No place outdoors is safe"

Strategies have been recommended for the safety of humans and livestock from a lightning strike. The principle that no place out of doors is safe from injury guides the basic dictum that shelter should be sought immediately when the risk is recognized, and that shelter should satisfy minimum criteria.

A lightning flash can extend from a point 10 km or more from its inception to its attachment. It is important that this be considered in the decision to seek shelter.

8.2 Individual actions

Individuals involved in outdoor pursuits are at risk of being struck. The most developed and cogent recommendations for safety from the threat of lightning can be found at the National Oceanic and Atmospheric Administration (NOAA) Lightning Safety web site (accessed at https://www.nhc.noaa.gov).

NOTE Recommendations can also be found in IEC TR 62713:2013 [66].

8.3 Basic principles

8.3.1 General

No site outdoors is absolutely safe from lightning injury. A popular lightning safety awareness theme is "When thunder roars, go indoors".

Thorough preparation for outdoor activities should be made. Examples of such preparations are a thorough review of weather forecasts, keeping an "eye to the sky" and having a plan for shelter if it becomes required. It is important to recognize the development of adverse weather conditions and take necessary actions as required.

If you are caught outside with no safe locations nearby, avoid open fields, the top of a hill or a ridge top. Stay away from tall, isolated trees or other tall objects. If you are in a forest, stay near a lower stand of trees. If you are in a group, spread out to avoid the current traveling between group members. If you are camping in an open area, set up camp in a valley, ravine or other low area. A tent offers no protection from lightning.

8.3.2 Individual lightning safety in the outdoors (NOAA recommendations)

When lightning could be a threat it is important to plan ahead. Portable weather radios are useful for outdoor activities. Otherwise one may stay up to date via internet, smart phone, radio or TV. Where applicable, time visits to open areas to fit local weather patterns. Be watchful for changing weather patterns and change plans if the risk grows.

If thunder can be heard, the lightning strike is 10 km to 15 km away and it is time to take shelter. The best shelter is inside a substantial enclosed building or inside a fully metal enclosed vehicle. The escape to these locations should be planned in the initial planning and changes of plan.

If one is absolutely not able to seek a protected location as recommended above, then safer terrain should be sought. Safer terrain is lower in altitude, descending a mountain on the non-windward side, avoiding peaks and ridges. Once in lower rolling terrain, strikes are somewhat random. A dry ravine or dry depression may offer some risk reduction in rolling areas.

The "lightning crouch" consists of crouching to adopt a low profile, presenting the minimum contact area with the ground. It offers no better than minimal reduction in the risk of injury due to a lightning strike.

Humans should avoid peaked areas and avoid standing in the shelter of and close to tall trees or other objects likely to be struck. Rocky overhangs and the mouths of caves should be avoided. Tents, lean-to structures, gazebos, and open sided structures do not provide sufficient protection.

Ensure that there is at least one person in any group capable of full CPR.

Once there has been no thunder or no visible lightning is seen for 30 min, it is safe to resume activities.

Cyclists, and motor cyclists should not proceed into threatening weather, and should pull over and stop in a substantial building until the danger is past.

Location on water is particularly unsafe, especially in a boat with no cabin. A trip should not proceed if weather forecasts are doubtful. If unable to return to land, one should stay low in the boat, bringing down as much rigging as possible. If the boat has a cabin, humans should remain inside the cabin, avoiding touching metal surfaces.

Consideration should be given to pets that may be located outside, especially those that may be chained or tethered. Consideration should be given to bringing the pets indoors or to a protected area.

8.3.3 Safe practice indoors

Indoor safety involves avoiding apparatus and surfaces that are electrically connected with the outdoors. Examples are discussed below.

Corded phones should not be used when there is lightning in the area [8], [17], [18], [19], [20], [21]. Portable phones may be used with caution. Injuries can also occur when touching electrical equipment. Remote control usage is satisfactory.

Plumbing and reticulated water should be avoided, as well as metal window and door frames.