Theodore Bernstein, Ph.D.[1]

Effects of Electricity and Lightning on Man and Animals

It is often difficult to prove whether a man or animal has been electrocuted. Since death from electrocution can occur with no marks on the body, it is important for pathologists and attorneys to be aware of the lethal effects of electricity from the viewpoint of the engineering expert witness who aids in the investigation of such cases.

There has been considerable work in the area of the effects of 60 Hz (1 Hz = 1 cycle per second) alternating currents on the human body because this is the most common form of electrical current utilized in the United States. From these investigations, current levels have been determined for man which cover the range of effects from the threshold of perception, let-go current, ventricular fibrillation, and cardiac standstill. Such data are not directly applicable to the types of impulse-like currents encountered in a lightning stroke, but certainly provide a starting point for such a study.

The study of heart fibrillation and defibrillation, required for the development of the defibrillator, has provided a wealth of information on the effects of impulse currents on the heart. These animal studies are applicable to man and show that the heart can be caused to fibrillate during any part of the heart cycle if the pulse energy is sufficiently large. The threshold for ventricular fibrillation seems to be related to the pulse energy. An electrical pulse shock with an energy of 25 to 50 watt-seconds (joules) may be the lower limit at which a single pulse will throw the heart into fibrillation. Standards for the electric fence controller set a limit on pulse shock energies on the order of 0.25 to 0.4 watt-seconds.

Because experiments involving dangerous electric shock utilize animals, the data presented in the literature deal directly with animals. Lightning death and injury to farm animals have been important in veterinary medicine since the veterinarian is usually called, in questionable cases, to determine whether a farm animal has been killed or injured by lightning or whether the animal died of natural causes. It is an important decision for the farmer and his insurance company.

Statistical Data

In order to appreciate the magnitude of the problem associated with death caused by electrical current and lightning, some representative data for such deaths were obtained for the United States. These help place the seriousness of the problem in perspective.

Received for publication 9 June 1972; revised manuscript received 14 Aug. 1972; accepted for publication 23 Aug. 1972.

[1] Electrical Engineering Department, University of Wisconsin, Madison, Wisconsin 53706.

Electrocution Statistics

There are approximately 1000 deaths per year in the United States from electrical current, excluding lightning. Table 1 provides statistical data from the *Vital Statistics of the United States* for the years 1962 to 1966 to show the overall number of deaths from electrical current and the most common locations where such deaths occur.

TABLE 1—*Deaths caused by electrical current in the United States* [1].

Year	Home	Farm	Industry	Street and Highway	Electrocutions from All Causes
1966	295	77	247	92	1025
1965	293	86	227	108	1071
1964	267	88	223	94	989
1963	254	64	189	89	878
1962	241	56	198	79	849
Average	270	73	217	92	962

Lightning Statistics

Every year more than 100 people are killed, and 300 people are injured by lightning in the United States. The death and injury of animals is on the order of thousands of animals annually. An extremely useful source of information concerning lightning damage is found in *Storm Data* published monthly by the U.S. Department of Commerce [2]. This publication is prepared from reports received from each of the state climatologists who obtain their data primarily from local press reports. There are surely more deaths and injuries than reported in this manner though the monthly tabulation is a good starting point. In addition, some of the injured reported this way may have died later because of their injuries.

An unofficial tabulation of human death and injury has been made from the *Storm Data* publications from January 1, 1968 to January 1, 1972. The average results for the monthly and annual totals for lightning death and injury are shown in Table 2. Also included in Table 2 are data for death and injury when the individual was near a tree or telephone when struck. The data of Table 2 show that most deaths and injuries occur in the United States during the 6-month period of April through September.

There seems to be a definite pattern for the activities or location where a person is apt to be injured by lightning. Locations or activities that seem to occur quite regularly are near a tree, on a golf course, on a tractor, using a telephone, near a clothes line, near a wire fence, and in a boat. Larger groups of people are injured at military camps while in the field or on athletic fields.

Causes of Death at Power Frequencies

Most of the data relating to electrical shocks have been obtained from animal tests with the data extrapolated to provide information on humans. This seems valid since the effects of electric shock on larger mammals is related primarily to body weight. The response of the body to electrical shock is quite dependent on the waveform and frequency of the electrical source. Studies indicated that power frequency currents, 50 to 60 Hz, are more dangerous with lower danger threshold than higher frequency, direct, pulse or impulse currents. The power frequency sinusoidal currents are certainly less like lightning

TABLE 2—*Lightning death and injury in U.S. Monthly and Annual Average. Time Period: January 1, 1968 to January 1, 1972* [2].

	Overall		Tree Related		Telephone Related	
	Killed	Injured	Killed	Injured	Killed	Injured
January	0	1	0	0	0	0
February	0	0	0	0	0	0
March	1	1	0	0	0	0
April	3	3	0	0	0	0
May	12	21	2	4	0	1
June	24	56	3	8	1	2
July	31	78	5	10	1	2
August	21	67	5	6	1	1
September	17	27	1	2	0	1
October	2	3	0	0	0	0
November	0	1	0	0	0	0
December	0	0	0	0	0	0
ANNUAL TOTAL[a]	109	260	12	26	2	5

[a] Round off error prevents annual total average from equalling the sum of the individual monthly averages.

currents than a pulse or impulse current, but the effects on the body are the same. Information concerning power frequency shocks is presented as a starting point for discussing electric shock because of the considerable data available and to present the shock effects on the body. This will be followed by information concerning impulse shocks which will more closely approximate lightning currents.

This discussion will primarily be concerned with the shock effects on the cardiovascular system as electrical shocks usually cause death because of their effect on the heart. It is generally agreed that it is the current which passes through a body that does the damage [*3,4*]. The voltage in a circuit is only important because of the magnitude of the current it can produce in the body. Large currents passing through or around a person can cause serious injury because of the heating and burning of tissue. This type of injury is more common at higher voltages used by power companies.

Death at lower voltages, such as 120 to 240 V often used for secondary distribution systems, can usually be attributed to one of three causes:

1. Ventricular fibrillation, most common
2. Respiratory arrest
3. Asphyxia

Depending on the type of electrical contact made and the current level produced by the voltage, death can occur at these voltages with no electrical burn marks on the body.

Ventricular Fibrillation

Ventricular fibrillation is an uncoordinated asynchronous contraction of the ventricular muscle fibers of the heart in contrast to their normal coordinated and rhythmic contraction. The heart seems to quiver rather than to beat. This condition is caused by an electrical shock where the path of current is through the chest, such as between two arms or between an arm and a leg. Once a person goes into ventricular fibrillation, his blood circulation ceases, he becomes unconscious in less than 10 seconds, and he can have irreversible brain damage in 4 to 6 minutes unless corrective action such as cardiopulmonary resuscitation is taken. The cardiopulmonary resuscitation is used as a temporary measure to provide some circulation of oxygenated blood since the only way to terminate the fibrillation is to use a defibrillator which applies a pulse shock to the chest to restore the heart rhythm. Ventricular fibrillation leaves no characteristic evidence for the pathologist after death. This fact, together with the fact that ventricular fibrillation is often the terminal condition in death from natural or other accidental causes, makes it possible for a person to be electrocuted without any positive postmortem findings.

A typical electrocardiogram is shown in Fig. 1. The time scale is in milliseconds (1 millisecond = 0.001 seconds). The "P" wave is the beginning of the heart cycle and indicates atrial contraction. The wave of excitation triggers the "QRS" complex which occurs as the ventricles contract as a unit and pump blood. When contraction is completed, the repolarization of the heart takes place during the "T" phase. Shocks during the "T" phase are most likely to cause the heart to go into ventricular fibrillation. To defibrillate the heart, it is necessary to employ a counter shock through the chest, which is large enough to depolarize all the muscle fibers of the heart, causing all of them to contract simultaneously. When the heart relaxes after this shock, the next "P" wave will usually restart the heart cycle unless ventricular fibrillation has continued too long [*5–7*].

Respiratory Arrest

Shocks with a current path through the respiratory center can cause respiratory arrest. The respiratory center in the medulla of the brain stem is at the base of the skull slightly above a horizontal line from the back of the throat. Thus shocks from the head, to a limb, or between two arms could lead to respiratory arrest [*8*].

Recent work indicates that shocks at current levels of energies above those that cause ventricular fibrillation can produce respiratory arrest even though the path of the current is not through the respiratory center. Shocks in dogs between the foreleg and hindleg caused convulsions and respiratory arrest at lower current levels than shocks between the two forelegs even though there would be a tendency for more current to be in the respiratory center for the latter case. Artificial respiration can help in this case [*9*].

Asphyxia

Asphyxia is caused by contraction of the chest muscles. When current is above a certain level, a person cannot let go of an electrically hot wire. Currents somewhat above this level

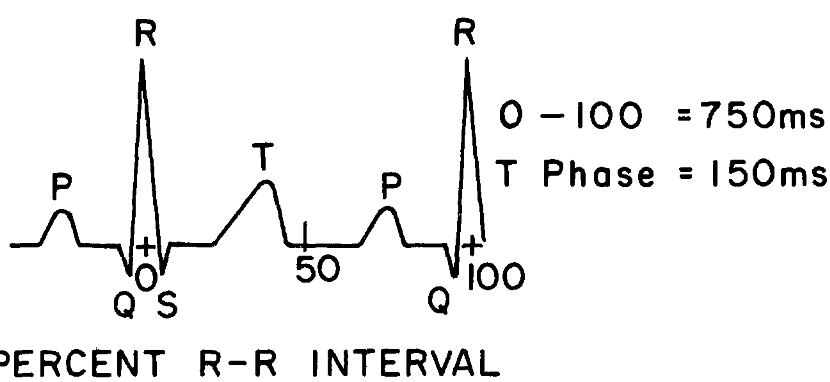

FIG. 1—*Electrocardiogram.*

may not be sufficient to cause ventricular fibrillation but may be sufficient to cause the contraction of the chest muscles and asphyxia since the victim cannot let go of the wire [8].

Electrical Parameters for Power Frequency Shocks

The electrical resistance between the limbs of an individual is highly variable when the skin is intact. It depends on the contact conditions such as dry skin versus moist skin, the tough skin of a laborer versus a baby's tender skin, and so on. Tests indicate that a good approximation for the normal resistance between any two limbs, excluding the skin, is 500 ohms. This is the measured resistance with a good contact under the skin. The skin has a variable resistance which is quite high for dry, intact skin and quite low for moist or torn skin. Using this figure of 500 ohms and applying Ohm's Law, a person across a 120 V line, touching the line with any two limbs, might have a current of 240 mA (1 mA = 0.001 amperes) through his body. Across 240 V, the current might be on the order of 480 MA.

Threshold of Perception

The threshold of perception for a finger tapping contact at 60 Hz is 0.2 mA. A current of 0.36 mA can be perceived by 50 percent of a group of men while 50 percent of a group of women can perceive 0.24 mA. This is an important parameter since a shock of such low level in itself is not dangerous, but it might startle an individual so that he falls from a ladder or has some other involuntary action which could be hazardous to the individual or an associate [*10*].

Let-Go Current

A somewhat higher current level than the threshold of perception, is the let-go current level. The let-go current level is important because the victim is involuntarily held to the energized wire and cannot let go. His resistance may then decrease so that lethal currents can pass through his body. Dalziel [*3*] has run tests on 134 men and 28 women to determine at what current level in his arm an individual cannot let go of an energized conductor. Since this let-go current level varies among individuals, he has used statistical methods to provide the let-go current data shown in Table 3. The let-go current level for women was lower than that for men; that is, at 60 Hz ½ percent of the women could not let go at 6 mA. The let-go d–c current is higher with a painful jolt being experienced when the circuit was broken. Let-go d–c current was taken as the value at which the subject refused to let go because of the jolt he would experience.

Asphyxia and Respiratory Arrest Current Levels

Asphyxia can be caused by 60 Hz currents of 40 to 60 mA across the chest. The victim should be pulled off the line, or the line should be deenergized to allow the chest muscles to relax and permit breathing.

TABLE 3—*Let-go current.*

Frequency	½% of Men (One Man in 200) Cannot Let Go	50% of Men Cannot Let Go	99.5% of Men Cannot Let Go
5 Hz	15 mA	25 mA	36 mA
60 Hz	9 mA	16 mA	22 mA
1 kHz	13 mA	24 mA	35 mA

Respiratory arrest is not as common at lower current levels as asphyxia and ventricular fibrillation since the current path in accidents is usually not through the respiratory center. There is no figure readily available as to current level causing this condition, but it is probably on the order of 0.1 A between the head and limb. Shocks above 5 amperes at 60 Hz for one second may cause a respiratory arrest even when the current path is from one hand to a foot and the respiratory center is not in the path of the current. Artificial respiration will certainly help in cases of respiratory arrest.

Ventricular Fibrillation Current Levels

Ventricular fibrillation is truly life threatening since the only real relief requires the use of a defibrillator. From experiments with animals extrapolated to possible human application, the 60 Hz current value for shocks with the current path through the chest which will produce ventricular fibrillation in one out of 200 people is given by the expression

$$I = (k/\sqrt{T}) \text{ mA rms } (8.3 \text{ ms} < T < 5\text{s})$$

The constant k is an empirical constant derived from animal experiments and is related to body weight *[11]*. The range of k is from about 100 to 185 with the lower range applicable for children and the upper range for men. For a 70 kg man, the value of k would be approximately 165. The factor T is the time of the shock in seconds while the limits show that the tests were valid for a range of time from 8.3 milliseconds, one half cycle at 60 Hz, to 5 seconds. Tests seem to indicate that from 5 to 20 or 30 seconds the threshold is essentially the same.

From this information it should be evident that 60 Hz currents as low as 0.2 mA can be dangerous because of involuntary startle reaction. A current of 9 mA might prevent a person from letting go of a conductor while a current of approximately 150 mA for one second could cause ventricular fibrillation.

It is important to note that the current levels described are for intact individuals who make contact with energized circuits. In hospitals where a patient may have probes or catheters inserted into his body, the electrical currents which can cause harm when introduced into the patient by way of a probe or catheter have lower danger threshold values.

Pulse and Impulse Electrical Shocks

There are three sources of information for the effect of pulse or impulse currents on the human or animal body. Recently, there has been considerable study using pulse and impulse currents on animals and on man in the development and use of defibrillators. Other studies have involved the analysis of accidents which have occurred where the power supply was a bank of capacitors that produced an impulse current shock. The third series of studies was conducted 20 to 30 years ago when the standards for electric fences were determined.

Defibrillator Tests

Peleska *[12–14]* and Kouwenhoven *[15,16]* have shown that capacitors discharged directly across the chest of a dog can cause fibrillation at any part of the heart cycle if the voltage is sufficiently high.

In defibrillators used on man, the energy content of the capacitor which is discharged across the patient's chest can be as much as 200 to 400 watt-seconds. Delay lines, inductors, and electronic circuitry can modify the shape of the discharge current to optimize the defibrillation. The shape of the capacitor discharge is important. Defibrillation ability is enhanced if the tail end of a normal capacitor discharge is removed by truncating the discharge curve at some preset value. This seems effective in eliminating the problem of the initial high current defibrillating the heart while the trailing low current causes fibrillation again. Shocks across the chest of greater than 1600 V or of duration longer than 10 ms can cause heart damage [*17–19*].

Study of Impulse Current Accidents

Dalziel [*20,21*] has made a study of accidents involving impulse currents. He has concluded that impulse shocks with an energy content of 50 watt-seconds may be the upper limit for a safe impulse shock.

This value of shock energy seems to be of a consistent magnitude with the results found in determining safe levels at power frequency. At 60 Hz it was determined that the threshold for ventricular fibrillation is approximately

$$i = (0.1/\sqrt{T})\ \text{A rms}$$

where T is in seconds. Then, if the body resistance is taken to be

$$R_b = 1000\ \text{ohms}$$

the power delivered to the body is

$$P = i^2 R_b = (10/T)\ \text{watts (joules/second)}$$

The energy delivered is

$$W = P \cdot T = 10\ \text{watt-seconds (joules)}$$

This simple calculation indicates that a shock with an energy on the order of 10 to 50 watt-seconds is a good threshold above which shocks will tend to lead to ventricular fibrillation.

Electric Fences

The Underwriters' Laboratories standard for electric fence controllers limits the magnitude and duration of the current the fence can deliver. A normal fence control cycle consists of a pulse or impulse of current for approximatly 0.2 s with an off period of approximately 0.8 s. During the on period the 60 Hz or pulse output into the 500 ohm load is limited to an energy of about 0.25 watt-seconds which can produce a disagreeable shock. The off period is required to permit a person to release his hold on the fence [*22,23*].

Experiments have shown that a single pulse shock will have a certain threshold level to produce ventricular fibrillation. Repeated pulse shocks below this threshold level can cause premature ventricular contractions. After 5 or 6 premature ventricular contractions caused by a pulse train, the level for producing fibrillation reaches its lowest value. This explains why prolonged exposure to a–c shocks or to a pulse train of shocks causes fibrillation at lower threshold levels than for very brief or single pulse shocks [*24*].

Lightning Shocks

A likely cause of death in lightning injury is ventricular fibrillation. This is particularly true when there are no marks on the body or when there is little tissue damage. It is probably best to use the energy content in the current impulse delivered to the victim in studies of the lethality of lightning. Energies as low as 50 watt-seconds may cause death.

Dr. Helen Taussig has emphasized the importance of providing prolonged resuscitation for lightning victims. In a case where several people are injured, it is probably wise to concentrate effort at first on those apparently dead. Those who seem to be living will probably survive while there is a good chance that some apparently dead can be revived after prolonged mouth-to-mouth resuscitation and closed chest cardiac massage [*25,26*].

Lightning and Animals

The problem of determining whether farm animals were killed by lightning or died of natural causes is an important one for veterinarians. They are often called by a farmer or his insurance company to make such a determination for insurance purposes.

Dr. James R. Howard, III, in his 1966 Ph.D. dissertation [*27*] at Iowa State did an extensive study of lightning effects on animals. In experimental work on sheep, he found that capacitor discharge shocks of greater than 1760 watt-seconds were necessary to kill sheep with one electrode placed on the back of the head and the second on the feet. From these tests and from a 3-year analysis of many reported animal lightning deaths in Iowa, he was able to arrive at some characteristics such as singed hair and skin which seemed to occur most frequently.

Most experiments have shown that mammals with a cardiovascular system like man have a susceptibility to electric shock related to body weight. There is an often expressed opinion that cows are more susceptible to electrical shock or lightning than human beings. There are no technical data to support this opinion. Farm animals probably are killed or injured by electricity or lightning because of the good conductivity of the ground around their feet and their exposure to the elements during a storm [*28*].

Legal Electrocution

In considering the effects of electricity on man, it is worthwhile to consider the case where electricity was deliberately applied to cause death by legal electrocution. Legal electrocution was one of the more widely adopted forms of capital punishment in the United States. Since the first legal electrocution at Auburn Prison, New York in 1890, more than 20 states adopted this form of execution. The electric chair has a head electrode and a second electrode for the calf of the leg. The State of Illinois had a typical installation where during an electrocution 7.5 A, 60 Hz, 2300 V power was applied for 7 s followed by the same current and frequency but only at 550 V for 52 s. This cycle was repeated a second time to complete the execution [*29,30*].

Since the method of application for the electricity by way of electrodes and the current and voltage levels are so different from those found in most home or industrial electrocutions, little scientific use can be made of the medical studies on electrocuted criminals.

Summary

The fact that a death is caused by electricity or lightning can be difficult to verify in some cases. Without any characteristic pathological finding, it is necessary to evaluate the electrical parameters involved to aid in ascertaining the probable cause of death.

In higher voltage and current accidents, the cause of death is often obvious because of the associated electrical burns. At lower voltages and currents, death is often a result of ventricular fibrillation. This fibrillation can be caused by currents through the chest as low as 100 mA at 60 Hz or by impulse shocks with energy content of 10 to 50 watt-seconds.

References

[*1*] *Vital Statistics of the United States*, Vol. II–Mortality, Part A., U.S. Department of Commerce.

[*2*] *Storm Data*, U.S. Department of Commerce, National Climatic Center, Federal Building, Asheville, N.C. 28801.

[*3*] Dalziel, C. F., "Reevaluation of lethal electric currents," *IEEE Transactions Industry and General Applications* IGA-4, No. 5, Sept./Oct. 1968, pp. 467–476.

[4] Keesey, J. C. and Letcher, F. S., "Minimum thresholds for physiological responses to flow of alternating electric current through the human body at power-transmission frequencies," Research Report, Project MR005, 08-0030B, Report No. 1, Naval Medical Research Institute, National Naval Medical Center, Bethesda, Md., Sept. 1969.
[5] Lee, W. R., "Electrophysiology" in *International Symposium on Electrical Accidents*, International Occupational Safety and Health Information Centre (Geneva, Switzerland), 1962, pp. 45–64.
[6] Lee, W. R., "The nature and management of electric shock," *British Journal of Anaesthesia*, Vol. 36, 1964, pp. 572–580.
[7] Kouwenhoven, W. B., "Human safety and electric shock," in *Electrical Safety Practices*, Monograph 112, Instrument Society of America, 1969, pp. 91–97.
[8] Lee, W. R., "Death from electric shock," *Proceedings of The IEEE*, Vol. 113, Jan. 1966, pp. 144–148.
[9] Hodgkin, B. C., Langworthy, O., and Kouwenhoven, W. B., "Effect on breathing of an electric shock applied to the extremities," *IEEE Transaction Power Apparatus and Systems*, Transactions Paper T 72 087–0, 1972.
[10] Kahn, F. and Murray, L., "Shock free electric appliances," *IEEE Transactions on Industry and General Applications*, IGA–2, No. 4, 1966, pp. 322–327.
[11] Smoot, A. W., "Lethal electric shock," *Lab Data*, Underwriters' Laboratories, Inc., Vol. 1, No. 4, Autumn 1970, pp. 12–15.
[12] Peleska, B., "Cardiac arrhythmias following condenser discharges led through an inductance," *Circulation Research*, Vol. 16, Jan. 1964, pp. 11–18.
[13] Peleska, B., "Optimal parameters of electrical impulses for defibrillation by condenser discharges," *Circulation Research*, Vol. 18, Jan. 1966, pp. 10–17.
[14] Peleska, B., "Cardiac arrhythmias following condenser discharges and their dependence upon strength of current and phase of cardiac cycle," *Circulation Research*, Vol. 13, July 1968, pp. 21–32.
[15] Kouwenhoven, W. B., "Effect of capacitor discharges on the heart," *AIEE Transactions*, 75, Part III, 1956, pp. 12–15.
[16] Milnor, W. R., Knickerbocker, G. G., and Kouwenhoven, W. B., "Cardiac responses to transthoracic capacitor discharges in the dog," *Circulations Research*, Vol. 6, Jan. 1958, pp. 60–65.
[17] Stephenson, H. E., Jr., *Cardiac Arrest and Resuscitation*, 3rd Edition, St. Louis, C. V. Mosby Co., 1969, Chapters 23, 56, and 57.
[18] Geddes, L. A. and Tacker, W. A., "Engineering and physiological considerations of direct capacitor–discharge ventricular defibrillation," *Medical and Biological Engineering*, Vol. 9, 1971, pp. 185–199.
[19] Schuder, J., H. Stoeckle, J. A. West, and P. K. Keshar, "Transthoracic ventricular difibrillation in the dog with truncated and untruncated exponential stimuli," *IEEE Transactions on Bio-medical Engineering* BMS–18, No. 6, Nov. 1971, pp. 410–415.
[20] Dalziel, C. F., "A study of the hazards of impulse currents," *AIEE Transactions*, 72, Part III, 1953, pp. 1032–1053.
[21] Dalziel, C. F., in *Handbook of Laboratory Safety*, 2nd ed., N. V. Steere, Ed., The Chemical Rubber Co., Cleveland, Ohio 1971, pp. 521–527.
[22] Whitaker, H. B., "Electric shock as it pertains to the electric fence," *Bulletin of Research. Underwriters' Laboratories*, No. 14, Dec. 1939.
[23] "Electric Fence Controllers," *Standards for Safety*, UL 69, 2nd ed., Underwriters' Laboratories, Chicago, Ill., June 1948.
[24] Sugimoto, T., Schaal, S. F., and Wallace, A. G., "Factors determining vulnerability to ventricular fibrillation induced by 60–CPS alternating current," *Circulation Research*, Vol. 21, Nov. 1967, pp. 601–608.
[25] Taussig, H. B., "Death from lightning and the possibility of living again," *American Scientist*, Vol. 57, No. 3, 1969, pp. 306–316.
[26] Coleman, T. H., "Death by lightning," *Pennsylvania Medicine*, Vol. 72, No. 3, Mar. 1969, pp. 56–58.
[27] Howard, J. R., III, "The effects of lightning and simulated lightning on tissues of animals," Ph.D. thesis, Iowa State University, 1966.
[28] Ramsey, F. K. and Howard, J. R., "Diagnosis of lightning stroke," *Journal of The American Veterinary Medical Association*, Vol. 156, No. 10, May, 1970, pp. 1472–1474.
[29] Hassin, G. B., "Changes in the brain in legal electrocution," *Archives of Neurology and Psychiatry*, Vol. 30, 1933, pp. 1046–1060.
[30] Elliott, R. G. with Beatty, A. R., *Agent of Death, the Memoirs of an Executioner*, E. P. Dutton, New York, 1940, p. 147.