

# Specific Resistance of Body Tissues

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The resistive properties of various tissues surrounding the heart were investigated in a number of living dogs. Alternating currents of a frequency varying between 10 and 10,000 c.p.s. have been used for this purpose. Technical problems associated with such measurements are analyzed. The results show that the resistive properties of most tissues are comparable and that the resistivity decreases slowly as the frequency increases.

**M**EASUREMENTS of tissue resistivity on excised tissues are summarized by Rajewsky<sup>1</sup> and Rosendal.<sup>2</sup> However, such values are subject to criticism. Blood is a good conductor of about 100 ohm cm. resistivity at body temperature<sup>3</sup> while tissues' resistivity is near 1000 ohm cm., as will be shown later. Small changes in blood volume may, therefore, cause noticeable changes in tissue resistivity. This, in itself, without considering that "live" tissue may be different from excised "dead" tissue, is sufficient justification for in situ measurements, in order to obtain values which may be considered relevant in electrocardiography.

In a previous report,<sup>4</sup> the problem of the electric conductivity of living tissues as it pertains to electrocardiography was surveyed. It was concluded that the early relatively qualitative attempts to answer the question of homogeneity were of little value except to indicate that the body is not absolutely homogeneous. Later, more sophisticated attempts to measure conductivity of living tissue in situ were undertaken.<sup>5</sup> They are important as first attempts in pointing out that the conductivities of various tissues surrounding the heart are comparable in order of magnitude. However, the statistical uncertainty of these results was still sufficiently high so that it was considered worthwhile to attempt more precise statements.

Since our previous report, technics have been developed to circumvent the difficulties in-

herent in the measurement of the conductivity and capacity of living tissue in situ. This paper presents our approach to the technical problems inherent in in situ work and data which characterize body tissue resistivity.

## TECHNICAL ASPECTS

*Electrode Design.* The catheter electrode design, shown in figure 1, was used for most of the resistance measurements reported in this paper. It is small enough in that the current field resulting from its activation is confined to the specific tissue under investigation. It is so shaped that its insertion into tissue does not result in major hemorrhage or trauma, and it can be inserted into vessels of relatively small caliber and consequently thin walls for measurements in tissues intolerant of direct puncture.

Experience with electrodes of 2 other types, 1 larger (6 mm. diameter) and 1 much smaller (0.8 mm. diameter) is reported to illustrate some of the technical problems. Measurements for liver, muscle and blood with the small electrode system showed that the resistances for tissue are much lower than those measured with the systems using larger electrodes\* and only slightly higher than those measured with the same system for blood. The low figures for tissue may be attributed to hemorrhage occurring when the electrode is introduced into the biological system. A minor amount of blood around the electrodes will surround the latter with a highly conducting material in an area where the electric field is most concentrated and, therefore, most likely to respond with a

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\* By editorial request, the tables pertaining to this paper have been omitted. They may be obtained by request from the authors.

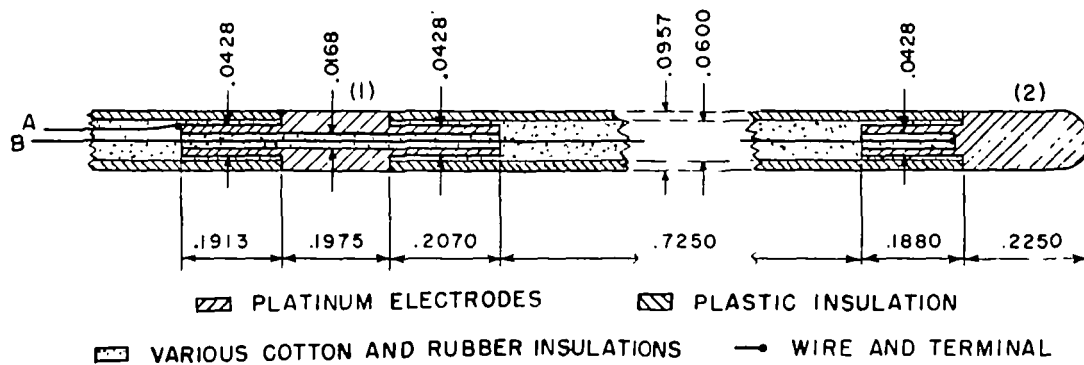


FIG. 1. Construction and dimensions of electrode system used for the determinations of the resistance data. The insulated wires *A* and *B* which connect with the platinum electrodes (1) and (2) run inside the hollow and flexible catheter shaft.

corresponding resistance decrease. The value reported for blood is too high by about a factor of three, due to excessive electrode polarization. The resistance values represent in reality, therefore, a combination of two effects, hemorrhage and polarization.

The thickness of the blood layer, which forms due to hemorrhage around the electrodes, does not depend much on the electrode size itself, while the diameter of the volume that determines resistance varies in direct proportion to the electrode size. Hence, the relative portion in this volume, which is occupied by the blood, should be least for the largest electrode. The agreement of the results obtained with the large and medium sized electrode arrangement, for lung tissue indicates that hemorrhage does not significantly disturb the measurements with either the large or medium sized electrode system. This conclusion is supported by further experiments in excised beef liver. The measured specific resistance was essentially the same in this tissue sample for the three electrodes.

**Measurement Technic.** The electrode system was connected through a shielded cable with a calibrated Wheatstone bridge described elsewhere.<sup>6</sup> The capacity, inductance and resistance of the long leads necessary to connect bridge and electrode system were determined and correction was made for these parameters by standard technics.

Before and repeatedly during each measuring series, calibration runs from 10 c.p.s. to 10 Kc. were taken with the electrode in physiologic saline solution. From the known resistivity of

this solution and the measured saline resistance, the cell constant of the electrode system was calculated. The measured resistance, after correction for electrode polarization, could be converted to specific resistance by application of the cell constant.

The magnitude of the influence of electrode polarization upon the crude data must be evaluated and suitable corrections made. The measured resistance  $R$  and the true resistance  $R_t$  are related by the equation<sup>7</sup>:

$$R = R_t + R_p + R_t R^2 \omega^2 (C - C_0)^2$$

where  $\omega/2\pi$  is the frequency,  $C$  the measured capacity,  $C_0$  the true capacity of the tissue and  $R_p$  the electrode polarization resistance.

Both  $R_p$  and  $R_t R^2 \omega^2 (C - C_0)^2$  decrease with increasing frequency. The dimensions of our electrode system are such that  $R$  and  $R_t$  are identical to 1 per cent at frequencies of 1 Kc. and above. From unpublished capacitance values of tissue we conclude that  $C_0$  is so much less than observed capacity  $C$  at frequencies of 10 c.p.s., that it may be neglected. The third term of the equation can, therefore, be calculated for 10 c.p.s. from observed resistance and capacity values. At frequencies from 100 c.p.s. to 1 Kc.,  $R^2 \omega^2 (C - C_0)^2$  is found to be sufficiently small to be neglected.

The values of  $R_p$ , greater than those of  $R^2 \omega^2 (C - C_0)^2$ , were determined as follows: The resistivity of physiologic saline solution ( $R_s$ ) is known to be frequency independent. With our electrode system, the measured values for  $R_s$  are identical with the true values at 10 Kc. and above, but increase slightly at

1 Kc. and appreciably at lower frequencies. This increase in measured resistance ( $R_t$ ), due to electrode polarization, may be represented by the equation quoted above which reads now:

$$R_t = R_p + R_s(R\omega C)^2$$

since the capacity  $C_0$  of saline solution is negligibly small. Hence,  $R_p$  may be calculated for our electrode system in saline from measured values  $R_t$ ,  $R$  and  $C$ . However, electrode polarization resistance is affected by the presence of cellular organization.<sup>7, 8</sup> In unpublished studies with excised muscle samples,  $R_p$  was found to be 1.5 to 2 times greater than in the saline system. However, a more reliable determination of  $R_p$  in the living tissue system was achieved from the capacity observed at low frequencies. The capacity at 10 c.p.s. is almost completely due to electrode polarization as stated above. The polarization interface capacity ( $C_p$ ) may then be calculated from observed resistance ( $R$ ) and capacity ( $C$ ) by use of the relationship<sup>7</sup>

$$C = 1/\omega^2 R^2 C_p$$

This value is compared with the polarization capacity found when the electrode system is immersed in electrolyte. The ratio of these two  $C_p$ -values is known to compare with the factor by which  $R_p$  is greater in the tissue insertion case than  $R_p$  determined from the electrolyte experiment.<sup>8</sup> Hence, from this factor and the known  $R_p$  in the electrolyte case polarization resistance in the tissue case is obtained. The  $R_p$ -ratios which we obtained this way varied from case to case between 1.1 and 3.

This technic for determining electrode polarization influence upon measured resistance assumes that the electrode surface does not change between tissue and electrolyte measurements. Actually, changes do occur, as already observed by Kaufman and Johnston<sup>6</sup> because some of the soft platinum black applied galvanically to the electrodes in order to minimize polarization is rubbed from the electrode when it is inserted into tissue. Measurements of  $R_p$  in saline were made both before and after tissue measurements to provide an upper and a lower range figure for correction. The electrode was first "aged" before the initial saline calibration by inserting it into

tissue repeatedly to keep the difference between the saline measurements before and after tissue measurement small.

With the electrode shown in figure 1, measured resistance at 1 Kc. did not require correction. At 100 c.p.s., 3-5 per cent, and at 10 c.p.s., 10-15 per cent of the resistance was caused by polarization. With the method for correction outlined above the results are in error as a result of polarization by not more than 3 per cent at 10 c.p.s., and less than 1 per cent at higher frequencies.

*Effects of Bronchial and Vascular Walls Upon Tissue Measurements.* The potential hazards of intravascular or intrabronchial use of the electrode system are illustrated in figure 2. The fluids in the vessel shunt the electrodes and the vessel wall establishes a resistance in series with the tissue resistance. The equivalent circuit depicted in figure 2 shows how measurements intended to be those of tissue resistance ( $R_t$ ) are increased by vessel wall resistance ( $R_v$ ) and lowered by vessel wall and fluid shunting resistance ( $R_b$ ). Vessel resistance measurements have been carried out with pieces of vein, pulmonary artery and bronchus slipped over the electrode system and measured alternately in air and in saline solutions of varying ionic strength. The resistance that the vessel wall material puts in series with the tissue resistance could be determined from such measurements. Estimates of specific resistance so obtained varied from 250 to 700 ohm cm. Since this is not very different from the resistivity of tissue, it does not seriously affect the determination of tissue resistivity. Since resistance values ( $R_v$ ) amount to only about 50 ohms, vessel wall impedance also does not seriously affect tissue resistance data (about 900

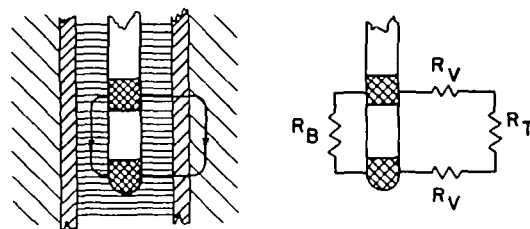


FIG. 2. How vessel fluid and wall material constitute additional resistive elements  $R_b$  and  $R_v$ , which may affect the determination of the tissue resistance  $R_t$ .

ohm cm.). The shunt due to vessel fluid on the other hand, can be appreciable. For example, comparison data obtained at 1 Kc. when the electrode system is introduced via the pulmonary artery with that obtained when it is inserted via the bronchus show that values obtained for pulmonary resistance are somewhat lower in the former.

This hazard was minimized by introducing the standard electrode system so firmly that the vessel walls fit over the electrode system snugly. The resistivity values obtained with the large electrode system (diameter 6 mm.), less likely to be subject to shunting effects, agreed within the normal range with those obtained with the standard electrode system shown in figure 1. After careful analysis of all factors, it is concluded that the measurements of the resistivity of the lung by the "vessel technic" are in error by not more than about 10 per cent.

*Excitation and Linearity of Tissue.* Change in impedance upon stimulation has been reported for nerve,<sup>9</sup> and is expected in any type of biological material that can be polarized. Consequently, stimulation must be avoided if one desires to obtain resistance data of interest in electrocardiography. The data reported in this article are obtained at subthreshold levels, i.e., they are characteristic for the "passive" behavior of tissues exposed to such weak currents as generated by the heart. Figure 3 shows results obtained in muscle tissue with varying intensity of current for a frequency of 10 c.p.s. It demonstrates the linear characteristics of the resistivity of tissue for subthreshold current intensities and the rather sudden change which occurs when threshold level for stimulation is reached. Since the tissue resistance was about 1500 ohms in this experiment and since the area for each electrode surface is 0.3 cm.<sup>2</sup>, it is concluded that a current density of about 2 ma/cm.<sup>2</sup> is the threshold level for nonlinear behavior. Other experiments at higher frequencies show that this level is not appreciably frequency dependent.

*Anisotropy of Tissue Resistivity.* It is known that "transverse" and "longitudinal" muscle resistance differ by as much as a factor of 2.<sup>10</sup> A theoretical understanding of this effect is achieved with the help of equations advanced originally by Maxwell and extended by

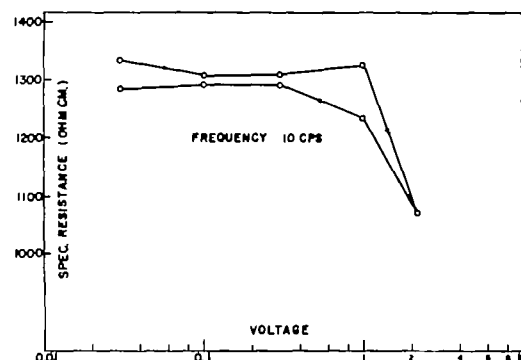


FIG. 3. Dependence of tissue resistance on electrode potential. Tissue resistance shows linear characteristics up to a potential of about 1 volt.

Fricke.<sup>11</sup> These equations relate cell shape, orientation in regard to electric field, concentration of cells and resistivities of intercellular fluid and total observed tissue with each other. We have pointed out at another place<sup>12</sup> that "longitudinal" resistance data can only be expected when a nearly perfect alignment between current field and cell orientation is achieved. For practical purposes, random orientation of cells and transverse orientation to the field yield values which are nearly identical and quite different from the longitudinal values. The character of the current field around our electrodes is close to that of a spherical electrode, i.e., current density in every direction from the electrodes may be assumed not to vary excessively, at least near the electrodes, where the major part of the total observed resistance exists. This means that our measurements refer to "random" orientation of cell fibers in relation to the electrical field. Experimental support for this statement has been provided in an attempt to orient the electrode system in line and perpendicular to the structure of the investigated muscular tissue. Practically the same results are obtained. This does not, of course, invalidate the concept of anisotropy of tissue. It merely demonstrates the ability of the electrode system to obtain "random" values, which are of practical interest in electrocardiography.

#### TISSUE RESISTIVITY DATA

In addition to many measurements made to develop technical proficiency or to evaluate the

validity of our methods, results reported here are derived from measurements in 7 dogs. The heart muscle measurements were recorded immediately after cessation of the electric activity of the heart. All other measurements were taken during life. Most of the measurements were taken by introducing the electrode catheter, pictured in figure 1, directly into the tissues. An exception was lung, which could not be punctured without seriously disturbing the normal state of the tissue. Lung measurements were made by inserting this catheter through the pulmonary artery or the bronchus. Some of the lung measurements via the bronchial route were made with a catheter of larger caliber, as noted. Also, liver measurements of dogs 3 and 4 were made with the illustrated catheter inserted into the hepatic veins via the jugular vein and superior vena cava.

The results of all tissue measurements made in the dogs at a frequency of 1 Kc. show that the averages for lung, muscle, liver and heart muscle range from 1000 to 750 ohm cm. However, the standard deviations for each type of tissue are comparable with the differences of the average values for the various tissues. Hence, the resistivities of these 4 tissues do not differ beyond the limits of statistical significance, although the resistivity of lung is probably a little higher than that of the other 3 tissues tabulated.

The resistivity of fat was found to be clearly divergent from that of the other tissues measured. It varied from 1500 to 5000 ohm cm. in a series of 8 measurements at 1 Kc. The average value in this restricted sample was about 3000 ohm cm.

#### DISCUSSION

It is not surprising that the resistivity of lung tissue is not drastically higher than that of other tissues. The large, highly resistive, air content is counteracted by the high blood content of very low resistivity (about 100 ohm cm.). Since the air content of lung is approximately four times that of blood<sup>13</sup> a computation using an equation of Maxwell<sup>10, 11</sup> would indicate a specific resistivity near 700 ohm cm. The measured figure of 1000 ohm cm. is a reasonable deviation from the roughly computed figure, inasmuch as the resistivity of interstitial

tissue of the lung is neglected. In the intact animal, hyperinflation immediately raised resistivity by about 30 per cent, whereas deflation, by external chest compression, lowered it by about 10 per cent. When the exposed lung was hyperinflated well beyond the physiologic range, resistivity could be raised to double the preinflation figure.

A reduction of blood content by gravity drainage immediately after death was also the apparent cause of a coincident rise in liver resistivity of 30-50 per cent measured by electrodes in the hepatic vein or inserted directly into the tissues. This change occurred before the temperature had changed significantly, and long before the period of about 24 hours required for cellular breakdown and resulting impedance changes previously observed in measurements of excised tissue.<sup>1</sup> A smaller rise of resistivity (average 5 per cent) followed cessation of circulation in the lung, but cannot be considered statistically significant.

Heart muscle measurements during life are difficult. The electric activity of the heart disturbs the recordings, and the process of depolarization and repolarization results in large, rhythmic variations in the resistivity of the tissue. Measurements of the resistivity of local segments of heart muscle were performed, therefore, immediately after cessation of electric activity. The resistivity of the total heart is difficult to define since the heart is not only a highly inhomogeneous volume conductor, but one in which the relative volumes of the major inhomogeneities (blood filled chambers and muscle tissue) are constantly changing.

The measurements tabulated and discussed at this point were made at a frequency of 1 Kc. With a few exceptions, the 1 Kc. measurement was but one of a sequence of measurements made also at 10 cps., 100 cps., 10 Kc. and, occasionally, at other frequencies up to 100 Kc. In all of these sequential measurements, regardless of tissue, resistivity (not including electrode polarization effects) falls as frequency increases. Characteristically, it falls by about 10-20 per cent in a frequency change from 1 Kc. to 10 Kc., and by about 50 per cent in a change from 1 Kc. to 100 Kc. Similarly, as frequency is reduced from 1 Kc. to 100 c.p.s., measured resistance rises by about 5 per cent,

or if the reduction is to 10 c.p.s., by about 20 per cent. Figure 4 shows measurements recorded in liver tissue. Similar curves are regularly recorded from muscle, heart muscle and lung tissue. In fatty tissue, a more linear decrease of resistance with increase in frequency is obtained. However, the total relative change in resistivity occurring as frequency increases from 10 c.p.s. to 100 Kc. compares with that found in the other tissues.

The reasons for frequency dependence of biological tissues have been analyzed elsewhere.<sup>14</sup> They relate to the cellular structure of biological materials and the frequency dependent characteristics of the cell envelopes. These effects are sufficiently well understood to state that the values at 10 c.p.s. are not more than a few per cent divergent from those at even lower frequencies, down to 1 c.p.s. It can be stated, therefore, that the measurements at 1 Kc., as used in the tables and figures, are applicable to the frequency spectrum of the heart (around 1–100 c.p.s.), although uniformly lower by about 20 per cent than resistance figures, at the heart frequencies.

The specific resistances reported here are much higher than the 250 ohm cm. reported by Burger and Van Milaan.<sup>15</sup> These authors applied a 4 electrode technic to body segments. It is suspected that their values are influenced by surface conductance and polarization phenomena. Burger and Van Milaan discuss the difficulties due to surface conductance of skin and describe their attempts to minimize this hazard. However, they do not prove conclusively the absence of any surface conduction. Furthermore, their statement that in 4-electrode systems electrode polarization can be eliminated if the "pick-up" electrodes do not draw current, is incorrect, as discussed at another place.<sup>12</sup> As evidence of the inherent defect in their technics the resistivity of blood is reported at 18 C. to be 230 ohm cm.<sup>18</sup> Accepted values by many other investigators<sup>16–19</sup> range from 120 to 170 ohm cm. referred to 18 C. The new figures are also higher than those reported previously by Kaufman and Johnston.<sup>5</sup>

The figures reported here are in the general range that might be predicted from theory. Tissue cells are practically nonconducting at

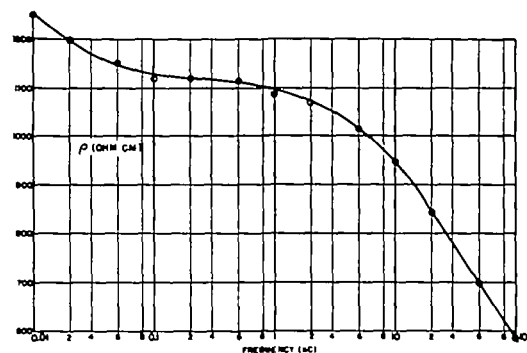


FIG. 4. Curve illustrating dependence of specific resistance of liver tissue on frequency.

frequencies below 1 Kc.<sup>20</sup> Hence, the total conduction is established through the blood and intercellular fluids. The resistivity of intercellular fluid is comparable to that of blood serum, and its value is about 60 ohm cm.<sup>3</sup> while that of blood is about 100 ohm cm. at body temperature. The intercellular fluid contents of dog tissues are in the 71–84 per cent range.<sup>21</sup> Application of a theoretical relationship<sup>22</sup> between cell size and concentration and specific resistances of intercellular fluid and total tissue predicts that for a cell concentration of 70 per cent, tissue resistivity should be about 400 ohm cm. and for 90 per cent, about 1200 ohm cm.

#### SUMMARY

The specific resistances of lung, skeletal muscle, liver and heart muscle were measured at frequencies from 10 c.p.s. to 10 Kc. in situ in anesthetized dogs. The specific resistance at a frequency of 1 Kc. is about 800 ohm cm. for muscle, liver and heart muscle tissue. Lung tissue has a slightly higher resistivity of about 1000 ohm cm. The specific resistivity of fat is considerably higher with values ranging from 1500 to 5000 ohm cm.

The resistivity increases with decreasing frequency. Values at 10 c.p.s. are about 20 per cent larger than those obtained at 1 Kc.

These experiments support indirect observations that no gross error exists in the assumption that the body tissues that conduct the signals recorded in electrocardiography establish an essentially homogeneous volume conductor. It is not implied that the known inhomogeneities within the heart may not

exert an important influence upon potential differences

#### SUMMARIO IN INTERLINGUA

Le resistencias specific de pulmone, musculo skeletal, hepate, e musculo cardiac esseva mesurate in canes anesthesiate, in sito, a frequentias de inter 10 cyclos e 10 kilocyclos per secunda. A un frequentia de 1 kilocyclo le resistencia specific de musculo skeletal, hepate, e musculo cardiac es circa 800 ohm/cm. Le pulmone ha un levemente plus alte resistencia; illo amonta a circa 1000 ohm/cm. Le resistencia specific de grassia es considerabilemente plus alte. Su valores varia inter 1500 e 5000 ohm/cm.

Le resistencia accresce con decrecente frequentias. A 10 cyclos per secunda le valores es circa 20 pro cento plus alte que a 1 kilocyclo.

Iste experimentos supporta le observation indirecte que nulle grande error es causate per le supposition que le histos del corpore que conduce le signales registrate in electrocardiographia representa un essentialmente homogenee conductor de volumine. Isto non significa que nos vole asserer que le cognoscite inhomogeneitates intra le corde non pote exercer un importante influentia super differentias de potential.

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