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Effects of ELECTRIC SHOCK

An engineering report discussing in detail the three major causes of accidental electrocution. Considerations of voltage, current, frequency and duration are taken up. Chances for survival under various conditions are analyzed. Electrocardiograms are shown

AN ELECTRICAL ENGINEER'S knowledge of the response to an applied electromotive force should not be limited to networks of resistance, capacitance, and inductance. It should include, also, the response of a human being. Unfortunately, the engineer usually knows little more than the layman about the latter subject, even though he is much more exposed to the hazards of electricity than is the average person. This article is written to acquaint the engineer with the basic principles of the effect of electricity on the human organism.

The first recorded death due to electricity was that of a stage carpenter at Lyon in 1879. He touched a 250-volt line. This, however, was not the first use of lethal electric potentials, for they were used as early as 1849 in the first performance of Meyerbeer's 'Il Prophète", and in 1857 in lighthouses in England. As early as 1890, the electric chair was introduced by the state of New York. Here voltages of 1200 to 1700 volts were used. In electrocutions currents up to 8 amperes were sent through the victim's body for 3 to 8 minutes.

The death rate due to accidental electric shock was low at the beginning of the century, being about 200 a year in countries like England, the United States, and Germany. It rose rapidly, until in 1915 the rate was 0.8 per 100,000 annually. Since then it has remained quite constant, and at present is 1 per 100,000 per year.

Causes of Death by Shock

Death by electricity is due to one of three fundamental causes: a cessation of respiration due to a block in the part of the nervous system controlling breathing; a serious reduction of the circulation of the blood, due to ventricular fibrillation of the heart; or an overheating of the body. Of the three, the second of these is the most dangerous, for there is no practical way of bringing a fibrillating heart into a normal beat. Of course, death may be the result of a combination of the above causes, or due to complications, such as a broken neck, etc. The mechanisms of death will now be discussed in more detail.

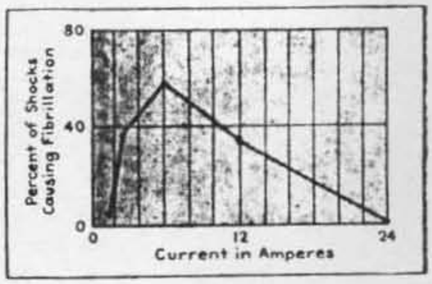

FIG. 3—Effect of electric current on susceptibility of sheep hearts to ventricular fibrillation. Each shock was applied for 0.03 sec at 60 cps, in the most sensitive part of the cycle

Variations in Body Resistance

In the layman's mind, (as well as in that of the engineer) a great deal of confusion exists as to whether the current or the voltage of the circuit is the determining factor in death. This is quite inexcusable, for as early as 1913[1] it was clearly understood that the current passing through a person's

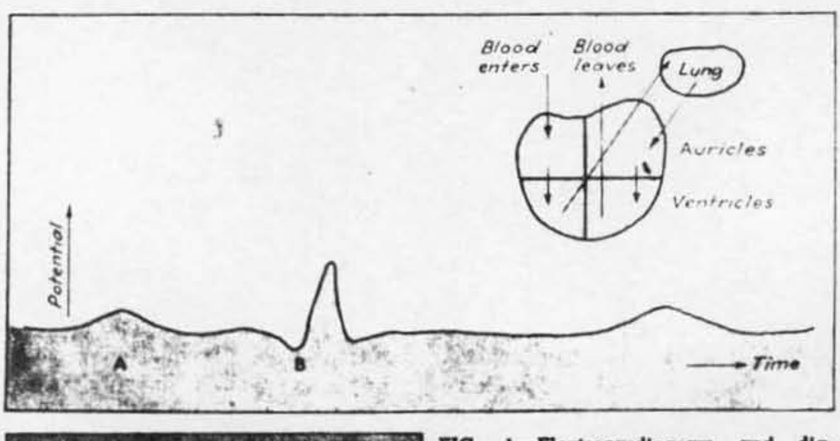

FIG. 1—Electrocardiogram and diagram of normal heart

FIG. 2—Electrocardiogram of a sheep's heart in ventricular fibrillation

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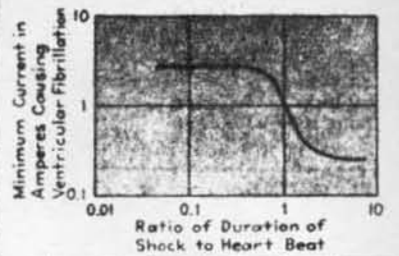
FIG. 4—Effect of position of shock in cardiac cycle on susceptibility of sheep hearts to ventricular fibrillation

FIG. 5 (RIGHT)—Effect of duration of shock on threshold current for sheep



body (rather than the voltage applied) was the determining factor. The reason for the wide variation in voltage required to send a lethal current through a human body is that the resistance of the body varies from 1000 ohms when wet to 500,000 ohms when dry.

The resistance of the body is made up of the skin resistance and the internal resistance. The former is large when the skin is dry (70,000 to 100,000 ohms per sq. cm.), but falls to less than a hundredth of this value when wet. The internal resistance is low because the tendons, muscles, and blood are relatively good conductors.

In high-voltage shocks serious burns are often produced because the high voltage punctures the outer skin. The body resistance then suddenly falls from a high value to the low value of the internal resistance.

It is understandable that the effect a given current will have depends on the current path through the body. It is found that the heart, the brain, and the spinal column are the three most critical regions.

Effect of Current Magnitude

Let us consider the effects produced when the magnitude of a 60-cycle current is slowly increased. Numerous studies[1] have shown that the threshold of perception is 1 ma. In other words, currents less than 1 ma are not even felt, provided abnormally large current densities, as result from pin-point contacts, are not produced.

Currents from 1 to 8 ma are perceptible, but not yet painful. When the currents reach a value of 8 to 15 ma they are painful, and cause an involuntary contraction of the muscles affected. Muscular control, however, can still be exercised. Currents of 15 to 20 ma are painful, cause involuntary contraction, and muscular control is lost. Currents of 20 to 50 ma, passed between arms, or an arm and a leg, involve the chest muscles and breathing becomes difficult. Currents of 100 to 200 ma, when passed through the body in a path that involves the heart region, produce ventricular fibrillation (an uncoordinated beating of the various heart muscles).

Currents in excess of 200 ma produce burns; if they take a path involving the heart region, the heart action is suspended for the duration of the current passage, but generally is resumed at the end of this period.

If the path involves the part of the nervous system controlling respiration (such as hand to hand, hand to foot, head to hand, etc.) a block in the respiratory system is produced. If artificial respiration is applied, the body may resume its own breathing after as long as 8 hours; if the damage to the respiratory - controlling nervous system is severe, however, breathing may be suspended indefinitely.

Ventricular Fibrillation

The phenomena of ventricular fibrillation and respiratory block deserve closer attention. Ventricular fibrillation is an uncoordinated contraction of the various heart muscles, which makes the heart practically useless as a pump. The phenomenon can better be understood by reference to the electrocardiogram and diagram of a normal heart in Fig. 1. The stimulus *A* corresponds to the contraction of the auricles, which contract together. The stimulus *B* corresponds to the contraction of the ventricles, which also contract together.

The electrocardiogram for ventricular fibrillation can easily be recognized, for it has the irregular pattern shown in Fig. 2.[2] Experimental work on human hearts in regard to fibrillation is of course impossible. But guinea pigs, rabbits, and sheep also are subject to fibrillation, so considerable work has been done with them.

The variation of the percentage of shocks causing fibrillation with the magnitude of the current passed through the body of a sheep is shown in Fig. 3.[2] Each point represents about 75 trials. Note that the susceptibility increases with cur-

UNDERSTANDING PROMOTES SAFETY

ESSENTIALLY medical in character, this paper explains why some people die and some don't after accidental contact with electric circuits

CATHODE-RAY and other electronic apparatus employs high voltages and it is the thought of the editors that the information contained in these pages may, therefore, save many lives

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TABLE I.
RESULTS OF A BRIEF EXPOSURE TO A-C POTENTIALS

Body resistance assumed to be	100 volts	1000 volts	10,000 volts
Very low, with good contact (About 1,000 ohms)	*Certain death;* slight burns	Probable death; marked burns	Survival; burns and other sequelae; very severe
Higher (About 10,000 ohms)	Painful shock; no injury	*Certain death;* burns probably slight	Probable death; severe burns
High with bad contacts (About 100,000 ohms)	Scarcely felt	Painful shock, but no severe injury	*Certain death;* burns slight if resistance remains high

rent up to a maximum, and then decreases as the current is increased further. This is in agreement with observed data on man, for it has been observed that as the voltage increases on high-voltage shocks, the percent that can be resuscitated increases.

For shocks short in duration compared to a heart cycle, the probability of producing fibrillation varies with the part of the heart cycle in which the shock occurs. This is shown by the dash-dash curve superimposed on the electrocardiogram in Fig. 4. This sensitive phase represents the decreasing contraction of the heart muscles. At any other time, the heart is quite insensitive to shock.

Duration of Shock

Finally, the effect of shock length was studied. The results are plotted in Fig. 5. Note the sudden increase in susceptibility to fibrillation as the shock length approaches the length of the heart cycle. What happens to this curve as the shock length is decreased to much smaller values, say one microsecond, is an interesting question, but no authentic data is available on this subject.

Resuscitation Principles

Numerous methods have been tried to bring a fibrillating heart back to a coordinated beat. Of these the method of counter shock first used by Abilgaard in 1775 to arrest fibrillation in cocks seems the most promising. It has been used with success on guinea pigs and dogs. It consists of an application of a shock of high intensity and short duration through the heart. The obstacles encountered in trying to apply this to humans are: (1) difficulty in determining whether a heart is actually fibrillating; (2) the availability of proper facilities for applying the shock; (3) the counter shock, if improperly applied, may actually become the cause of the death. As a result, the recommended procedure in all cases of electric shock is to apply resuscitation immediately, and not attempt to apply counter shock.

In many cases of electric shock the victim becomes unconscious and stops breathing, but his heart keeps on beating. This is due to a break in the nervous system controlling respiration. The nerves are paralyzed by the currents and no longer transmit stimuli to the lungs. Here one difference between the operation of the heart and lungs becomes evident; the nervous center which controls the lungs is located in another organ, the brain.

The brain and heart must always be supplied with oxygen. If the oxygen supply ceases, the person first becomes unconscious. If the supply of oxygen to the brain is cut off for more than 5 to 8 minutes, damage is done to the Betz cells in the cortex of the brain. This damage is permanent and cannot be repaired by the body. If the person should be brought back to life his mental capacity will be impaired. Serious damage of this kind results in idiocy.

If the damage to the nervous system is not too severe, the block will pass away (0 to 8 hours) and the person will resume breathing of his own accord, provided the person has been kept alive by supplying the vital cells of the body with oxygen in the meantime through artificial respiration. This explains the prescribed procedure in all cases of electric shock: apply artificial resuscitation immediately and continue until rigor mortis sets in.

In cases of severe damage to the cells of the nervous system controlling respiration (dislocation of the nuclei, swelling of the nucleoli, and cytoplasmic loss of granule) the natural breathing of the body is never resumed.[4]

The third cause of death is excessive heating of the body. The reason for death here is not obscure. The detailed mechanism of death is a medical matter and its discussion would lead us too far astray. It is sufficient to remark that death is due to the destruction by heat of some vital organ, or to hemorrhages, or to third-degree burns.

Effect of Frequency

A further characteristic of current that determines its effect on an organism is its frequency. A ready example is that of direct current and 60-cycle alternating current. The bearable direct current is

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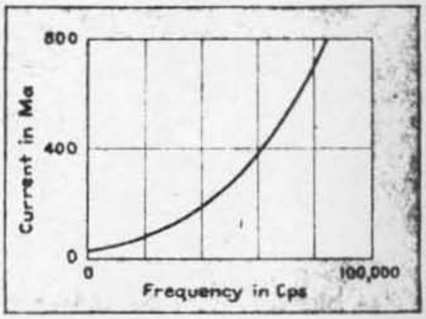

FIG. 6—Effect of frequency on tolerance current

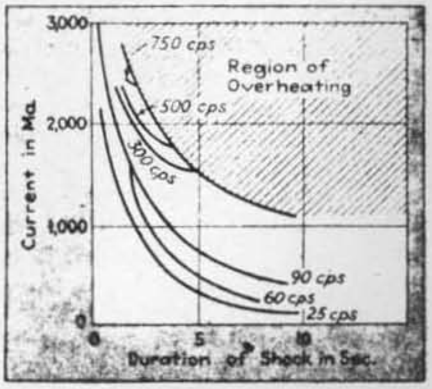

FIG. 7—Minimum currents necessary to cause death from shocks of different duration at several frequencies

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Electric Sho[illegible]

(Continued from pa[illegible])

about three times that [illegible] cycle current. This pr[illegible] been studied from two [illegible] the maximum current wh[illegible] son could stand before dis[illegible] caused and second, the am[illegible] current required to kill lab[illegible] animals.

The former method of atta[illegible] taken by A. E. Kennelly and [illegible] Alexanderson.[5] Their data is [illegible] marized in Fig. 6. In each c[illegible] current was slowly increase[illegible] it was felt that further [illegible] would cause distress. Note that [illegible] current that can be tolerated w[illegible] out distress rises rapidly with [illegible] quency.

Above 100,000 cps the only e[illegible] produced by the current was [illegible] of heat. The explanation that [illegible] been advanced for this behavio[illegible] that the alternations of the curr[illegible] are too rapid to have any effect [illegible] the nerve cells.

The heating effect of the high[illegible] frequency currents is used to [illegible] vantage in diathermy machi[illegible] where frequencies of 500,000 [illegible] 1,000,000 cps with currents of [illegible] to 5 amperes are used. A seco[illegible] application is electrosurgery. He[illegible] a platinum needle and a large ele[illegible] rode are used. The needle produc[illegible] such a high current density tha[illegible] the tissues are completely de[illegible] stroyed by heat.

The second line of attack was taken by A. G. Conrad and H. W. Haggard[6]. They studied the currents necessary to cause death for shocks of different durations at various frequencies. Their results on rats are summarized in Fig. 7. Note that the amount of current required to kill increases with the frequency.

These results as well as those of W. Kouwenhoven, D. Hooker and E. Lotz[7] show that the frequencies that are the most dangerous are those in the neighborhood of 60 cps.

Let us turn our attention to the number of electrical accidents that actually occur, and the percentage of them that turn out to be fatal. An analysis by E. Krohne[8] of 848 electrical accidents in Germany from 1930 to 1935 showed that 314 involved voltages under 500 volts, with an average fatality rate of [illegible] percent. The remaining 534 [illegible] ceived voltages over 500 volts, w[illegible] a fatality rate here of 33 perce[illegible]

W. McLachlan[9] gives more [illegible] tailed information based on stu[illegible] of 475 cases where electricity al[illegible] was the cause of death, not lack [illegible] resuscitation, broken necks, bur[illegible] etc. (Data by Krohne includes [illegible] these cases, hence this differe[illegible] must be kept in mind when comp[illegible] ing the figures. The difference [illegible] particularly noticeable at hi[illegible] voltages, where death from bur[illegible] etc., is more probable.) McLac[illegible] lan's figures are based on U. S. a[illegible] Canadian industrial accidents, a[illegible] divide the accidents according [illegible] the potential of the circuit involved:

Record of Accidents by Potential of Circuit Involved

Volts	Total Cases	Successful Revival
0–749	65	63%
750–4999	212	65%
5000–39,999	167	69%
40,000 and over	26	88%

Note that the danger does not necessarily increase with the voltage. This is due to two reasons: first, the muscular reaction is more pronounced at high voltages, making it more likely that the person will be thrown clear of the circuit; secondly, as data on animals has shown, the heart is not thrown into fibrillation by very large currents (greater than 250 ma).

Segregation of these cases according to the method of clearing revealed that of 282 who fell clear, 70 percent were successfully revived of 179 who were pulled clear from the circuit, 63 percent were revived. This may appear puzzling at first, for one would expect the difference to be more pronounced. Remember, however, that it takes only a shock of a fraction of a minute to throw the heart into a fatal fibrillation or to cause a respiratory block. After that, the effect is a heating of the body. It is true that if the heating is very severe, it may cause damage to the cells of the nervous system or severe burns, but often it is not.

The data by McLachlan shows that if resuscitation is instituted soon after the accident, the fatality can be reduced to 33 percent. This is in agreement with the figure of 23 percent obtained by Kawaranura in a study in Japan; the figure of 23 percent obtained by Baralta in a study in France; and the average fatality rate for 1930–1935 in Germany of 24 percent quoted earlier.

Jex-Blake[1] summarizes in a practical form in Table I much of the data presented in this paper.

Life-Saving Precautions

We will close with a few practical pointers:

1. Don't entertain a false feeling of security by believing that resuscitation can always bring a person back to life after an electric shock. If the heart is thrown into fibrillation (and this is quite possible) for all practical purposes death is instantaneous.
2. In case of electric shock, apply artificial resuscitation immediately. Do not delay to summon a doctor but try to get help while resuscitating the victim.
3. Never handle electric circuits with wet hands or when feet are wet.
4. If there is no other means of rescue, use your foot rather than your hand to free the victim from the live circuit.
5. When working on high voltage, be sure the floor is not a good conductor (as far as electric shock is concerned, a concrete floor is a good conductor).
6. When handling high-voltage circuits, it is a good rule to keep your left hand in your pocket.
7. Don't work in a position where your head is likely to become a conductor in an electric shock.

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