# THE ELECTRICAL CONDUCTIVITY OF THE TISSUES NEAR THE HEART AND ITS BEARING ON THE DISTRIBUTION OF THE CARDIAC ACTION CURRENTS

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IN THEORETICAL studies of the factors which determine the form of the electrocardiogram, it has usually been assumed that the heart is, in effect, immersed in an extensive medium which may be regarded as homogeneous with respect to those properties which determine the distribution of electrical currents of the kind produced by the heartbeat.[1-3] Those who have made this assumption have not maintained that it is strictly in accord with the facts, but merely that, considering the purposes which they had in mind, it represents the true situation with adequate accuracy. Recently the validity of this claim has been challenged as a result of the interpretation placed upon indirect experiments of various kinds.[4-7] So far as the writers have been able to ascertain, however, systematic direct measurements of the specific electrical resistances of the living tissues of anesthetized mammals have not previously been made. This is because of the great technical difficulties encountered in the application to such tissues of the methods available to the physical chemist for the measurement of specific conductivity.[8-12] It is the purpose of this article to describe the development, properties, and use of simple electrode systems which we have employed to measure the specific resistances of living tissues in situ.

*Theoretical Considerations.*—The current flow through an electrolyte or other conductor in an ordinary conductivity cell is determined by the size and shape of (a) the electrodes and (b) the walls of the cell. In the simplest case of plane circular electrodes, located at the ends of a cylindrical tube and perpendicular to its axis, the resistance, $R$, is defined by the equation

$$R = TL/A$$

where $T$ is the specific resistance; $L$, the length of the tube; and $A$, its cross-sectional area. The cell constant is then $K = R/T = L/A$. For more complicated cell forms the cell constant is usually determined experimentally by the use of an electrolyte of known specific resistance, $T$. For the present purpose, however, it is not practical to obtain nonconducting boundaries corresponding to the walls of a cell from which the cell constant may be computed or measured. The obvious expedient is then to consider an unbounded or infinite medium.

The resistance between two small spherical electrodes of radii $a$ and $b$ separated by a distance $l$ in an infinite medium of specific resistance $T$ is given by Mason and Weaver[13] as

$$R = T/4\pi \left( \frac{1}{a} + \frac{1}{b} - \frac{2}{l} \right) \qquad (1)$$

As $l$ is made large its effect becomes negligible, and the resistance is the sum of two parts, one for each electrode. The cell constant for a single spherical electrode is then $\mu = 1/4\pi a$. Similarly, for a buried disc of radius a, $\mu = 1/8a$, and if the disc rests on a flat surface of the medium, $\mu = 1/4a$.
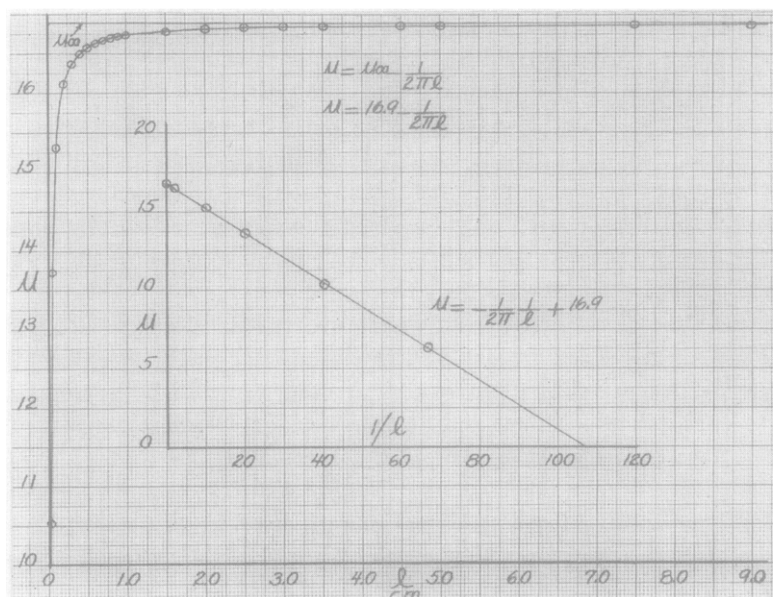


Fig. 1.—Curves showing the relation between the cell constant, $\mu = R/T$, of a pair of point electrodes placed in an infinite medium and the distance between them, $l$. The large graph represents the equation $\mu = \mu\infty - \frac{1}{2\pi l}$, which was obtained by substitution of values for $a$ and $b$ and $\alpha$ and $\beta$ in Equation 2 (see text). The small insert shows that when $\mu$ is plotted against $1/l$, a straight line is obtained.

The most practical experimental technique has been to use cylindrical wires which were insulated except at the ends. The electrodes in contact with the electrolyte or tissue were then circular discs with the diameters of the wires. With thick insulation the cell constant of each electrode would be that of a disc applied to the surface, or $\mu = 1/4a$. The cell constant has not been calculated for thin insulation, but it will be smaller than $1/4a$, and will probably approach the value $1/8a$, which is that of the buried disc with both faces exposed. In general then, we may write

$$R = T (1/\alpha a + 1/\beta b - 1/2\pi l) \qquad (2)$$

where $\alpha$ and $\beta$ depend upon the shapes of the electrodes and the insulation, but certainly lie between $4$ and $4\pi$. The relation between $\mu = R/T$ and $l$ is shown in Fig. 1. If $a$ and $b$ are nearly equal and $l$ is more than

twenty times the radius $a$, the proximity effect will be less than 5 per cent. The requirement of an infinite extent of a single tissue cannot be met rigorously, and the effects of adjacent tissue have been calculated. It has been found that if each electrode is more than twenty times its radius from the nearest surface, the boundary proximity effect is less than 5 per cent for any conductivity of adjacent tissue from zero to infinity.

If two electrodes are placed more than twenty times their radii from each other and from the boundaries, the cell constant should be within 10 per cent of the value for a large separation in an infinite medium. For any particular organ or tissue these conditions can always be met by making the electrodes sufficiently small, but other difficulties may arise. The electrodes should not be as small as the tissue cells, for the measured resistance will then depend upon their position relative to the nearest cells. Furthermore, as the electrodes are made smaller, the polarization impedance of the electrode surface increases more rapidly than the measured resistance. A limit is then set by the efficacy of the platinization which can be obtained. In the case of a disc, the platinization near the center is not fully effective because the current density is much lower there than it is near the edge.

*Equipment.*—A portion of the work reported here was performed in the Electrochemical Laboratory and the remainder in the Heart Station. As regards essentials, the equipment was the same in both places. It consisted of a modified Jones and Josephs[8] bridge, which measured parallel resistance $(R_p)$ and capacity $(C_p)$, a thermostat, a standard conductivity cell of a design recommended by Jones and Bollinger,[10] an oscillator, and platinum electrodes of various types. The bridge used in the Heart Station differed from that employed in the Electrochemical Laboratory in that it had an amplifier in the phone circuit. The oscillator used in the latter place had a fixed frequency of 1,000 cycles per second and a fixed output, whereas both the frequency and the output of the oscillator used in the former could be varied. The small electrodes hereinafter designated as point electrodes, or points, were made of platinum wire about 0.25 mm. in diameter and were insulated except at the tips by a variable thickness of glass.

<div align="center">EXPERIMENTAL RESULTS</div>

*Measurements of Point-Electrodes Systems.*—Measurements were made with point electrodes in different combinations, at various separations, and in several media and shapes and sizes of vessels. Only those pertinent to the present investigation will be discussed. Aqueous solutions of sodium chloride, potassium chloride, ammonium chloride, hydrogen chloride, and zinc sulfate were used. For certain experiments the electrolyte was dissolved in 2 per cent agar-agar (Difco Bacto-Agar), which was subsequently allowed to solidify. The resistance of all aqueous solutions was measured in the standard conductivity cell be-

fore and after it was measured with the special electrode systems. A 3-liter beaker filled with the solution to be studied served as a first approximation to an infinite medium.

*Electrode Polarization and Platinization.*—The polarization impedance at the surface of bare platinum was too large to permit the use of small electrodes of this material; consequently, all electrodes were electrolytically coated with platinum black before they were used. The point electrodes were platinized by passing current from a storage battery through them after they had been immersed in chloroplatinic acid. A commutator was used to reverse the polarity of the current once per second. The resistance in the external circuit, which was located mainly at the electrode-acid junction, varied continuously in an unknown fashion as the degree of platinization increased. As the elec-
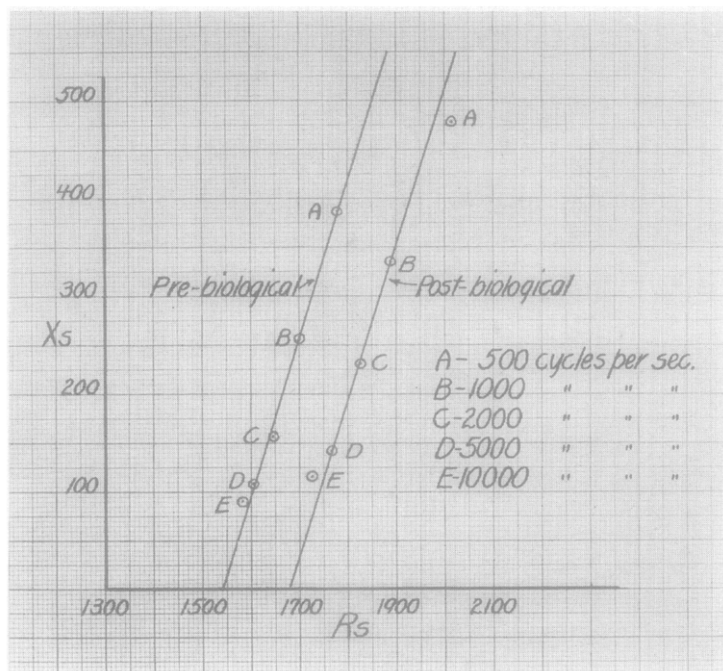


Fig. 2.—Impedance loci of a pair of point electrodes before and after they were used to measure the resistance and reactance of living tissue.

trodes were platinized for increasing lengths of time, the effects of polarization at first decreased rapidly and then more slowly (Jones and Bollinger[12]). After 150 seconds of platinization, the electrodes were usually satisfactory. The series resistance and reactance of such a pair of electrodes in normal saline were computed from the measured parallel resistance and capacity, and are plotted as an impedance locus in Fig. 2. The intercept on the resistance axis is the electrolyte resistance approached at high frequencies. The reactance and added

resistance at each frequency constitute the electrode polarization impedance. For many purposes this is negligible. It was found, however, that for measurements made at the single frequency of 1,000 cycles, the apparent cell constant of point electrodes increased as either the concentration or the temperature of the electrolyte was increased. For unselected electrodes the changes in the value of $\mu$ produced by variations in the temperature and concentration of the solutions studied amounted to between $\pm 4.5$ and $\pm 8.5$ per cent of its mean value. For any given concentration, $\mu$ was constant for a given pair of electrodes (separated by a distance of at least 3 cm.) to within 0.5 per cent. This constant did not vary with changes in the output of the oscillator at any frequency. These effects are probably results of the changes of the polarization impedance with concentration and temperature.

When two point electrodes were immersed in a 3-liter "infinite" medium, the point-point resistance and $\mu$ increased gradually with greater separation of the electrodes, but this increase was most rapid when the separation was less than 1 cm. From the data of Table I it was found that $\mu \infty = \dfrac{1}{a\alpha} + \dfrac{1}{\beta b} = 16.9$ cm.$^{-1}$ If $a = b = 0.125$ mm. then $\alpha = \beta = +9.5$. This lies between the values of 8 for the double-sided disc, and $4\pi$ for the sphere, indicating that the surface was probably convex outward. Substituting this value in equation (2), the theoretical curve of Fig. 1 was obtained. It agrees well with the observations, and shows a proximity effect of 5 per cent for a distance of 2 mm.

TABLE I

COMPARISON OF THE OBSERVED VALUES OF $\mu$ AND THOSE CALCULATED FROM THE EQUATION, $\mu = \mu \infty - \dfrac{1}{2\pi l}$, OF FIG. 1

| $l$ CM. | $\mu$ | |
|---|---|---|
| | CALCULATED | OBSERVED |
| 0.5 | 16.58 | 16.65 |
| 1.0 | 16.74 | 16.74 |
| | | 16.81 |
| 4.0 | 16.86 | 16.81 |
| 4.5 | 16.86 | 16.86 |
| 5.0 | 16.87 | 16.88 |
| 10.0 | 16.90 | |

When the volume of the medium was reduced from 3,000 to 60 c.c. and the diameter of its cross section from about 15 cm. to 4.5 cm., the resistance and the relation between the resistance and the distance between the electrodes were the same (within the physical limitations as regards separation of the electrodes imposed by the smaller volume of the medium) as when the medium was more extensive. The data given in Table II indicate that the electrode proximity effect and the boundary proximity effect are about 1 per cent for the range investigated.

TABLE II

VALUES OF THE CELL CONSTANT, $\mu$, OF A PAIR OF POINT ELECTRODES IN A RESTRICTED MEDIUM (60 C.C. OF NH$_4$Cl SOLUTION IN A CYLINDER 4.5 CM. LONG, AND 4.5 CM. IN DIAMETER) AND IN A MORE EXTENSIVE MEDIUM (3,000 C.C. OF NH$_4$Cl SOLUTION IN A LARGE BEAKER)

| | DISTANCE BETWEEN ELECTRODES, $l$CM. | $\mu$ |
|---|---|---|
| Restricted medium | 1.5 | 18.69 |
| Restricted medium | 2.0 | 18.77 |
| Restricted medium | 2.5 | 18.84 |
| Unrestricted medium | 1.5 | 18.90 |

When 2 per cent by weight of agar-agar was dissolved in aqueous solutions of a number of inorganic substances and permitted to solidify, it caused no change in the conductivity of the original aqueous solutions. The resistance-distance relationship of the point-point electrode system inserted into the agar block was the same as for a medium of the original composition and of comparable shape and volume.

As a test of our method, we calculated from point electrode measurements the resistance that would be observed when the medium was placed in a standard conductivity cell, and then attempted to confirm our prediction by observation. Since $R_k/R\mu = K/\mu$, the factor $K/\mu$ may be ascertained by measuring the resistance at a given frequency of a solution of known conductivity by both methods. When $R\mu$ has been measured with an unknown solution, $R_k$ may be calculated. As a check, $R_k$ for the unknown solution may be measured directly. For example, the resistance $(R_k)$ of an aqueous solution of approximately 0.9 per cent NaCl measured 2,574 ohms in the standard conductivity cell. The predicted value of $R_k$ for an agar block containing 2 per cent agar-agar dissolved in 0.9 per cent NaCl, obtained by computation from $R\mu$, was 2,584 ohms.

*Summary on Electrode Systems.*—The properties of simple point-electrode systems were investigated theoretically and experimentally with reference to their suitability for the measurement of specific conductivities under a variety of conditions. In the form used by us these special electrode systems have certain limitations and do not permit measurement of specific conductivity with the same degree of precision as the standard conductivity cell. They do, however, make it possible to ascertain, with an accuracy sufficient for many purposes, the specific conductivity of materials which cannot be placed in a standard conductivity cell and have not heretofore been satisfactorily measured.

MEASUREMENT OF THE SPECIFIC RESISTIVITY OF LIVING
MAMMALIAN TISSUES

Our animal experiments were carried out upon dogs which were anesthetized with morphine and urethane. Various operative procedures were used to gain access to the organs or tissues studied. When the chest was opened, the lungs were ventilated with room air by

TABLE III

MEASUREMENTS OF THE SPECIFIC RESISTANCE OF LIVING TISSUE IN OHM CM.

| DATE 1938 | MUSCLE | LIVER | LUNG | HEART | PERICARDIUM | FAT | BLOOD | SERUM |
|---|---|---|---|---|---|---|---|---|
| 4/28 | 492-506<br>425-416 | 524-460<br>513 | 768-791<br>810-757<br>784-839<br>713<br>*401<br>624 | 153-143<br>307-285 | 434-405 | | | |
| 5/9 | 707-565 | 1,083-789 | 850-719 | 212-199 | | | | |
| 5/12 | 722-525<br>752<br>701-569 | 517-419 | †1,368-1,332 | | | | | |
| 5/17 | 552-539<br>587-527 | 778-758 | †1,563-1,243 | 265-251<br>224-212 | | 1,960-1,757 | | |
| 5/19 | 636-672 | | 765-681 | | | | | |
| 5/20 | 1,103-938 | | | | | 2,450-1,859 | | |
| 6/1 | 426 | | 397-804<br>686-615 | | | | | |
| 6/4 | 1,532-760 | 697-390 | †1,278-1,108 | 185-151 | | | | |
| 6/6 | 610-320 | 595-222 | †1,257 | | | | | |
| 6/7 | | | | | | | 235-195<br>225-175 | |
| 6/9 | | | | | | | | 178-98 |

The figures given first are those based on the prebiologic calibration of the point electrodes.
The figures given last are those based on the postbiologic calibration of the point electrodes.
*Lungs deflated.
†Lungs superinflated.

means of a pump designed by Erlanger and Gesell.[14]  All measurements of tissue conductivity were preceded by the calibration of a set of two point electrodes separated by a distance of 2 or more centimeters. The calibration consisted of measuring, at frequencies of 500, 1,000, 2,000, 5,000, and 10,000 cycles per second, the parallel resistance and parallel capacities required to balance the bridge after the electrodes were immersed in an "infinite" medium of approximately 0.9 per cent saline at a temperature close to that of the tissues to be studied. The conductivity of the 0.9 per cent saline, maintained at the same temperature, was measured independently in a standard conductivity cell. As soon as the point electrodes had been standardized, they were placed on the surface or within the substance of the tissue or organ under investigation, and the parallel resistance, $R_p$, and parallel capacitance, $C_p$, required to balance the bridge for the above frequencies were ascertained as rapidly as possible. After the tissue measurements were completed, the electrodes were restandardized.

TABLE IV

AVERAGE VALUES FOR THE SPECIFIC RESISTANCES OF LIVING TISSUES IN OHM CM.

| TISSUE | NO. OF ANIMALS | NO. OF OBSERVA-TIONS | SPECIFIC RESISTANCE PREBIOL. CALIBRA-TION | SPECIFIC RESISTANCE POSTBIOL. CALIBRA-TION |
|---|---|---|---|---|
| Muscle | 9 | 13 | 711 | |
| (somatic) | 9 | 11 | | 575 |
| Liver | 6 | 7 | 672 | |
| | 6 | 6 | | 506 |
| Heart | 4 | 6 | 224 | 207 |
| Pericardium | 1 | 1 | 434 | 405 |
| Lung | | | | |
| At end of normal inspiration | 4 | 9 | 766 | |
| | | 7 | | 744 |
| Superinflated | 4 | 4 | 1,367 | |
| | 3 | 3 | | 1,227 |
| Deflated | 1 | 1 | 401 | |
| Fat | 2 | 2 | 2,205 | 1,808 |
| Serum | | 1 | 178 | 98 |
| Blood | | 2 | 230 | 185 |

The specific resistance of the saline solution (approximately 0.9 per cent) used in standardizing the point electrodes was roughly 50 ohm cm. at 37° F., or about one-fourth that of defibrinated blood.

The series resistance and reactance at each frequency were calculated for the electrodes in saline before and after the tissue measurement.*  The characteristics in each case are shown in the impedance loci of Fig. 2. The "cell" constant and the electrode polarization were not the same after the electrodes had been in contact with tissue as

*In computing the series resistance, $R_s$, and series reactance, $X_s$, the following formulas were employed (see Cole and Cole[15f]):

$$R_s = \frac{R_p}{(1 + R_p^2\ C_p^2\ W^2)} \qquad X_s = \frac{R_p^2\ C_p\ W}{(1 + R_p^2\ C_p^2\ W^2)}$$

$R_s$ = Series resistance; $X_s$ = series reactance; $R_p$ = parallel resistance; $C_p$ = parallel capacitance; $W = 2\ \pi$ frequency.

before, perhaps because of the absorption of proteins. The specific resistance of the tissue and the polarization corrections were calculated from these data. Higher values for the specific resistivity of the tissue were usually obtained when the first or prebiologic calibration curve was used than when the second or postbiologic calibration curve was used, but the reverse was sometimes the case (Tables III and IV). It should be pointed out in this connection that since several tissues were measured with the same pair of electrodes in the course of each experiment, the prebiologic calibration for all except the first tissue studied was also the postbiologic calibration for the preceding observation. In some instances the series resistance and reactance of the tissue were calculated, and the polarization resistance and reactance subtracted at each frequency.

The impedance loci for muscle, liver, and lung shown in Figs. 3, 4, and 5 were obtained by plotting the resistances and reactances which had been computed in this manner. These loci are probably circular arcs such as have been found over wider frequency ranges for other tissues and cells.[15d, 15f] It is possible to extrapolate the lower frequencies and direct current resistances from these data. However, the resistance for the range of frequencies below 500 cycles per second, which occur in the electrocardiogram, are only slightly larger than those at 1,000 cycles. Consequently, only these latter values will be considered.*

The simplest biologic tissue studied was defibrinated dog's blood, which consisted, by volume, of half cells and half extracellular fluid. About 500 c.c. of defibrinated blood in a beaker with a diameter of 10 cm. constituted the "infinite" medium. The electrical resistance was measured both in the standard conductivity cell and by calibrated point-electrode systems. The resistance and capacitance measured by the point electrodes in a large medium are resident in a relatively small volume of circumelectrodal medium, and are not influenced to any great extent by the medium lying outside this region. This is shown by measurements made by immersing the point electrodes in defibrinated blood before and after the blood was allowed to sediment. The resistance of the mixed whole blood was 4,900 ohms; whereas, after sedi-

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*The specific resistances shown in Table III were computed in the following way. Approximately 0.9 per cent saline solution at body temperature was measured in a standard conductivity cell at the beginning and again at the end of the experiment, and the mean of the two readings ($R_k$) was used. The cell constant of the conductivility cell, K, was known to be 39.37. The same solution was measured with the point electrodes before and after each observation. The prebiologic constant of the point electrodes was ascertained from the first reading, $R\mu$ (at 1,000 cycles per second), by the formula:

$$\mu = K \frac{R\mu}{Rk}$$

The postbiologic value for the cell constant ($\mu$) of the point electrodes was ascertained from the second reading in the same way. The specific resistance of the tissue was computed by dividing the measured resistance of the tissue at 1,000 cycles per second by the cell constant.

mentation was complete and the electrodes were in the serum, a reading of 2,940 ohms was obtained. The latter value was evidently due largely to the resistance of the serum.
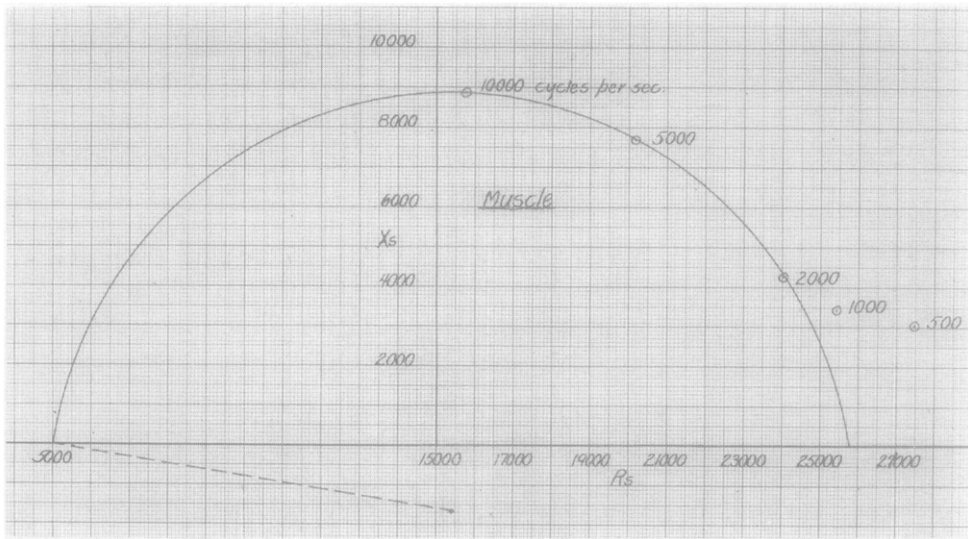


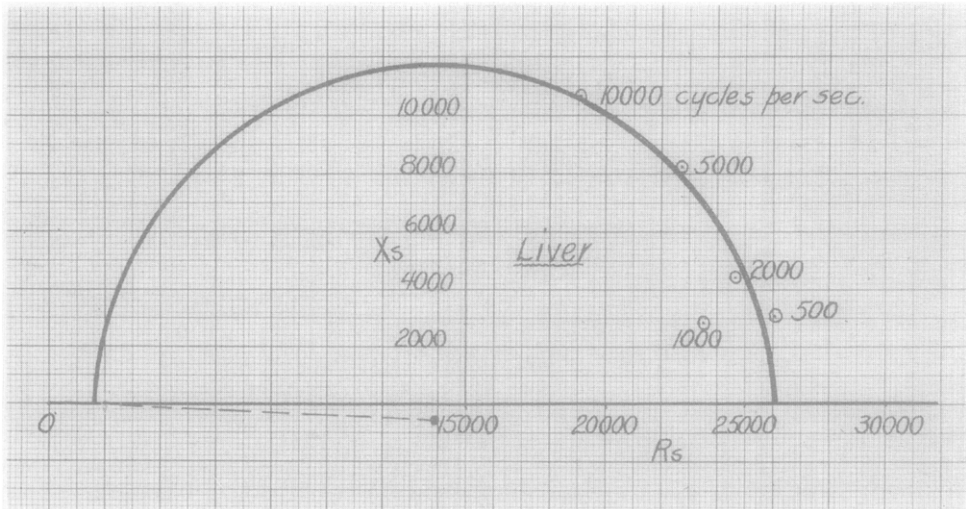Fig. 3.—Impedance locus of triceps muscle based on experiment of May 19, 1938.



Fig. 4.—Impedance locus of liver based on experiment of May 9, 1938.

*Lungs.*—In a number of experiments in which the pulmonary specific resistivity was measured, the lungs were rhythmically inflated in a manner which approximated normal ventilation before the chest was opened. Many sites on the lung surface from the hilar to more lateral regions and from apical to basal fields were explored. When the electrodes were inserted into the lung tissue, the resistances obtained were

entirely comparable to those obtained with the electrodes on its sur-
face. Since the resistance of lung tissue varied from expiration to in-
spiration, the specific resistance was measured arbitrarily in most ani-
mals under conditions approximating the height of normal inspiration.
The range of variation from normal expiration to normal inspiration
was ascertained by holding the lung in an expiratory, and again in
the maximal normal inspiratory, position until measurements could be
made. When a series of measurements, over the range of frequencies
used, was made with the electrodes in a given position on either the
surface or in the depths of the tissue, and was then repeated imme-
diately, there was practically no difference between the second and the
initial series of measurements. This indicates that possible tissue
changes due to placing of the electrodes did not have an important
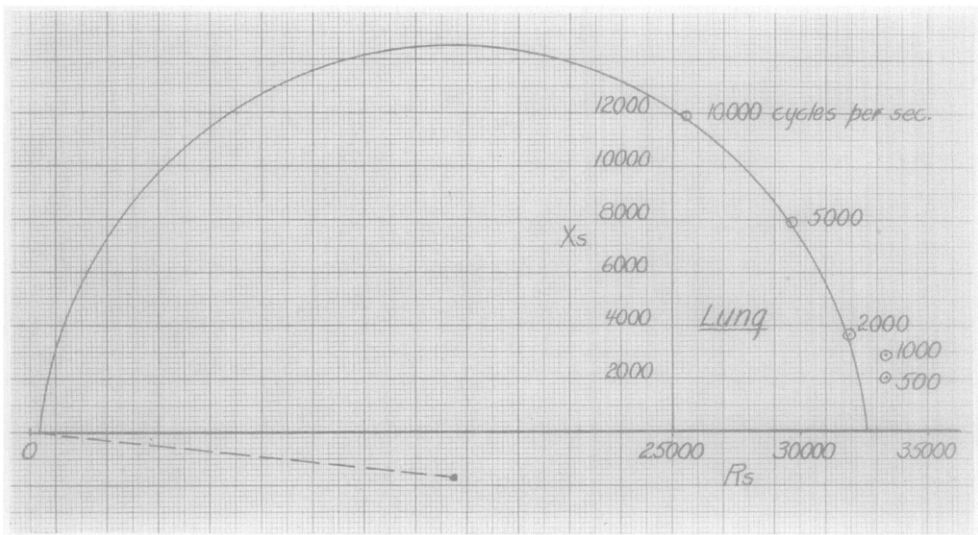effect upon the final value for the resistance under these experimental



Fig. 5.—Impedance locus of lung based on experiment of May 9, 1938.

conditions. In a number of instances the lungs were overinflated until
they were grayish-white in color, and bulged from the chest so that
both expiratory and inspiratory volumes were greatly in excess of
those possible in the living animal with an intact thoracic cage. The
maximal resistance of the lung tissue of living animals under these
conditions was about twice as great as that at the height of normal
inspiration. When, however, death occurred suddenly with the lung
at any volume, as a result of ventricular fibrillation induced by multi-
ple air embolism of the smaller branches of the coronary arteries, the
resistance of the rhythmically inflated lungs rose beyond the range of
the measuring instruments.

*Muscles.*—The specific resistance of voluntary muscles (triceps, quadriceps, biceps, deep muscles of the back, intercostal muscles, recti, and diaphragm) was ordinarily studied after the fascial envelopes were incised. The measurements made on muscles included observations on the midportions, as well as on regions near the ends, where the connective tissue components became the more prominent constituents. The average resistance of muscle was not very different from that of normally inflated lung tissue. The specific resistance of the liver, as measured with the electrodes on the surface and in the depths of its substance, was nearly the same as that of muscle and lung tissue.

An attempt was made to measure the resistance of cardiac muscle during diastole. This was an especially difficult task when the heart was beating rapidly. The specific resistance of living cardiac muscle, with the electrodes either on the surface or imbedded, was found to be approximately one-third that of lung, muscle, and liver tissue, and about the same as that of blood. Fat and connective tissue had the highest resistances of any tissues measured. Bone and nerve were not studied.

The average values of the specific resistances of the various tissues are given in Table IV.

### SUMMARY AND CONCLUSIONS

The specific resistances of living mammalian tissue in situ may be ascertained by measurement of the resistance between two small electrodes placed upon its surface or within its substance. The basis and scope of this method have been considered theoretically and verified by measurements of simple electrolytes and blood.

Measurements on the living tissues of the anesthetized dog show that muscle, normally inflated lung, and liver have specific resistances of the same order of magnitude. These measurements establish experimentally the validity of the assumption that the errors in theoretical studies of the form of the electrocardiogram, made by considering the tissues which surround the heart uniform with respect to their specific resistivity, are of no practical importance.

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