THE CURRENT FLOWING THROUGH THE HEART UNDER
CONDITIONS OF ELECTRIC SHOCK

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Received for publication January 12, 1932

In studying the effect of electric shock upon rats (1, 2, 3) it became
evident that the injury was in the main confined to the portion of the body
that was traversed by the current. The present paper is directed specifi-
cally to a study of the effect upon the heart since this organ is believed
to be especially liable to injury in electric shock. The purpose of the
present experiments was two-fold; to ascertain the proportionate value of
the total current which actually flows through the heart when contact at
various points on the body is made with the circuit and to determine the
minimum current necessary to establish ventricular fibrillation.

Dogs, completely anesthetized with morphia and ether, were used
as experimental animals because the ventricles of the dog's heart are readily
thrown into a permanent state of fibrillation by the application of relatively
weak currents as is assumed to be the case in man.

The source of the current was a 60 cycle, alternating current circuit.
Ring or through type current transformers were employed to measure
the current traversing the heart, the heart itself forming the primary
winding of the transformer. The iron cores of these transformers were
ring shaped and of the highest quality magnetic material.1 They were
approximately square, having a cross-sectional area of 0.01 square inch
(0.07 sq. cm.). Each ring was uniformly wound with approximately 2000
turns of no. 36 Brown and Sharp enamel insulated copper wire which
served as the secondary winding on the transformer. The rings were of
varying inside diameters, ranging from $\frac{1}{2}$ inch up to 3½ inches, so that
they could be slipped over hearts of different sizes. The current flowing
through the heart induces an electro-motive force in the secondary winding
of the transformer encircling it. The terminals of this secondary winding
were connected across a potentiometer type rheostat, and the desired por-
tion of the voltage drop in this rheostat was fed into an amplifier whose

1 The authors wish to take this opportunity to thank the Bell Laboratories Inc.
and the Westinghouse Electric and Manufacturing Company for their kindness in
furnishing the transformer cores.
output was a measure of the current flowing through the heart. The complete details of the electrical equipment are given in another paper by one of the authors (4).

In order to check the operation of the ring transformers they were immersed at the center of a conducting bath consisting of a ten per cent sodium chloride solution. The bath was over six feet in length and approximately five by five inches in cross-sectional area. In a bath of these dimensions, placing the electrodes at the extreme ends insures a uniform current distribution at the center. Tests proved that when the plane of the ring was perpendicular to the direction of the current flow, the amplifier reading measured the total current flowing through the area inclosed by the ring. When the ring was turned so that its plane was parallel to the current path the amplifier reading was zero. In all of the tests it was found that the amplifier output was equal to the current actually flowing through the area inclosed by the ring. Therefore, with the ring inclosing the heart it measured the current through that organ.

**Application of transformer.** The thorax was opened under artificial respiration and the pericardium freed from its attachment to the diaphragm. A ring transformer of suitable size was passed over the apex until it fitted snugly about the mid-region of the ventricles where it was held in place by ligatures passing through the pericardium. After the ring was in place the pericardium was sewed closely to its original attachment on the diaphragm. The fully insulated lead wires were carried to their proper connections and the thorax was then roughly closed, to establish approximately normal conditions.

The heart is such a mobile structure that it is difficult to determine its electrical conductivity at any single instant. Its only permanent connection is with the great vessels at its base. During expansion of the lungs they make good contact at the sides, a contact which is less perfect during expiration. The apex of the heart lies in proximity to the diaphragm but the effectiveness of contact at this point varies continually. Moreover the operation upon the chest caused a further change in these normally variable conditions. By closure of the chest after insertion of the ring and applying mechanical inflation and deflation of the lungs throughout the experiments, physiological conditions were preserved as carefully as possible.

The equipment controlling the voltage supplied to the electrodes was such that any desired value of voltage could be obtained and the total current passing through the body held constant. An ammeter inserted in the circuit measured the total current.

**Period during which current distribution is constant.** With different points of contact on the body the amount of current passing through the heart could be determined upon the animal after death provided no appre-
ciable change developed in the current distribution through the body. Figure 1 shows the results of one experiment. In this case the total current through the animal (head to tail) was held constant by controlling the voltage of the supply circuit. Artificial respiration was continued even after the heart ceased to beat and the current flowing through the heart varied slightly, presumably with the amount of air in the lungs, but it is apparent that satisfactory constant conditions prevail for at least thirty minutes.

With these data in hand, which were confirmed in other experiments, it was felt justifiable to continue observations on the dead animal for the period specified in order to conserve material.

In a number of experiments the total current flowing through the body was varied from a low value to several hundred milliamperes, and the current flowing through the heart noted. The heart current proved to be a fixed percentage of the total current flowing.

The change in the current distribution apparently coincides fairly closely with the onset of complete rigor mortis. It was noted in the experiments that rigor of the neck musculature was judged to be complete one-half hour after death.

Current passing through heart for different current paths. Tests were made on a number of animals with the ring transformers encircling the heart, thus measuring the current that flowed through the heart for various current paths. In these experiments the total current flowing through the body was varied in the different animals, but in any given animal it was held constant during the test. The electrodes were first placed on the head and tail. The total current through the animal was adjusted to the desired value and that through the heart read on the amplifier. The electrodes were then shifted to a new position, the total current through the dog readjusted to the given value and that through the heart measured. The electrodes were then shifted to the next position and the procedure repeated. When all the important current paths had been tried, the electrodes were shifted back to head and tail and a second series begun. It was possible to obtain four to five series of readings on each

Fig. 1. Variation of current through heart with time following the death of the animal.
animal during the half hour period before rigor mortis set in. Thus each value of heart current for a given current path found in table 1 represents the average of four or five separate readings taken at intervals of six or seven minutes. In some of the tests only a few current paths were studied and in these cases the data in the table are the average of a larger number of readings.

It is evident from table 1 that there is a fair agreement between the results obtained with the different animals when the current flowed downward through the trunk. However, for points of contact where the current path was at right angles or nearly so to the trunk the agreement is poor and there is a wide variation in the values obtained with different animals. The lack of agreement is probably due to several causes, the principal one being the difficulty of restoring complete normal conditions when closing up the opening in the chest cavity.

A study of the results in table 1 shows that approximately nine per cent of the total current flowing down through the trunk from the head to the lower extremities passed through the heart. It is interesting to note that more current flowed through the heart when the current entered the right fore-leg and passed out at either hind-leg or tail, than when it entered via the left fore-leg. These results check the earlier experiments (2) made on rats when it was found that only 33 per cent recovered when the current...
path was from right fore-leg to tail, while 58 per cent recovered when the left fore-leg was used in place of the right. It was found that when the current path was from hind-leg to hind-leg, no current flow through the heart could be detected. This result also confirms experimental data found with rats (2).

The last three columns of table 1 give the data for the cases where the current pathway was from the head to either fore-leg or from one fore-leg to the opposite fore-leg. When contact at the body is made at these points the current flows more or less transversely through the thorax. As already pointed out, the agreement here is poor. A few experiments were made with the two inch ring transformer sewed along the right side of the heart, thereby fixing its plane parallel to the body axis. The current path in these tests was between the fore-legs and the average current flowing through the ring was found to be three per cent of the total current in the circuit. This value also checks closely that found with the transformers encircling the heart.

**Current necessary to initiate fibrillation.** In seven experiments the current through the heart necessary to initiate fibrillation was measured. The electrodes were attached to the head and tail of the animal, and the total current was gradually increased using a five second shock at each value. The current actually flowing through the heart for each shock was determined from the amplifier output. After each five second shock the thorax was opened and the condition of the heart visually determined. There was considerable variation among the individual animals as was to be expected. In one case a heart current of six milliamperes caused fibrillations, in another the value was 15 milliamperes. The average value was 8.6 milliamperes.

**Fibrillation experiments.** In order to check the accuracy of the results several tests were made to find the amount of current that must be applied to the surface of the body with different leads in order to produce ventricular fibrillation without the ring transformers in place. In these tests one electrode was kept permanently connected to the right fore-leg while the other was connected to either the left fore-leg or to the two hind-legs which were used as a single terminal.

Two experiments were made with the heart perfused in situ. With the current pathway down through the trunk, the current through the animal was increased until fibrillation was initiated. Then the heart was recovered by the injection of potassium chloride into the coronary arteries (5). Next the movable electrode was transferred to the left fore-leg and the current now flowing transversely through the body adjusted to the value that would initiate fibrillation for this current pathway.

The results of one of these experiments are given in table 2. These data show clearly that for this animal a total current of 90 milliamperes
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flowing in at the right fore-leg and out at the lower extremities was enough to set the heart in fibrillation. With the current flowing transversely between the fore-legs it required 243 milliamperes to start fibrillation.

The data in table 1 gave the average heart current as 7.8 per cent of the total body current for a current pathway from the right fore-leg to either

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hind-leg. In this experiment using the same current path it required 90 milliamperes flowing through the animal to initiate fibrillation. This was equivalent to a current through the heart of seven milliamperes. In the cases where the current path was from fore-leg to fore-leg the current
through the heart was approximately 3 per cent of the total current, which corresponded in this check experiment to 7.3 milliamperes through the heart. This test was successfully repeated several times and the current values check closely, as may be seen from table 2. The results obtained with the other animal tested in this manner were equally good.

SUMMARY

It is evident from these experiments that 9 or 10 per cent of the total current passing through the body flows through the heart for a current pathway parallel to the body axis. When the current flows transversely only about 3 per cent passes through the heart. Thus as far as the heart is concerned fibrillation will be produced by a much smaller total current flowing from the upper to the lower extremities than between the fore-legs.

In most industrial accidents the current path is from right hand to the feet and under these conditions the heart carries a greater proportion of the total current than when contact with the circuit is made at any other location on the body.

The authors wish to take this opportunity to acknowledge their appreciation to the Committee on Physiology of the Conference on Electric Shock for providing funds for this work.

BIBLIOGRAPHY


