Capacitive Properties of Body Tissues

By HERMAN P. SCHWAN, PH.D. AND CALVIN F. KAY, M.D.

The electric capacity of various tissues surrounding the heart has been investigated in living dogs, using frequency ranges from 10 to 10,000 c.p.s. Electrode polarization, a serious source of error in such measurements, has been corrected for. Discussion of our results and of resistivity data previously obtained in body tissues proves that the electric properties of body tissues are primarily resistive ones.

The electric activity of the heart can be studied only indirectly by means of the small fraction of the heart potential that reaches the body surface. So far it has been assumed that the electric properties of the tissues that separate the heart and body surface are purely resistive and establish a homogeneous volume conductor. While the assumption of homogeneity of resistivity has been found valid no investigation of possible non-resistive components of the body tissues has been conducted in situ. Investigations of the electric properties of excised muscle tissue were conducted at low frequencies. The ratio of capacitive to resistive current which we calculated from these data is shown in table 1 as function of frequency. These ratios, while small, are indicative of noticeable reactive current components. Since the capacitive components had been found to deteriorate rapidly with time in excised tissue the possibility exists that considerably larger values exist in situ.

If tissue impedance should include a noticeable reactive component, the transfer impedances which are defined by body surface potentials and current generated by the heart would also be in part reactive. As a consequence, the various frequency components which in sum establish the heart signal, would be subjected not only to attenuation, but also to phase shift between heart and body surface. As a consequence, it is unlikely that a signal would result on the body surface which would be identical with the one to be anticipated if the medium between heart and body surface were purely resistive.

This paper considers only the reactive components of various body tissues in situ in order to provide the necessary information for further discussions of phase shift.

METHODS

Measurement of capacitance in situ requires the elimination of electrode polarization. The polarization potential, developed between electrodes and tissue, is proportional to the current passing the electrode for sufficiently small current density (less than about 1 ma./cm.²) as always used in our measurements. Therefore, it may be characterized by an impedance.

The total capacity (C*), as observed by the electrode system, can be expressed as a sum of two components,

\[ C^* = C + \frac{1}{\omega^2 RC_p} \]  

whose first term \(C\) is the true capacitance of the sample and whose second term characterizes the contribution due to electrode polarization (Cp) capacity of the electrode impedance, \(R\) observed resistance, \(\omega/2\pi\) frequency). Reduction of the second term may be accomplished by increasing \(C_p\), by provision of a heavy coat of platinum black on platinum electrodes or by use of a sufficiently large electrode area. Excessive coating with platinum black leads to unstable electrodes for tissue work. The other approach of large electrodes also has limitations, due to the necessity of obtaining meaningful, local capacitance determinations and the desire of using an electrode system which can be introduced into tissue without major operative procedures. The electrode system and technic previously described was used. The polarization contribution \(1/\omega^2 RC_p\) is compared for a typical experiment with the tissue sample capacity in table 2. Since \(1/\omega^2 RC_p\) decreases rapidly with increasing frequency table 2 shows that the tissue values for frequencies above 1 Kc. are not

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**Table 1.** Ratio of Capacitive and Resistive Component of Tissue Impedance as Function of Frequency in Excised Muscle

<table>
<thead>
<tr>
<th>Frequency (c.p.s.)</th>
<th>$R_u/C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.01</td>
</tr>
<tr>
<td>10</td>
<td>0.01</td>
</tr>
<tr>
<td>20</td>
<td>0.01-0.02</td>
</tr>
<tr>
<td>50</td>
<td>0.02-0.03</td>
</tr>
<tr>
<td>100</td>
<td>0.02-0.03</td>
</tr>
<tr>
<td>200</td>
<td>0.02-0.04</td>
</tr>
<tr>
<td>500</td>
<td>0.03-0.04</td>
</tr>
<tr>
<td>1000</td>
<td>0.04-0.05</td>
</tr>
</tbody>
</table>

**Table 2.** Effect of Electrode Polarization on Measured Capacitance Values ($C^*$)

<table>
<thead>
<tr>
<th>Frequency (c.p.s.)</th>
<th>$C^*$</th>
<th>$C$</th>
<th>$1/\omega R_u C_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>12</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>$\sim 200$</td>
<td>$\sim 2000$</td>
</tr>
</tbody>
</table>

affected by polarization. The values below 1 Kc., however, are affected increasingly. In practice, it has been found that the polarization component of the capacity can be obtained with an accuracy of about 10 per cent, as outlined below. This means that from observed capacitance values $C^*$ the true tissue capacitance could be obtained accurate to 1 per cent at 1 Kc. and accurate to about 10 per cent at 100 c.p.s. if electrode polarization were the only factor determining inaccuracy of results. At 10 c.p.s. the polarization contribution is about 10 times larger than the sample tissue capacitance itself. At this frequency, tissue capacitance may be estimated only within a factor of 2 or 3.

In order to obtain a good estimate of the polarization contribution in equation (1), the polarization capacity $C_p$ must be known. Unfortunately, $C_p$ depends on the medium in which the electrode system is immersed. A good estimate of the factor by which the polarization capacity in tissue is smaller than the polarization value obtained with a physiologic saline solution may be obtained as follows: The "masking factor" which differentiates $C_p$ "in tissue" from $C_p$ "in saline," is frequency independent.3 The frequency dependence of the polarization capacitance can be obtained readily from an experiment in physiologic saline solution, which has negligible capacitive and known resistive properties. Thus, if $C_p$ in tissue is known at any one frequency, it can be computed for all the others. Knowledge of $C_p$ in the tissue is obtained best at 10 c.p.s., since here polarization is very pronounced in its contribution to the total capacity. Under the assumption that tissue capacitance values obtained at 100 c.p.s. may be extrapolated proportionally down to 10 c.p.s., as indicated by the dashed line in figure 1, values for tissue capacitance are obtained which are about 10 times smaller than established by polarization. If we assume an accuracy of the tissue capacitance extrapolation which allows the true capacity to vary from zero to double the extrapolated value knowledge of the polarization contribution and $C_p$ in tissue accurate to within 10 per cent is obtained.

The following independent arguments support the correctness of this procedure:

1. Measurements conducted in excised samples of tissue where more advanced technics for the elimination of polarization could be used show that the capacity increases as frequency decreases from 100 to 10 c.p.s. by less than a factor of 5.

2. Measurements with larger electrodes having considerably less polarization and applied by the same technic yield similar results. If the assumption concerning the frequency behavior which we have formulated above for tissue were grossly wrong, the measurements with the larger electrode would yield different results. The resultant error would be greater with the standard electrode system than with the large electrode system.

3. The values for polarization capacities $C_p$ obtained with our technic permit calculation of polarization resistance $R_p$ values by use of a relationship formulated by Fricke.6 Fricke's law has been checked by us and is found to provide resistance data in fair agreement with experiments. (Error smaller than 20 per cent over most of the frequency range from 10 to 100,000 c.p.s.). The polarization resistance values obtained in this manner deviate from experimental ones with technics outlined previously by less than a factor of 1.5.

4. The polarization values obtained by comparison with polarization values in saline provide reasonable masking factors. If the polarization capacities in tissue were more than twice as large as estimated, masking factors far in excess of any previously discussed factors would result.

All measurements were carried out on live dogs with a bridge described elsewhere. The technic of recording the data is substantially the same as pro-

![Fig. 1. Frequency dependence of the dielectric constant of liver tissue in situ in a live dog. Accuracy of results declines rapidly below 100 c.p.s. (vertical lines).](image-url)
 Resistance measurements were taken simultaneously in order to permit calculation of ratio of capacitive to resistive current. Bridge readings of capacitance were taken in multiples of 1000 µF, corresponding to multiples of 10,000 in dielectric constant. Hence, absolute accuracy of the data at frequencies lower than 1 Kc. is completely determined by electrode polarization as discussed above.

Results

Capacitance data are given for lung, muscle and liver in table 3 and expressed in terms of dielectric constants* at the frequencies 100 c.p.s., 1 and 10 Kc. Values at 10 c.p.s. are not given, since they are inaccurate by a factor of 2. However, it can be stated that they are between 3 and 10 times larger than the values at 100 c.p.s.

It is noted that the variation from sample to sample within each group of tissue is comparable with the variation between the averages of various types of tissues as tabulated in table 4. A possible exception is the fatty material with its somewhat lower dielectric constant.

A possible exception is the fatty material with its somewhat lower dielectric constant. Therefore, the capacity of all tissues with high water content recorded here is the same within a factor of about 1.5 with the exception of lung, which has lower values. Figure 1 shows that a very pronounced frequency dependence exists in a manner which gives increase in capacity as the frequency decreases. The reasons for a similar behavior in excised tissue have been reported elsewhere.² The variation below and above the average values are only in part due to uncertainty in electrode polarization as discussed above. Accuracy of reading established an additional source of possible error of about 10 per cent.† Hence, true variation in tissue need be only about 20 or 30 per cent. A summary of all dielectric constants is given in table 4, together with values of RoC-products as calculated from dielectric constant and simultaneously carried out resistance measurements. It is noticed that the RoC-values are smaller than 0.1 in the frequency range from 100 to 1000 c.p.s. At 10 Kc. they start to in-

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* The dielectric constant is identical with the capacitance of a cm.³ tissue, measured in µF and multiplied with the factor 3.6 π.

† The determination of tissue capacitance is much more difficult than the determination of tissue resistivity due to the fact that tissue has predominantly resistive character. The RoC-products listed in table 2 show that the capacitive current is less than 1 of the resistive current. Hence, its determination and consequent determination of capacitance which is always based on the measurements of this current are 10 to 100 times more difficult than measurement of resistive current.
Table 5.—Dielectric Constants ($\times 10^6$) for Human Lung and Dog Lungs

<table>
<thead>
<tr>
<th>Human lung (excised)</th>
<th>Dog lung in situ (1 hour dead) I</th>
<th>Dog lung (dead) II</th>
<th>Dog lung in situ (dead) III</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>140</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>90</td>
<td>90</td>
<td>180</td>
<td>180</td>
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<tr>
<td>150</td>
<td>110</td>
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<td>100</td>
<td>150</td>
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<tr>
<td>140</td>
<td>120</td>
<td>190</td>
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<tr>
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<td>90</td>
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<td>110</td>
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<td>140</td>
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<td>120</td>
<td>130</td>
<td>70</td>
<td>110</td>
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<td>120</td>
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<tr>
<td>100</td>
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<td>140</td>
<td>170</td>
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<td>160</td>
<td>160</td>
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<td>110</td>
</tr>
<tr>
<td>100</td>
<td>80</td>
<td>110</td>
<td>110</td>
</tr>
</tbody>
</table>

The similarity of the tissue capacitance data reported with those found in studies with excised material suggests that the reason for the frequency dependence is the same in both cases. The higher accuracy obtainable in studies with excised material showed that the change in the low frequency band below 10 c.p.s. and 100 c.p.s. is explained by an electric relaxation effect. It was found that the total change in capacitance ($\Delta C$) and total change in resistance ($\Delta R$) throughout the low frequency range of interest are related by the equation

$$\frac{\Delta R}{\Delta C} = 2\pi f_0 R_0^2$$

where $f_0$ is the frequency for which the capacitance has been reduced from its value at zero frequency (DC) by a factor of 2. The excised studies showed that the frequency $f_0$ is between 10 and 100 c.p.s. This means that the change in capacitance below 10 c.p.s. must be smaller than by a factor of 2. Resistance change, on the other hand, has been reported to be very small between 10 to 100 c.p.s. Its change below 10 c.p.s. must likewise be small in view of the fact that $f_0$, characteristic for both resistance and capacitance change, has been found to be larger than 10 c.p.s. The combination of the stated resistance and capacitance changes to be anticipated below 10 c.p.s results in $R_0C$-values which continue to decrease below 100 c.p.s.

Since $R_0C$ values characterize the ratio of capacitive to resistive current, it can be stated that the heart produces currents which are at least 90 per cent resistive in character. However, if capacitance data would have been larger than recorded by only one order of magnitude, the assumption of a predominantly resistive medium around the human heart would have been grossly in error.

**Summary**

The dielectric constant (capacity) of various tissues, lung, muscle and liver has been investigated with alternating currents in situ in anesthetized dogs. The frequency range extended from 10 c.p.s. to 10 Kc. The dielectric constant at 1 Kc is approximately 100,000. Lung tissue and especially fatty tissue have a
somewhat lower dielectric constant than liver and muscular tissue.

The dielectric constant decreases rapidly as the frequency increases. Values at 100 c.p.s. are about five times larger than at 1 Kc. and values at 1 Kc in turn about three times larger than values at 10 Kc.

The ratio of the capacitive to the resistive current component has been determined from measured capacitance and resistance data and found to be smaller than 0.1 as long as the frequency is smaller than 1 Kc. Hence, it is justified to a good approximation for frequencies up to 1 Kc. to consider body tissues as a resistive medium.

SUMMARIO IN INTERLINGUA

Le constante dielectric (capacitate) de varie tessutos—pulmone, muscolo, e hepate—eseva investigate per medio de currentes alternante in sito in canes anesthesiate. Le frequentias variava inter 10 cyclos per secunda e 10 Kc. Le constante dielectric a 1 Kc es approximativemente 100.000. Tessutos pulmonar e specialmente tessutos grasse pote haber un constante dielectric un paucio plus basse que tessutos de hepate e muscolo.

Le constante dielectric decresce rapidemente con le elevation del frequentia. A 100 cyclos per secunda, le valores es approximativemente 5 vices plus grande que a 1 Kc, e le valores a 1 Kc es in torno approximativemente 3 vices plus grande que le valores a 10 Kc.

Ab le datos mesurate de capacitance e resistencia, le proportion inter le componentes capacitive e resistive ha esse determinate. Illo se trova 0,1 durante que le frequentia remane infra 1 Kc. Ergo, il es justificate como un bon approximation—pro frequentias usque a 1 Kc—considerar le tessutos corporee como un medio resistive.

REFERENCES

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