A theoretical model capable of explaining the relationship between the EMF generated by the heart and the electrocardiographic lead voltages must be based on quantitative knowledge of the resistivities of the tissues of the thorax. At the time this study was undertaken, the most recent investigations of tissue resistivity in living animals were those whose results are summarized in the first three columns of table 1.

More recently, the results summarized in column 4 were published. Differences in results range from 40% for lung to 400% for heart muscle, and no two groups of investigators are in substantial agreement on all measurements.

An additional investigation of animal tissue resistivity is reported here and the conclusions are presented in column 5 of table 1. A limited attempt was made to discover the sources of the discrepancies in previously published data. This was done by repeating the reported measurement procedure, by theoretical studies and by reviewing the work of other investigators. Both Kaufman and Johnston, and Schwan and Kay, employed a two-electrode technique. Only the more recent work of the latter group was investigated in detail.

The present study appears to explain satisfactorily the existing differences in the reported resistivities of thoracic tissue with the possible exception of lung.

**Methods**

Measurements of specific resistance of tissue were carried out on approximately 50 live, anesthetized, mongrel dogs weighing from 14 to 30 kilos. The anesthetic was 0.5 cc./kilo of pentobarbital initially with additional small doses as needed. Observations of intact thorax and arm resistivities were made on eight human subjects.

The basic technique employed was that of the four-electrode measurement in which a controlled current was introduced and removed from the specimen being measured by means of two 'current' electrodes and a resulting potential difference measured between two points on the specimen with two additional 'potential' electrodes.

The current electrodes were connected to a circuit shown in figure 1, consisting of a 540 volt battery in series with a 4 megohm resistor and a manually operated contact. The contact was closed for about 0.1 seconds during the measurement thereby generating a pulse waveform at the potential electrodes with approximately the same frequency spectrum as the QRS complex.

A potential difference was measured on the tissue surface by means of two needle electrodes, each connected to an open grid of a cathode follower. The output of the cathode followers supplied the differential input of a Sanborn polyviso recorder which recorded the voltage waveform on heat sensitive paper (fig. 2). The animal was grounded to the electrical system at points remote from the measuring electrodes.

Three distinct electrode arrangements were required for the various measurements. These will be designated by the letters A, B, C, as described in the sequel.

The four-electrode method was chosen primarily to provide a means of eliminating the effects of contact resistance variations on the measurements. Such effects were made negligible at the potential electrodes by the very high input impedance of the cathode followers and at the current electrodes by use of a high voltage in series with a very high resistance as a current source. The needles used for all potential electrodes insured exact knowledge of their locations on the tissue. The use of a square pulse as the measuring signal permitted detection of unusual polarization or other effects which might have been associated with measurement errors. The entire electrode array was made small whenever this was feasible to minimize the effects of remote tissues on the measurements. Lastly, the same electrode assemblies devised for isotropic tissues proved useful for anisotropic measurements.

Electrode set A consisted of four needles whose...
TISSUE RESISTANCE

TABLE 1

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Column 1 Kaufman and Johnston</th>
<th>Column 2 Burger and van Milaan</th>
<th>Column 3 Schwan and Kay</th>
<th>Column 4 Burger and van Dongen</th>
<th>Column 5 Rush, Abildskov, and McFee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood</td>
<td>208</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>1021</td>
</tr>
<tr>
<td>Liver</td>
<td>506</td>
<td>840</td>
<td>700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart</td>
<td>216</td>
<td>965</td>
<td>563*</td>
<td>252</td>
<td></td>
</tr>
<tr>
<td>Lung</td>
<td>744</td>
<td>1120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fat</td>
<td>2060</td>
<td>1500-5000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skeletal muscle (human or dog)</td>
<td>443</td>
<td>905</td>
<td>675*</td>
<td>2300*</td>
<td></td>
</tr>
<tr>
<td>Skeletal muscle (rabbit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human trunk</td>
<td>415</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torso sheath (dog)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2811</td>
</tr>
</tbody>
</table>

*ρ₀ and ρ₁ are high and low resistivities of anisotropic tissue.
†Data from only two subjects.
‡Data taken from the literature.

points touched the tissue at four equally spaced points along a straight line (fig. 3). Electrodes of this type are commonly used in geophysical explorations where the technique is called the Wenner-Gish-Rooney method. The needles were mounted on a small plastic bar which in turn was fixed on a V-shaped steel wire. The electrode assembly was thus free to move in the vertical and horizontal directions to accommodate the movements of the tissue being measured (fig. 5).

The equation from which the unknown resistivity, ρ₁ of the tissue was determined is

\[
V_{sh} = \frac{ρL}{2\pi n} \tag{1}
\]

in which 'a' is the electrode spacing, 'I' the current and \( V_{sh} \) the potential difference measured between electrodes 's' and 'h'. Equation 1 applies exactly when the electrodes are on the plane surface of a homogeneous, isotropic conductor of infinite extent which the tissue is assumed to approximate.

For media which are anisotropic with one direction 'y' of low resistivity, ρ₀, parallel to the bounding plane and with two high resistivity, ρ₁, directions 'x' and 'z', (fig. 4) equation 1 becomes

\[
V_{sh} = \frac{\sqrt{\rho_0 \rho_1}}{2\pi n} \frac{1}{\sqrt{\cos^2 \varphi + (\rho_1/\rho_0) \sin^2 \varphi}} \tag{2}
\]

\( \varphi \) is the angle the electrode alignment makes with the 'x' axis. By aligning the electrodes alternately along the lines \( \varphi = 0, \ varphi = \pi/2 \) we have from equation 2

\[
V_{sh} \varphi = 0 = \frac{\sqrt{\rho_0 \rho_1}}{2\pi n} \frac{I}{\sqrt{\cos^2 \varphi}} \ ; \ V_{sh} \varphi = \pi/2 = \frac{\rho_1 I}{2\pi n} \tag{3}
\]

From the two expressions in equation 3, ρ₀ and ρ₁ can be found.

Electrode Set B was devised to find the 'y' and 'z' directions on anisotropic tissue and this information was used, in turn, to orient Set A in accordance with equation 3. Referring to figure 3, it was formed by making the spacing e-h and e-f very large and arranging electrode 'g' so that it could be placed sequentially at eight equally spaced points on a circle centered at 'e'. Electrodes 'e' and 'f' were mounted on a common spring assembly similar to that described for Set A. Electrode 'g' pierced the center of a plastic button which had eight small holes equally spaced around a circle of 0.5 cm radius. Electrode 'g' was arranged so that it could be withdrawn from a hole then turned and reinserted into another hole without disturbing the positioning of the remainder of the electrode assembly (fig. 5).

The equation for \( V \) around a circle of radius 'a' is, with the exception of a small constant term, given by equation 3. The constant term depends on the location of electrode 'h' and can be made small by locating it far from the current electrodes. The values of \( V \) on the circle in any case will, if plotted on polar coordinate paper,
FIGURE 1
Current circuit for four-electrode measurement. $V = 270$ volts, $R = 2$ megohms and 'e' and 'f' represent point-electrodes through which a fixed current passes when key is closed.

FIGURE 2
Potential measuring circuit. $V_1 = 90$ volts, $V_2 = 45$ volts, $R_k = 0.1$ megohms and 'g' and 'h' are potential measuring electrodes.

FIGURE 3
Arrangement of four point-electrodes for measuring the resistivities of a semi-infinite ($z > 0$ an insulator) medium.

Circulation Research, Volume XII, January 1963

Electrode Set C was employed to measure cylindrical sections such as the arm and thorax. The technique is essentially that described by Burger and van Milaan. Current was introduced and removed from the specimen through large remote electrodes and the potential electrodes were formed by needles touching the specimen at points spaced along a line parallel to the axis of the cylinder. In measurements of the thorax of humans, current was introduced through three electrodes at the wrists and neck, and removed through two electrodes at the ankles in order to obtain a uniform distribution in the chest. Similarly placed electrodes were used for dog thorax measurements.

The electrodes at each end of the body were interconnected with 20,000 ohm resistors to minimize the effects of skin resistance variations on the distribution. On human subjects, the potential electrodes were formed by sterile hypodermic needles spaced a measured distance apart with the tips placed just under the skin surface and the remainder insulated.

The equation for the mean resistivity of the cylindrical part being measured is

$$\rho = \frac{V_{gh}A}{I_n}$$

where 'a' is the distance between potential electrodes and A is the cross-sectional area of the cylinder. If the cylindrical part is in turn composed of 'm' parallel cylinders of different resistivities, acting as resistors in parallel, the mean resistivity of equation 4 is given by

$$\rho = \Lambda \left[ \sum_{n=1}^{m} \frac{A_n}{\rho_n} \right]^{-1}$$

in which $A_n$ is the cross-sectional area of the cylinder of tissue identified by the symbol, n, and
TISSUE RESISTANCE

\( \rho \) is the resistivity of that tissue. The total area, \( A \), is the sum of the individual tissue areas. Equation 5 is applied here to measurements on the arm and thorax which are assumed to consist of cylinders of fat, bone, muscle, etc.

That the electrodes actually performed in accordance with the theoretical predictions of equation 1 was checked by using a standard solution for which the resistivity, \( \rho \), was known precisely. The equation checked to a value well within the predicted \( \pm 5\% \) construction tolerance of the electrode array and remained constant for long periods of time. In addition, during the resistivity measurements, the applicability of the assumption of an infinite medium was evaluated for each tissue. This was done by monitoring the thickness of the layer being measured as well as the resistivity of the underlying layer and checking these against theoretical estimates of the effects of these variables on the measurement.

In practice, the current \( I \) and \( V_{gb} \) were not directly measured. Instead, at various times during an experiment, the electrode pairs e-g and h-f were connected to opposite terminals of a variable standard (Shallcross No. 835 Decade Potentiometer) resistance. After adjusting the calibrating resistance, \( R_c \), to give a pen deflection comparable to that produced by \( V_{eh} \) of the medium being measured, the calibrating potential difference \( V_{eh} \) is given by Ohm's Law as

\[
V_{eh} = R_c I
\]

which combined with equation 1 for example gives

\[
\frac{V_{eh}}{V_{gb}} = \frac{\rho}{2\pi R_c}
\]

The ratio \( V_{eh}/V_{gb} \) is given by the ratio of pen deflections, hence \( \rho \) can be found.

Results

TISSUE MEASUREMENTS

Unless otherwise noted, the data for each tissue represents measurements on approximately seven animals at one to three different sites on each animal.

Liver

The liver resistivity was measured using electrode Set A. The tissue was exposed by incisions through the abdominal wall or lower ribs depending on the experiment. The result obtained by this method was 700 ohm-cm with a per cent standard deviation of \( \pm 14\% \).

Comparing this with the value of 840 ohm-cm given by Schwan and Kay, a difference of about 18\% is seen to exist. By repeating their measurement, i.e., by measuring the resistance with a bridge between two electrodes mounted on a catheter-like holder and placed in the tissue, results essentially identical with theirs were obtained.

The difference in the results given by the four-electrode and 'catheter' electrode measurements is probably not significant from the viewpoint of electrocardiography but it is considered too large to be of a statistical origin. Two possible explanations are:

1. Polarization Errors. The method employed by Schwan and Kay may be inaccurate because certain unverifiable assumptions
were involved in deducing the corrections for polarization. Burger and van Dongen have given credence to this possibility by measuring the frequency dependence of muscle and finding none in the range from d-c to 5,000 cycles. This is in direct contrast to the strong frequency dependence for liver, muscle and other tissues reported by Schwan and Kay. If the resistivity of liver is also frequency independent in this range, a higher frequency measurement with the electrodes of Schwan and Kay should be more representative of the true situation since polarization effects can be expected to disappear as the frequency is raised. Schwan and Kay measured a resistivity of liver equal to that given by the four-electrode method, 700 ohm-cm, in the vicinity of 5,000 cycles.

2. Boundary Effects. The effects of insulating boundaries on a resistivity measurement with a catheter electrode of the dimensions given by Schwan and Kay were estimated by placing the electrodes 0.5 cm from the wall of a glass beaker 9 cm in diameter containing a solution of known resistivity. An apparent increase of 15% in the resistivity of the standard solution was observed. In making resistivity measurements on liver and heart with the same electrodes, it proved difficult to place the electrode structure so that the electrode surfaces were consistently at distances greater than 0.5 cm from the air boundaries. The latter therefore may be a contributing factor to the higher results obtained for several tissues with the catheter electrode.

To summarize, we have obtained a value of 700 ohm-cm for the resistivity of liver using the four-electrode method. On the other hand, using techniques similar to those employed by Schwan and Kay, their published value of 840 ohm-cm was obtained. The higher values of the latter technique may be attributed to polarization and/or boundary effects.

Heart
The resistivity of the muscle of the left ventricular wall of the dog heart was measured using in sequence electrode Sets B and A. The animal was placed on its right side, artificially respirated and the thorax opened at the fifth or sixth intercostal space. The ribs were spread apart, the intervening portion of the left lung pushed aside and the pericardium opened to expose the left ventricle. Electrode Set B was positioned on the exposed tissue and measurements were taken sequentially with the electrode ‘g’ at the eight indexed sites equally spaced around a circle centered at current electrode, e. The resulting curve was plotted and directions of high and low resistivity marked on the dog’s skin. Electrode Set A was then aligned alternately with the marked axes and readings taken for use with equation 3. In all cases, the measuring signal was superimposed on the heart’s electrical signal; but a large number of measurements randomly spaced in time yielded a sufficient number of measurement pulses in a relatively quiet and refractory portion of the electrical cycle for readings to be taken. Additional measurements not described here, showed that the resistivities in the refractory portion and other parts of the electrical cycle were essentially the same. Corrections of the measured values which take account of the effect of the curved surface and the proximity of the underlying blood layer were estimated by mathematical analyses. Since these were always less than 20% and in opposite directions for the two variables, the net correction required was assumed negligible.

The results of the four-electrode measurements showed a slight anisotropy of about 2:1 with a high resistivity value of 563 ohm-cm and a low resistivity value of 252 ohm-cm. The per cent standard deviations were ± 15% and ± 30% for the high and low values respectively. These are considerably lower than the value of 965 ohm-cm measured by Schwan and Kay. Their results however, were obtained by measurements following poisoning of the experimental animal and cessation of all electrical activity in the heart; and therefore may not be representative of resistivity values prior to that time.
To investigate this question, a catheter electrode and bridge was again employed with a visual detection device (ECG pen). Crude balances could readily be obtained in this fashion without affecting the heart’s action significantly and the mean value at 50 cycles was thus determined to be 516 ohm-em. In addition, upon administration of lethal doses of barbiturates, a rapid rise in resistivity followed. In two such experiments increases of 25% in 15 minutes were observed.

The value 516 ohm-em obtained by us with the catheter electrode is to be compared to the result obtained using electrode Set A. Analytical considerations, based on the potential solution for a sphere in an anisotropic medium, indicates that the catheter electrode should measure about 1.13 \( \sqrt{\rho_1 \rho_h} \). Thus, there is actually a fairly small discrepancy between the results obtained by the two methods corresponding to the figures 516 and 430 ohm-em. Again the former quantity is uncorrected for polarization effects and possible boundary influences both of which tend to give high values. In addition, the electrodes are not spherical in shape and the analysis on this basis may contribute to the difference.

To summarize, the measurement of the muscle of the left ventricle of the heart shows a resistivity ratio of about 2:1 with \( \rho_1 = 252 \) and \( \rho_h = 563 \) ohm-em. These values are far below that of 965 ohm-em given by Schwan and Kay whose technique ignored the anisotropy and involved elimination by poison of the electrical activity of the heart. By omitting the last mentioned step from the catheter-electrode procedure, values in reasonable agreement with the theoretical estimates of such a measurement based on the \( \rho_1 \) and \( \rho_h \) given above, were obtained.

**Lung**

Electrode Set A, modified slightly to prevent piercing of the delicate tissue, was used to measure the resistivity of lung. The dog was placed in a crouching position and opened on both sides of the thorax at the fifth and/or sixth intercostal space. To provide the correct degree of lung inflation, the respirator pressure was monitored by a water manometer and adjusted to provide a peak pressure equal to the peak pressure normally existing between the pleural cavity and the trachea, i.e., 8 mm of Hg.\(^8\) The haunches were raised 5.5 cm to compensate for the loss of negative intrathoracic pressure thereby minimizing the change in venous return due to this factor. The electrodes were held in place manually and resistivity measurements were taken at the extremes of inflation and deflation.

The resistivities corresponding to the peak of inflation and maximum deflation during the forced breathing cycle, were found to be 2,390 and 1,950 ohm-em respectively, with a mean of 2,170 ohm-em. The percent standard deviation of the measurements was \( \pm 17\% \).

The ratio of lung resistivities as measured by ourselves and Schwan and Kay can be seen from table 1 to be about 2:1. The measurements of the latter group have the advantage over ours of being performed in a closed chest. On the other hand, the catheter electrode assembly was placed in the bronchi or pulmonary arteries which are conceded to have an effect on the measurements.\(^3\) The magnitude of this effect was estimated by Schwan and Kay from measurements on excised bronchi. Measurements of excised tissues, however, may not yield values representative of their in situ characteristics. In addition, it was not possible to observe the actual situation around the electrodes with regard to their location, tightness of fit of the bronchi about the electrode, collection of fluid about the electrodes, proximity to major blood vessels and possible collapse of the lung about the plugged airway.

In the present study, measurements were made at a variety of locations with the electrodes in view on the outer surface of the lung. Factors which arose from the open chest condition were accounted for as described. In addition, measurements of the lung made through the pleural membrane in an intercostal space with the chest interior still airtight, though too erratic to give quan-
**TABLE 2**

Results of 4-Electrode Measurements of Skeletal Muscle

<table>
<thead>
<tr>
<th>Electrode configuration</th>
<th>Tissue</th>
<th>Parameter (average value)</th>
<th>Value ohm-cm</th>
<th>Per cent standard deviation</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(longissimus dorsi and spinalis dorsi muscles of dog)</td>
<td>$\rho_n$</td>
<td>1885</td>
<td>48%</td>
<td>14</td>
</tr>
<tr>
<td>A</td>
<td>et cervicos</td>
<td>$\rho_1$</td>
<td>205*</td>
<td>40%</td>
<td>14</td>
</tr>
<tr>
<td>A</td>
<td>muscles of dog</td>
<td>$(\rho_1 \rho_2)^{1/2}$</td>
<td>588</td>
<td>10%</td>
<td>14</td>
</tr>
<tr>
<td>C</td>
<td>human arm muscle</td>
<td>$\rho_1$</td>
<td>1069</td>
<td>10%</td>
<td>5</td>
</tr>
</tbody>
</table>

* $\rho_1$ is obtained by combining direct measurements of $\sqrt{\rho_1 \rho_2}$ and $\rho_n$ (see equations 4 and 5).

**Skeletal Muscle**

The resistivity of skeletal muscle was measured with electrodes Sets A, B, and C. The marked anisotropy of the muscle presented special difficulties necessitating a fairly complicated procedure to obtain both the high and low resistivity values with satisfactory accuracy. The final results, table 1, are 2,900 and 150 ohm-cm in directions transverse and parallel respectively to the muscle fibers.

Electrode Sets A and B were employed to measure the resistivity of the muscles along the spine of the dog, (these were selected on the basis of their thickness) in a fashion similar to that used on the heart. In this case, however, measurements with Set B indicated that visual observation of the fiber directions satisfactorily indicated the parallel and transverse directions.

The results of these measurements, table 2, showed $\sqrt{\rho_1 \rho_2} = 588$ ohm-cm with a per cent standard deviation of ± 10% and $\rho_n = 1,885$ ohm-cm with a per cent standard deviation of ± 48%. The combination of these values gives $\rho_1 = 265$ ohm-cm with a per cent standard deviation of ± 40%. The large spread of the measurements of $\rho_n$ is attributed primarily to the extreme sensitivity of this measurement to the electrode orientation. Errors in orientation tend to give lower than true values of $\rho_n$, equation 2. The calculations of $\rho_1$ reflect the variability of the $\rho_n$ measurements. On the basis of these results it was concluded that the measurement of $\sqrt{\rho_1 \rho_2}$ was satisfactory but that other procedures described later, were necessary to evaluate $\rho_n$ and $\rho_1$. 

Circulation Research, Volume XII, January 1963

Quantitative results, clearly indicated a resistivity much higher than the 1,100 ohm-cm reported by Schwan and Kay.

Finally, since the measurements discussed were made in different regions of the lung, one in the interior and the other on the outer portion, it is possible that both are correct representations of the conditions in their respective regions.

To summarize, a mean value of lung tissue resistivity over the breathing cycle has been measured at 2,150 ohm-cm. This is in contrast to a value of 1,120 ohm-cm, reported by Schwan and Kay. The low values of the latter measurements have been attributed to the uncertain conditions around the electrodes, most of which would tend to lower the high value we have measured, and/or the fact that the interior of the lung around the bronchi and arteries actually may have a lower mean resistivity than the regions nearer the outer lung surfaces.

**Fat**

The resistivity of fat was measured with electrode Set A on various layers on the chest wall of the animal. The results, table 1, show a value of 2,500 ohm-cm with a large per cent standard deviation equal to ± 30%.

Schwan and Kay list a range, 1,500-5,000 ohm-cm at 1,000 cycles/sec, as the only resistivity data on fatty tissue, and these may be considered in agreement with the results of this study. Further discussion of the subcutaneous fat layer will be found in the section on skeletal muscle.
TISSUE RESISTANCE

An independent estimate for \( \rho_1 \) was deduced from the measurements on the human arm. Electrode Set C was used. Current electrodes were located on opposite wrists. Potential electrodes were located on the dorsal surface of the forearm approximately 5 cm distal from the elbow. The mean longitudinal resistivity of the arm was computed using equation 4. This measurement reflects primarily the value of \( \rho_1 \) but corrections for the effect of bone, subcutaneous fat, and skewed fiber directions are necessary. The corrections for bone and fat are based on equation 5.

The bone was taken as a non-conductor as indicated by measurements on the exterior wall of excised bone and by other investigators.\(^2\) The effect of marrow was neglected because there is no apparent low resistance path to the bone interior. The area of the bone was taken from an anatomical atlas and was assumed the same on all subjects.

The skin and subcutaneous fat layer of the arm were taken to have the same resistivity as the fat measured on the chest wall with a thickness determined as one-half the measured skin-fold dimension. To substantiate this choice of resistivity value two additional considerations were taken note of. First, while attempts to measure the resistivity directly of this layer on the dog gave erratic results the minimum estimate so obtained was of the order of 300 ohm-cm. In view of the relatively small cross-sectional area of fat relative to the total arm cross-section and the shunting effect of the muscle, even this lowest value would change the figures presented by no more than 5%. Second, statistical considerations indicate that the fat corrections improve the data. For example, the per cent standard deviation of measurements of the arm before fat corrections was \( \pm 20\% \) while the same statistic was reduced by the corrections to \( \pm 9\% \).

These two corrections for inhomogeneity, that is for bone and fat, applied to the value of 234 ohm-cm for the whole arm, give a value for the longitudinal resistivity of the muscle of 160 ohm-cm.

The non-parallel orientation of the muscle fibers was considered also. For anisotropic materials with a high ratio of resistivities, analysis shows that the appropriate correction factor is closely related to the additional length of the fibers, due to skewed directions, between two planes perpendicular to the axis. The maximum mean deviation of the fiber directions, as read from an anatomical atlas, from a direction parallel to the axis was estimated to be 30°. The corresponding factor, \( \cos 30° = 0.875 \), applied to the upper bound of 160 ohm-cm yields a value of 140 ohm-cm as a lower bound. The mean of this range, i.e., 150 ohm-cm, has been taken as the best estimate for \( \rho_1 \) of skeletal muscle.

Using the value \( \sqrt{\rho_1 \rho_0} = 588 \) ohm-cm obtained with electrode Set A and \( \rho_1 = 150 \) ohm-cm as described above, \( \rho_0 \) was calculated to be 2,300 ohm-cm.

Measurements by Burger and van Dongen, table 1, on rabbit muscle yield 125 to 1,500 ohm-cm, results which closely approximate ours. Their measurements on human arms and legs, however, give results for skeletal muscle which are lower for \( \rho_0 \) and higher for \( \rho_1 \). If, in computing \( \rho_0 \), they had taken into account the subcutaneous fat and the imperfect alignment of the muscle fibers with the axes of the arm and leg, their results for this parameter would have been comparable to ours. The low values they attributed to \( \rho_0 \) from measurements transverse to the axes of the arm and leg may have been due to the deviations of muscle fiber directions from these axes. Even small deviations of this type can be shown to have a very large effect on their transverse measurements.

The value presented by Schwan and Kay for muscle, 965 ohm-cm, represents some kind of mean value of resistivity for anisotropic tissue. An analysis similar to that described in the discussion of the heart indicates that according to our results, the catheter-electrode should have given values between 820 and 700 ohm-cm depending on electrode orientation. As in the measurements of liver and heart, the two-electrode tech-
Reference directions on torso.

The technique gave results about 20% higher than the four-electrode measurement.

To summarize, a value of 150 ohm-cm for $\rho$ of skeletal muscle was deduced from various measurements of the whole arm and tissues therein. The geometric mean of the resistivities, $\sqrt[4]{\rho_1\rho_2\rho_3\rho_4}$, was obtained from direct measurements on skeletal muscle with electrode Set A. The combination of results gave the high resistivity value, $\rho$, as 2,300 ohm-cm.

These numbers agree reasonably with other direct measurements on muscle; those of Burger and van Dongen on rabbit muscle and those of Schwan and Kay on dog muscle. In addition, the method of obtaining these results, i.e., by correcting for the fat layer, explains how the human arm resistivities given by Burger and van Milaan and Burger and van Dongen are to be reconciled with the latter group’s measurements of $\rho$ of rabbit muscle.

**Blood**

Measurements of human blood resistivity were not carried out in this study. The literature of four investigations shows agreement within ± 3% of their mean value which is reported in table 1, i.e., 162 ohm-cm. Further, of these studies, two were made with a four-electrode technique and two with a two-electrode technique. Correction factors on which there is substantial agreement, were necessary to normalize all the results to a common temperature of 37°C.

The value of 100 ohm-cm mentioned by Schwan and Kay for human blood is based primarily on measurements of sheep blood. It is well known, however, that blood resistivity is critically dependent on the hematocrit which in turn is a function of red cell size and count. The last mentioned factors are markedly different for sheep than for humans or dogs. By using the data on blood count and serum resistivity given in Schwan’s paper and relating the blood count to hematocrit from data on sheep blood counts and hematocrits given by Wintrobe, it is possible to reconcile the 100 ohm-cm value for sheep blood quite naturally with the values for human blood quoted here.

**Thorax**

A number of measurements of the human thorax, dog thorax and of dog thorax minus heart and lungs were made with electrode Set C. The current electrodes were connected as described earlier. The potential electrodes were placed along a line parallel to the spine on the side of the body. They were spaced 6 cm apart and centered at the level of the center of the heart.

Seven measurements were thus made of the resistivity of the human thorax with a mean of 463 ohm-cm.

On the intact dog thorax, a mean of 445 ohm-cm was measured.

To measure the thorax minus heart and lungs, the dog was placed supine and opened along the sternum. The inferior vena cava and esophagus were cut and tied and the heart and lungs encased in a plastic bag, after which the measurements were made. The cross-sectional area of the exterior shell was obtained by moulding a strip of solder around its perimeter. This mould was later traced and the area measured with a planim-
Tissue Resistance

The average of two such measurements of the shell resistivity was 281 ohm-cm.

The results obtained for the human thorax were compared with an alternate estimate of the mean thorax resistivity based on the resistivities of the individual tissues, equation 5. The tissue resistivities used were those obtained in this study. The tissue cross-sectional areas were obtained by averaging the areas shown in Sections 25 and 26 of Eyeshmyer and Schoemaker's *A Cross-Section Anatomy*.\(^{14}\) In order to treat the highly anisotropic muscles of the chest as a single tissue in equation 5, it was necessary to choose a representative value for the muscle resistivity in the thorax measurement. Anatomical data show the different muscles on the chest almost randomly distributed over the longitudinal and transverse directions (fig. 6). Theoretical considerations, based on random directions, give \(\overline{p} \approx \pi/2\) as the appropriate value for muscle in the thorax measurement.

The mean value for the thorax based on individual tissue measurements was thus calculated from equation 5 to be 500 ohm-cm; 8% higher but substantially in agreement with the value measured on the trunk exterior.

**SUMMARY OF RESULTS**

The resistivities of lung, fat and liver as measured by the four-electrode Set A are contained in table 1. The per cent standard deviations of the readings from their means are 17%, 30% and 14% respectively. The values of resistivity reported for heart muscle in table 1 are those obtained by assuming the heart to be a semi-infinite homogeneous anisotropic medium bounded by a plane surface. The per cent standard deviations for \(\rho_h\) and \(\rho_l\) are 15% and 30% respectively. The estimates of \(\rho_l\) and \(\rho_h\) for skeletal muscle reported in table 1 were obtained by combining a variety of measurements as explained earlier. Results of actual measurements with electrode Sets A and C are reported in table 2 for the longissimus dorsi and spinalis dorsi et cervicis muscles along the spine of the dog and for the human arm muscle.

---

**FIGURE 7**

Schematics of resistivity models of thorax.

The mean resistivity of the human and dog thorax was measured in a direction parallel to the spine using electrode configuration 'C'. The values given for human blood have been obtained from the literature. These results are also presented in table 1.

**Discussion**

It was necessary to make most individual tissue measurements (fat, lung, heart muscle and liver) on dogs and to assume that these are representative of human tissue. The near equality of the mean thorax resistivities of humans and dogs supports this assumption.

That the predicted value of human thorax resistivity, based on measurements reported in column 5 of table 1 and anatomical data, is within 8% of the value of the measured thorax resistivity; lends some support also to the measurements on the individual tissues.

The existence of a surface layer of low resistivity covering the thorax is of significance in electrocardiography. McFee and Parungao\(^{10}\) have reported an anomalous effect in making measurements on lead systems which they attribute to this factor.

The work reported here has bearing on the models used to investigate the nature of electrocardiographic leads. Among such models previously used are (a) the homogeneous thorax, (b) the homogeneous heart-blood mass with higher resistance exterior,\(^{16}\) and (c) blood cavities of low resistivity surrounded by homogeneous tissue of resistivity ten times higher.\(^9\) The data of this study present a more complex picture as can be seen in the schematic drawing of figure 7 in which a mean resistivity of 400 ohm-cm for the outer thorax layer; skin, fat, muscle, and bone has been used.

---

*Circulation Research, Volume XII, January 1963*
Summary

The resistivity of tissues of the thorax of dogs has been measured in situ under nearly normal conditions. Additional data have been obtained from humans.

Approximate values of tissue resistivity found are 160 ohm-cm for blood, 2,000 ohm-cm for lung, 2,500 ohm-cm for fat, 700 ohm-cm for liver, 250 and 550 ohm-cm (anisotropic) for heart muscle and 150 and 2,500 ohm-cm (anisotropic) for skeletal muscle. Reasons for the differences between these and previously reported values have been found, and in some cases, verified experimentally. Predictions of whole trunk resistivity based on anatomical data and these measurements are within 8% of actual trunk measurements.

References

Resistivity of Body Tissues at Low Frequencies
STANLEY RUSH, J. A. ABILDSKOV and RICHARD MCFEE

Circ Res. 1963;12:40-50
doi: 10.1161/01.RES.12.1.40

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1963 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circres.ahajournals.org/content/12/1/40

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in
Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the
Editorial Office. Once the online version of the published article for which permission is being requested is
located, click Request Permissions in the middle column of the Web page under Services. Further information
about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org/subscriptions/