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doi:10.15199/48.2016.02.31

Lightning Induced Ventricular Fibrillation risk during wandering

Abstract*. Wandering is a popular way of spending leisure time especially for the urban population. Health problems arising from such outdoor recreational activities are better understood today and may improve survival in case of accidents if sufficient awareness of clinical staff is established. The purpose of this paper is to shed light on this physiological phenomenon by investigating the connection between the physics associated with lightning strikes and the physiological response of the human body. From the results a minimum safety-distance from different trees species is derived. Flat rooted trees are more dangerous than tap rooted trees. In the worst case it may be considered safe if a distance of at least 25 meters to tree trunks is maintained.*

Streszczenie. *Turystyka piesza jest popularnym sposobem spędzania wolnego czasu, szczególnie dla mieszkańców miast. Problemy zdrowotne wynikające z tej aktywności są dobrze poznane, ale w szczególnych przypadkach wiedza o zagrożeniu może być pomocna i może się przyczynić do zwiększenia szans na przeżycie. Celem tej publikacji jest pokazanie związku pomiędzy wyładowaniem piorunowym a reakcją organizmu ludzkiego. Na podstawie otrzymanych wyników wyznaczono bezpieczny odstęp od drzew podczas wyładowań piorunowych. Drzewa z systemem poziomym systemem korzeniowym stwarzają większe zagrożenie niż drzewa z systemem palowym. W najgorszym przypadku bezpieczny odstęp od pnia drzewa wynosić powinien co najmniej 25 metrów. (****Ryzyko fibrylacji komór serca turystów pieszych wywołane wyładowaniem piorunowym****).*

Keywords: wandering, lightning strike, thunderstorm, safe distance.
Słowa kluczowe: turystyka piesza, wyładowanie doziemne, burza, bezpieczna odległość.

Introduction

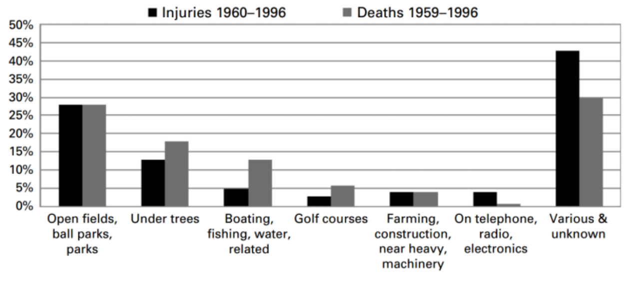
The National Oceanic and Atmospheric Administration (NOAA), International Lightning Safety Initiative (NLSI) and National Outdoor Leadership Scholl (NOLS) point out that lighting safety for people is a global issue[1]. According to Holle, there are some about 24,000 lightning deaths and 240,000 injuries annually worldwide [2].

In the common opinion lightning strikes appear suddenly and unexpectedly. In the era of universally accessible media, information about the shock of humans caused by lightning discharge are widely disseminated. The increase of available data due to the new media supports concerns about health and life of people exposed to a thunderstorm in open areas. Unfortunately, a lot of the information released does not respect established scientific standards and sometimes is simply not correct. Medical aspects are skipped very often. Unreliable information cause erratic and rapid growth of interest in safety issues regarding lightning strikes during thunderstorms. Everyone is paying particular attention to the safety tips to be followed while encountering a thunderstorm. Due to the nature of the phenomena, the situation is not always simple and obvious.

Accidents involving electric shock caused by lightning discharges take place during work, rest and the activities of daily living. They are always associated with fear and even have an impact on the tourist industry, finally.

According to the monthly magazine Storm Data (NOAA) over 30 percent of all lightning deaths involve individuals who work outdoors and over 25 percent involve outdoor recreationists - details in Table 1.

Table 1. The place of occurrence of lightning deaths and injuries in the United States, 1959-1996. Adapted from Storm Data, US National Climatic Data Center, NOAA, Ashville, North Carolina



Lightning Induced Ventricular Fibrillation

Four different electrical mechanisms of lightning injury have been described:

1. Direct strike, where a person suffers from a direct lightning hit.
2. Contact, where a person touches an object that is directly hit by lightning.
3. Side flash, where a part of the lightning energy is transferred to the person's body physically close to the primary impact point.
4. Ground current, where a person is standing with his/her legs apart close to the lighting impact point [7,10,11].

Each of them can cause a cardiovascular injuries such as hypertension, tachycardia, non-specific electrocardiographic (ECG) changes, prolonged QT intervals, and myocardial injury [5].

An electrical current pulse of 60 to 120 mA could result in VF if a substantial portion of that current flows through the heart during a critical period of a cardiac cycle [5,7].

It has to be pointed out that one lightning flash consist of several strokes [11,12,13,14,15,16], which is discerned as a single lightning flash by the human eye. Measurements prove that a single lightning strike consists of up to several dozens of current pulses [11,12]. A normal lightning flash encountered during a natural thunderstorm features a time separation between individual current pulses, which is on the proper scale to be crucial for VF initiation. Further distinctive features of partial lightning strikes are their polarity (negative or positive), and their temporal position in the lightning discharge (first, subsequent or superimposed partial strikes of lightning)[14,15,16]. A collection of possible combinations of partial lightning strikes are shown in Figure 1.

The study conducted by Thomson showed that the number of strokes per flash does not vary significantly from one geographical region to another [17]. In his statistical analysis Thomson investigated whether there is a significant difference between the interstroke intervals measured in studies conducted in different geographical regions [17]. The typical time between current pulses is 76 ms [12] (Arithmetic mean). Details are shown in Table 2.

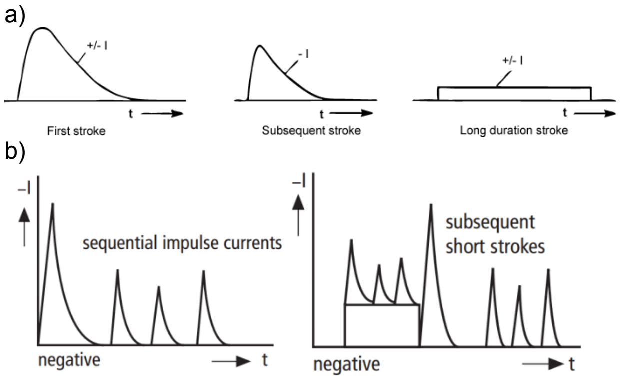


Fig. 1. Prescriptive (a) and possible components (b) of lightning flashes [14,15,16].

In this paper we propose a hypothesis that lightning induced step voltage could provoke VF with respect to the number of strokes. The step voltage induced by a natural lightning features a waveform shape, which is similar to QRS complex and partially to ST segment. In order to investigate the effect of natural lightnings on the human body reproducible measurements have been performed in well-tuned experiments, which have been designed under the objective to be as close to the natural conditions as possible (figure 2). For this reason we have chosen the next tree trunk around the corner of the block as the site for our investigation. The high voltage power surges used in the experiments have been set up in such a way that they mimick all the properties of natural lightning discharges we are aware of as discussed before. This way it is possible to systematically investigate the safety and the risk to the human body in the vicinity of tree trunks in a representative experimental setup.

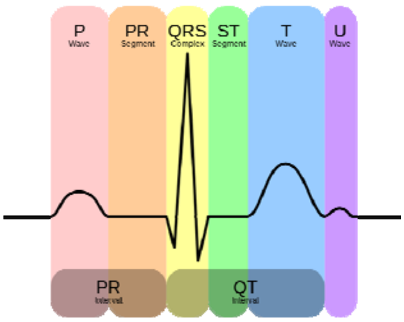


Fig. 2. Complex ECG pattern [39].

Table 2. Inter stroke time intervals observed in different studies conducted at different geographical regions

Study	Total number of flashes	Total number of strokes	Arithmetic mean [ms]
Heidler and Hopf, Germany 1986 [18]	-	116	87
Heidler and Hopf, Germany 1988 [18]	-	414	87
Thottapillil *et al.*, Florida 1992 [19]	46	199	57
Cooray and Perez, Sweden 1994 [20]	271	568	65
Cooray and Jayaratne, Sri Lanka 1994 [21]	81	284	83
Rakov *et al.*, Florida 1994 [22]		270	60
Qie *et al.*, China 2002 [23]	50	238	64
Miranda *et al.*, Brazil 2003 [24]	26	131	69
Saba *et al.*, Brazil 2006 [25]	186	608	83

Methods

In the first place real measurements of semi lightning inducted step voltages have been performed. As a source of semi lightning current a high voltage current surge generator is used. It produces surge currents that are very similar to those encountered in natural lightning discharges. As effect of the current discharge we measure the current induced step voltages in the surrounding area. These step voltages are measured and compared to ECG. Especially to QRS complex and ST segment. We find qualitative agreement when comparing the measured voltages to the data available about the natural lightning discharges regarding the number of strokes in real lighting strike. Based on the measurements a mathematical model for the lightning discharge has been worked out, which allows to gain a deeper insight into the experiment using computer simulations. By comparing the results of the computer simulations based on the mathematical model and the experimental data the mathematical model has been validated. The validated model was used to recalculate the step voltage SV for real lightning current value and shape. The results of the calculation allow to determine the VF safety distance from the object during the lightning strike. The safe VF level were taken from standards and from scientific publications [32,33,34,35,36].

High voltage experiment

Many accidents occur in case a lightning strikes one the highest objects nearby. This object can essentially be a human body, a building or a tree for example. There are different mechanisms of lightning injury [26]. For reasons of safety a normal current spread case has been selected for the experiment. In this situation a lightning strikes an object and the associated current flows into the ground. In the case analyzed, a high voltage surge current will spread out in the vicinity of the tree. The current flowing in the ground goes along with a voltage drop on the ground due to the finite resistance of the conducting ground. This voltage drop is the step voltage SV. Typically SV is defined as a potential difference between a person's outstretched feet (normally 1 meter apart - see figure 3) without touching any other objects [27]. For the experiment a maple tree has been chosen as the entry point for the current. A Maple tree represents the worst case with respect to SV level, because it has a flat root system [28].

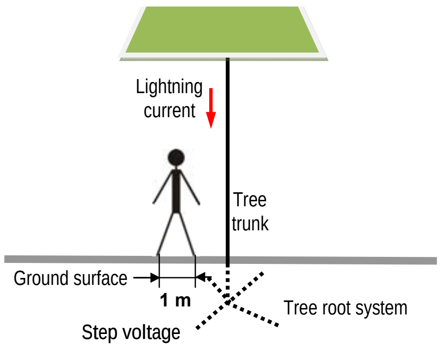


Fig. 3. Step voltage nearby tree [27].

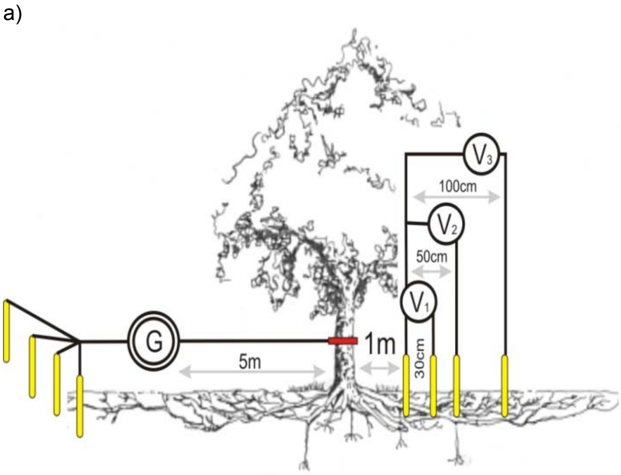
A high voltage surge generator is used as source for our artificial lightning current. It outputs 37 kA current surge with shape 8/26 μs. This kind of current is similar to current induced in surrounding objects during the natural lightning strike [29]. The arrangement of the equipment during experiment is illustrated in Figure 4 and 5.

The high voltage generator was connected to maple tree by copper ring installed on tree trunk 1,3 m above ground level. Second generator output was connected to four symmetrically located current electrodes nearby tree. Current electrodes have length equal 40 cm. The electrodes were made of galvanized steel.

SV have been recorded by our Tektronix's DPO 7254 digital oscilloscope and measured using Tektronix's P6015A high voltage probes. Human feet have been imitated by using circular plates with a radius of 0,08 m. Both feet have been directly connected to high voltage probes. Plates were pressed to ground with force of 250 N in order to provide a realistic electrical contact to the ground as is the case for a natural human body of average weight [30]. In order to include a human body from the electrical perspective into the experiment a linear resistor of 1000 Ω has been used [31]. This model of a human body is well established in the scientific community when considering its electrical properties. Recorded SV can be calculated for different body models easily, due to the linearity of the resistor.

SV were measured for three different distances between the two feet. Standard - 1 m and nonstandard ones 0.5m and 0.3m. Those distances represents different step lengths for more precise results. The first one – when a person makes a step of the nominal length of 1m. Second one – when person makes a small step of only 0.5m. Third one – when person stands with anatomical pose (0.3m).

a)



b)

Fig. 4. Experimental setup (a) for SV measurement (G - high voltage generator, V - digital oscilloscope for SV record), b) photo taken during measurements

The recorded step voltage SV during our high voltage experiment is found in Figure 6. From a medical point of view it is interesting that the step voltage SV drops by 4 kV in the negative direction after 2μs. Shortly after this drop the step voltage SV increases again and changes its polarization. After 18μs the step voltage reaches a positive peak value of 2,7 kV. Afterwards the step voltage SV oscillates with frequency close to 26 kHz.

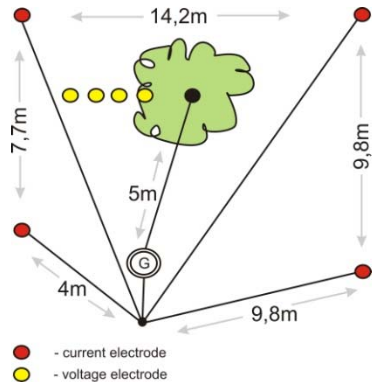
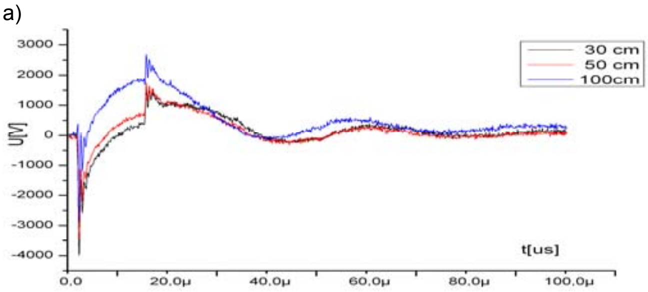


Fig. 5. Additional electrodes arrangement used in experiment stand.

a)



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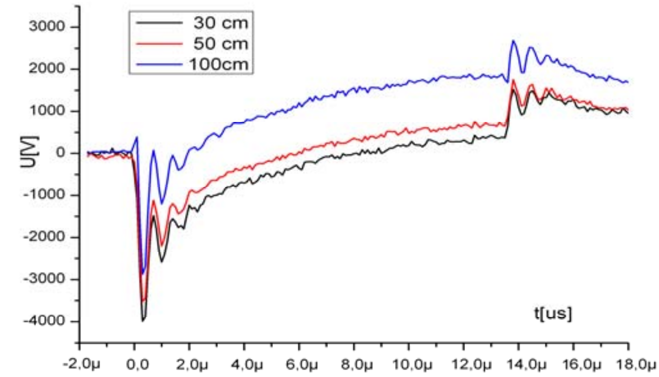

Fig. 6. Recorded step voltage with respect to step length, (a) view for t∈<0;100>μs, (b) t∈<0;18>μs

This Experiment shows that the step voltage waveform has got a similar shape as the ECG illustrated in figure 2. The lightning induced step voltage measured in the experiment is shorter than the QRS segment but the oscillation of step voltage in the natural lighting strike extend the shock time, such that resonance stimulation is becomes more likely. Repetition of SV in real multiplies VF risk. Repolarisation occurs many times for real lightning strike and in this way VF initiation routine are repeated increasing VF risk. The fact that repolarisation occours several times in a row can cause cardiac arrest via resonant stimulation. In consequence, it can decrease the CPR effect and subsequently causes brain death. We propose that multiple lighting strokes provoke SV desynchronization.

VF threshold of multiple current bursts

VF threshold depends on the peak current, current flow path, current frequency spectrum, current effect time etc. According IEC 60479-2 [32] standard multiple bursts of current separated by less than the period of a normal heartbeat can provoke disturbances in the heart with cumulative effects. These cumulative effects can lead to VF even though each burst of current in the series is significantly lower than the threshold of VF applicable to each of the single bursts of current occurring alone - table 3 [32]. For lightning flash multi current pulse increase VF risk ten times or more.

Table 3. VF threshold after each burst of current in a series [32]

Burst of current in a series of bursts separated by less than 1 s	Estimated VF threshold after each burst of current in a series
First current burst	100%
Second current burst	65%
Third current burst	42%
Fourth current burst	27%
Fifth current burst	18%
Sixth current burst	12%
Seventh and subsequent current burst	10% or less

There are many different studies about VF threshold. In real conditions it is real hard to find out about it. Most of the data available originates from calculations based on estimation. Table 4 shows the step voltage thresholds of VF for lightning strikes available in the literature. There seems to be an agreement about the order of magnitude.

Table 4. Step voltage threshold of VF

Study	Step voltage
	[kV]
IEC 60479-2 [32]	25
Neuhaus [33]	15
Dalziel [34]	32,4
Human body flows theory [35]	26,6
Flisowski [36]	24

VF safe zone during lightning strike

In order to study the VF induced by lightning strikes we have performed numerical simulations. Measurements for natural lightning strikes are very hard to obtain, because the strike point is not known in advance. In a natural situation the risk of suffering from VF during direct lightning strike is very high. For other injury mechanisms the risk is lower and can be calculated.

In the following we want to compute the minimal distance between the human body and the tree like strike point that has to be maintained in order to be in the ventricular fibrillation safe zone. For this reason our starting point is the most conservative voltage listed in Table 4, which is 15kV.

All numerical calculations were performed by using the Multi Fields software package[37]. The procedure for the computation consists of the following steps:

- creation of a 3D mathematical model of the object under study (each conductive or semi-conductive element is represented by one segment in 3D space),
- lightning current surge waveform in time domain were decomposed (FFT) to perform frequency domain computations for single harmonic unit current,
- superposition of the frequency domain computations modulated by the amplitude of the lightning current (IFFT), this allows to compute current flow in analyzed object,
- using the model in the numerical computation of the flow a step voltage can be estimated.

The case of a direct lightning strike to a tree has been investigated. In the natural situation there will be not much of a difference between a tree and other similar objects such as flag stands, buildings lighting rods or simple lightning protection systems, which could possibly be hit by a lightning strike. From this point of view we believe that our results are universally applicable regarding the scope of the order of magnitude of the numerical results.

A 3D mathematical model consist of segments defined in 3D space with a specific resistivity defined in each of them. The human body is represented by two segments with total resistance equal to 1000 Ω. The resistivity of wood has been defined to 1000Ω·m, which is a reasonable assumption. The model proposed includes a tree root network as well as a simplified representation of above ground elements such as tree branches and leafs. The resistivity of the ground soil has been assumed to be 100 Ω·m.

Calculation routine was performed for three basic classes of tree root systems [28]:

a) tap root (for example: hickory, walnut, butternut, white oak, hornbeam),
b) heart root (for example: red oak, honey locust, basswood, sycamore, pines),
c) flat root (for example: birch, fir, spruce, sugar maple, cottonwood, silver maple, hackberry).

The tap root system is modeled as vertical segment with length equal 20 m. Additionally 20 segments inscribed a 5m circle were used as a near surface root system. For heart one 20 segments inscribed a 10 m circle were used in the model. The flat one uses the same 20 segments inscribed in a 20 m circle as a model. A graphical illustration of the tree model is presented in Figure 7.

For simulation purposes the lightning current has been injected to the top of the trees (point A in Figure 7) and is represented as an ideal current source in the model. The temporal current waveforms have been modeled by using the well-established function [38]:

$$i(t) = \frac{I}{\eta}\left(e^{-\alpha t} - e^{-\beta t}\right) \qquad (1)$$

with *t the time, current scale I=100kA and the coefficients, α = 2049,38 s^{-}, β = 563 768,3 s$^{-1.}$ and* current scale correction factor η *= 0,976.*

The parameters of lightning current surge were taken from IEC 62305-3 standard [38]. Such waveform describes the first lighting strike in the channel (peak value equal 100 kA, front time equal 10 μs, time to half value 350 μs).

In order to find the step voltage in an area surrounding the trees it was necessary to calculate the rise in ground potential (GPR) at the ground surface. Afterwards, the difference between the GPR values has been calculated for electrodes separated by 1 Meter according to our definition of the step voltage [27]. This way the distribution of the step voltage is derived in the vicinity of the trees.

Figure 8 shows the step voltage in the time domain for four different points located one, two, three and 4 meters from tree trunk. It can be seen that the peak voltages drop rather quickly with the distance from the tree making it more safe at larger distances. Time domain waveforms are useful only from ECG point of view, because Figure 8 and Figure 5 can both be compared with Figure 6. Step voltage distribution in the vicinity of trees are very useful. They present SV nearby trees graphically. Figure 9, 10 and 11 illustrate the results of our calculation at a specific instant in time, which is 2 μs after the lightning strike. At this moment the oscillations disappear and the value of the step voltage is stabilized and can be compared with lightning induced VF threshold levels.

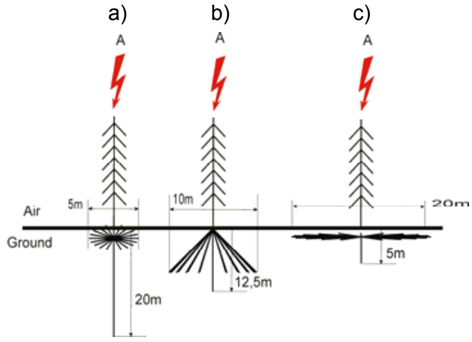

Fig. 7. Graphical representation of tree model for: a) tap root system, b) heart root system, c) flat root system.

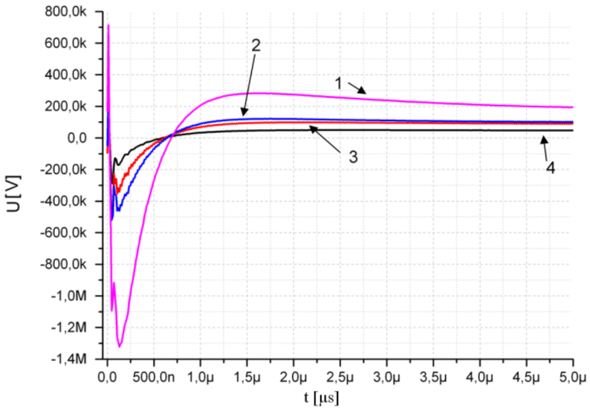

Fig. 8. Step voltage waveform for tap root system t∈<0;5> µs

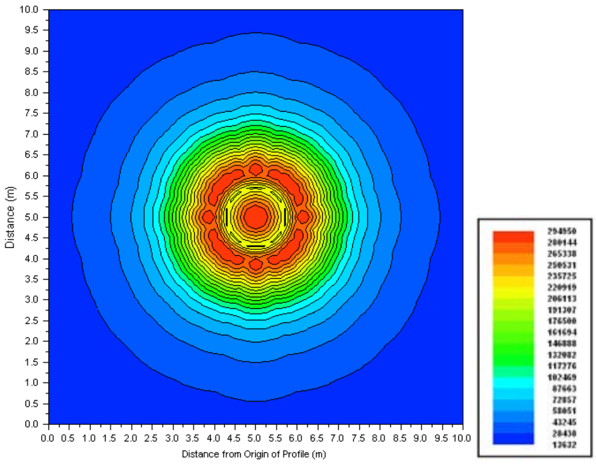

Fig. 9. Spacial step voltage distribution for a tree with tap root system at time t=2 µs

The results of the calculation allow to determine a safety zone nearby the tree and comparable other objects struck by a lighting. Other objects don't have a root system but they have grounding system (flag mount, lighting protection system of building). Relationship should be similar. For detail results other calculations should be made. Maximal value of step voltage nearby tree for different root systems obtained from calculation results are presented in table 5.

For three different types of trees VF free zone is within:

- 10 meters radius (for tap root system),
- 15 meters radius (for heart root system),
- 25 meters radius (for flat root system).

Safe distance where determined from Figures 9, 10 and 11 with respect lowest SV Neuhaus [33] threshold (worst case). In case a less conservative choice of the VF threshold is made according to Table 4. The resulting difference in distance is found to be approximately 2 meters or less. This is because the step voltage drops rapidly enough with the distance such that the result for the practitioner is scarcely affected when changing the ventricular fibrillation threshold by a factor of two.

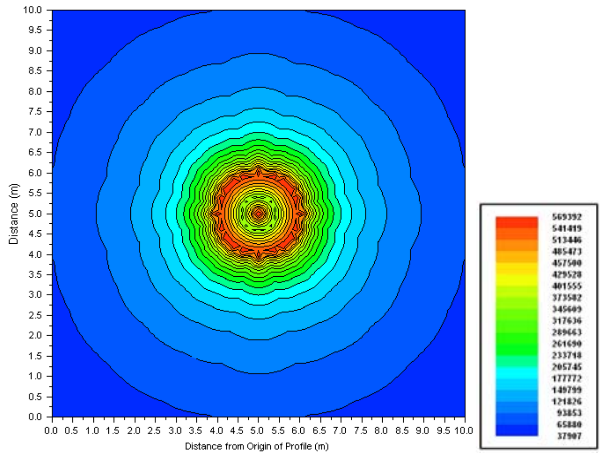

Fig. 10. Spacial step voltage distribution for tree with heart root at time t=2 µs

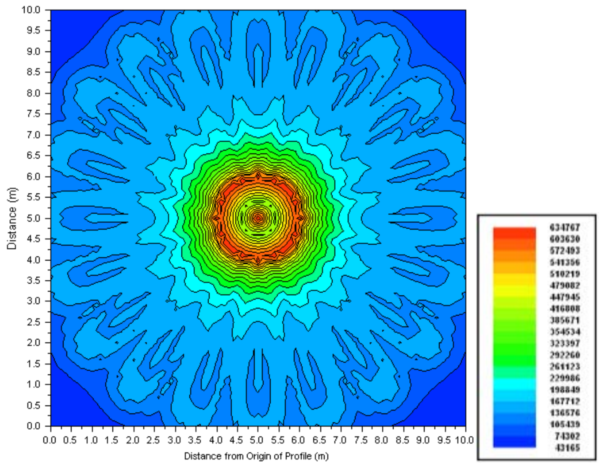

Fig. 11. Spacial step voltage distribution for tree with flat root system at selected moment in time t=2 µs

Table 5. Maximal value of step voltage nearby tree for different root systems (obtained from calculation results - Figure 9, 10, 11)

Tree root system	Maximal step voltage [kV]
Tap	294
Heart	569
Flat	634

Conclusions

Our experiment proves that lighting strike causes the repolarization effect and shows that the lightning step voltage has some similarities to the typical ECG voltage shape. In case a living human body encounters a lightning induced step voltage at the proper moment in time around the peak of the T wave, multiple SV repolarization can result in precipitate VF or resultant asystole [5,7]. Prolonged respiratory arrest resulting in severe hypoxia may also precipitate terminally refractory VF or asystole.

This study has revealed that there exists a ventricular fibrillation safety zone for people wandering in the forests. As common knowledge suggests this study supports the most prominent risk factor to be the distance from human body to lighting strike point. Further factors are the type of the object struck by the lightning and the resistivity of the ground. Trees such as hickory, walnut, butternut, white oak, hornbeam provide the lowest step voltage level in their vicinity. Trees such as birch, fir, spruce, sugar maple, cottonwood, silver maple, hackberry provide the highest step voltage due to the structure of their root system. For objects other than trees there is a need for further studies in order to determine VF safety zones, which will be the subject of further studies.

In conclusion we wish to have people and especially wandering tourists informed about the risks of ventricular fibrillation caused by lightning strikes during thunderstorms and the proposed safety zones.

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