Electrical Impedance of Cardiac Muscle

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It has long been held that transmission of excitation from cell to cell in cardiac muscle is effected by local-circuit current. Recent electron microscopy has shown that the myocardium is not a morphological syncytium; the intercalated discs are actually cell boundaries. If the resistances of the disc membranes are high, then local-circuit current transmission is unlikely, and the major possibility remaining would be that of chemical junction transmission. Several lines of evidence have led to a questioning of the validity of the electrical theory of transmission.

The present report deals with an effort to determine the resistance and the capacitance of the transverse membranes by measurement of tissue impedance in the direction of fiber orientation, before and after reduction of the interspace ion concentration. This work is an extension, with impedance measurements, of a previous report which presented D.C. resistance measurements. The passive current flow paths through a muscle strip may be lumped into two major parallel paths: (a) the path through the extracellular fluid (ecf), and (b) the path through the cell membranes and intracellular fluid (icf). The resistance of the extracellular path depends on the inter-space volume relative to the cell volume, and the resistance of the cellular path depends on the number and on the resistance of the cell membranes and on the myoplasmic resistance.

Methods

Strips of parallel fibers were obtained from papillary muscles and ventricular trabeculae of the cat. Impedance of frog sartorius muscle was measured for comparison. Each muscle strip was selected for uniform thickness throughout its length, and no strip thicker than 2 mm. was used. The lengths were generally greater than 15 mm. The impedances were measured with A.C. Wheatstone bridge techniques employing a cathode ray oscilloscope as the null-point detector. A sine wave generator was used to supply sub-threshold A.C. current at frequencies of 10, 100, 1,000 and 10,000 c.p.s. A metal clip mounted on a manipulator served as one electrode. The clip supported one end of the muscle in a vertical position. The other end was fixed so that the muscle was under constant resting tension. The muscle was lowered into a reservoir by means of the manipulator and the distances moved were measured on the manipulator scale. A second electrode was immersed in the reservoir which was filled with Ringer's solution. A layer of mineral oil above the Ringer's solution completely covered the muscle and served to prevent evaporation from the muscle during the measurements. The muscle was lowered into the Ringer's reservoir in three steps at 5-mm. intervals, and the impedance at each of the four frequencies was measured for the length of muscle in the oil layer at each step. A plot of impedance (at each frequency) versus muscle length was linear, and from the slope the impedance per centimeter length of muscle was calculated. These impedance measurements for each muscle were compared before and after interspace ion depletion. Interspace ion concentrations were reduced by soaking for two hours in several changes of isotonic sucrose solution. All procedures were carried out at room temperature.

Results and Discussion

Figure 1 summarizes the effect of frequency on the relative impedance of cardiac and skeletal muscle before and after soaking in isotonic sucrose solution. The impedance of a given strip at each frequency was compared to that in Tyrode's solution at 10 c.p.s. which was taken as unity. These relative impedances are plotted on the ordinate. The A.C. frequency is plotted on the abscissa on a logarithmic scale. Reduction of the interspace ion concentration of skeletal muscle raised the impedance about twofold. Furthermore,
The impedance of cardiac muscle in Tyrode's solution was independent of frequency in either solution. In contrast, the impedance of cardiac muscle in Tyrode's solution was dependent upon frequency, so that at 10,000 c.p.s., the impedance was about 75 per cent of that at 10 c.p.s. Reduction of the interspace ion concentration raised the impedance over tenfold, and there was a marked fall in impedance at the higher frequencies, so that at 10,000 c.p.s. the impedance was about 48 per cent of that at 10 c.p.s.

The above data and calculations, based on data previously reported, are summarized in Table 1. Previous data on the D.C. specific resistances are given for cardiac, skeletal and smooth muscles before (RT) and after (R'T), a tenfold reduction of the interspace ion concentration. The specific resistance of cardiac muscle (268 ohm-cm.) is about double that of skeletal (133 ohm-cm.) or smooth (118 ohm-cm.) muscles. With a tenfold reduction of interspace ion concentration, the resistance of cardiac and smooth muscles increased 7.0 and 6.7 times their initial values, respectively, whereas that of skeletal muscle increased 2.9 times.

The resistances of the extracellular pathway (r_{ecf}) and of the cellular pathway (r_{cell}) may be calculated from the relationship of total resistance (R_T) to these two parallel resistances. Two equations describe the strip before (equation 1) and after (equation 2), a tenfold increase in interspace resistance. Upon solution, expressions for the two parallel paths are obtained (equations 3 and 4). The interspace volumes (equation 5) were calculated by dividing the specific resistivity of frog Ringer's solution (60 ohm-cm.) or Tyrode's solution (44 ohm-cm.) by the resistance of the interspace.

\[
\frac{1}{R_T} = \frac{1}{r_{ecf}} + \frac{1}{r_{cell}} \quad (1)
\]

\[
\frac{1}{R_T} = \frac{1}{10r_{ecf}} + \frac{1}{r_{cell}} \quad (2)
\]

\[
r_{ecf} = 0.9 \frac{R_T' - R_T}{R_T'} \quad (3)
\]

\[
r_{cell} = \frac{r_{ecf} \cdot R_T}{r_{ecf} - R_T} \quad (4)
\]

\[
V_{locf} = \frac{R_{Ringer's}}{r_{ecf}} \quad (5)
\]

The calculated resistance of the cellular pathway (r_{cell}) in cardiac and smooth muscles

**Table 1**

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Relative impedance (Zio.000 e.p.e./Zio c.p.e.)</th>
<th>Specific resistance (ohm-cm.)</th>
<th>Ratio (R'/R_T)</th>
<th>r_{ecf} (ohm-cm.)</th>
<th>r_{cell} (ohm-cm.)</th>
<th>Vol_{ocf} (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal</td>
<td>1.0</td>
<td>268</td>
<td>133</td>
<td>2.9</td>
<td>188</td>
<td>2.4</td>
</tr>
<tr>
<td>Cardiac</td>
<td>0.75</td>
<td>268</td>
<td>1876</td>
<td>7.0</td>
<td>207</td>
<td>2.4</td>
</tr>
<tr>
<td>Smooth</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

**Figure 1**

Effect of frequency on the relative impedance (Z) of cardiac and skeletal muscle before and after soaking in isotonic sucrose solution. The relative impedance is the impedance of a given strip during the experimental conditions divided by the strip impedance at 10 c.p.s. Stars represent cat papillary muscle and ventricular trabeculae; circles represent frog sartorius. The open symbols represent the impedances in Tyrode's solution, and the closed symbols, in isotonic sucrose solution. See text for explanation.
Figure 2
Comparison of the extracellular (I_{ecf}) and intracellular (I_{icf}) current flow pathways in cardiac and skeletal muscle. See text for explanation.

is much higher than that of the extracellular pathway (r_{ecf}). In cardiac muscle, the resistance of the extracellular pathway is 281 ohm-cm., compared to 5,560 ohm-cm. for the cell pathway (see table 1). In smooth muscle, the values are 125 and 2,130 ohm-cm., respectively, and in skeletal muscle the values are 188 and 454 ohm-cm., respectively. The ratio of the resistances of the cellular and extracellular pathways, \( r_{cell}/r_{ecf} \), is 19.8, 17.1, and 2.4 for cardiac, smooth, and skeletal muscles, respectively. Calculations based on the resistance data show cardiac muscle to have the smallest interspace volume, 16 per cent, compared to 35 and 32 per cent for smooth and skeletal muscles, respectively. If the resistance of the cellular pathway of skeletal muscle, 454 ohm-cm., is assumed to be the myoplasmic resistance (r_{icf}) and is subtracted from \( r_{cell} \) of cardiac and smooth muscles, there remains a difference of 5,106 and 1,676 ohm-cm., respectively. This excess resistance in the cellular pathway may reside within transverse cell membranes (r_{disce-cm}).

The data suggest the presence of high resistance, high capacitance transverse membranes in cardiac muscles and perhaps in smooth muscle (fig. 2). If a large proportion of the current passes through the cells, then increasing the extracellular resistance tenfold would not markedly affect the tissue resistance. In skeletal muscle, the ratio of the resistances, \( R'/R \), is only 2.9. Therefore, in skeletal muscle, where the individual cells extend almost the whole length of the muscle and there are no transverse membranes, a large proportion of the current passes through the cells. The ratio of current through the interspace to current through the cells (I_{ecf}/I_{icf}) calculated to be 2.4. Since neither pathway involves capacitive cell membranes, there is very little frequency effect. However, if most of the current passed through the extracellular path, increasing the extracellular resistance tenfold would increase the tissue resistance almost tenfold. In cardiac and smooth muscles, in which the cells are short, \( R'/R \) is 7.0 and 6.7, respectively. Therefore, the cellular pathway is of much higher resistance than the extracellular pathway. By calculation, \( I_{ecf}/I_{icf} \) is 19.8 and 17.1 for cardiac and smooth muscles, respectively. In cardiac muscle, the resistance of the cell pathway is so high that it cannot be readily accounted for except by high-resistance transverse membranes. However, at high frequencies, the high-resistance component of this transverse membrane appears to be short-circuited by a capacitive component. Thus, as the frequency is increased, the impedance of the cellular pathway decreases, due to decreased capacitive reactance. The frequency effect is more pronounced in sucrose than in Ringer’s, because the proportion of current passing through the cellular pathway is larger, and the capacitance probably resides in the cellular pathway. In conclusion, the intercalated discs of cardiac muscle may be suspected to have a resistance and a capacitance comparable to that of the rest of the cell membrane.

Summary
Impedances of cat cardiac muscle and frog sartorius muscle were compared at several frequencies before and after interspace ion depletion. Strips of parallel fibers were obtained from papillary muscles and ventricular trabeculae. The impedances were measured in the direction of fiber orientation. Interspace ion concentrations were reduced by soaking the tissues in isotonic sucrose solution. The D.C. specific resistance of cardiac muscle compared to skeletal muscle was previously reported to be two times as large in Ringer’s and over five times as
large in 0.1 Ringer’s-sucrose solution. In the present study, the relative impedances of cardiac muscle at 10,000 c.p.s. compared to that at 10 c.p.s. were 75 and 48 per cent in Ringer’s and sucrose solutions, respectively. The impedance of skeletal muscle was independent of frequency in Ringer’s and in sucrose solutions. These results suggest the presence of transverse membranes (perhaps the intercalated discs) of high resistance and high capacitance.

References