Note on the Anisotropy of Extracellular Resistivity in Cardiac Muscle

In their recent paper, Roberts et al. (1979) report the following values of intracellular (i), extracellular (o), longitudinal (L), and transverse (T) resistivity for canine ventricular muscle: \( r_i = 450 \) ohms-cm, \( r_o = 750 \) ohm-cm, \( r_L = 360 \) ohm-cm, and \( r_T = 3800 \) ohm-cm. The ratio \( r_T/r_L \) is 1.67.

In an earlier paper, Clerc (1976) reported the following resistivity ratios for trabecular bundles from the right ventricle of calf heart: \( r_T/r_L = 9.4 \pm 1.0 \) (mean \( \pm \) SE) and \( r_T/r_o = 2.69 \pm 0.26 \). Clerc gives his resistivity data in terms of the specific resistivity of the intracellular and extracellular fluids. On the other hand, Roberts et al. use an effective resistivity, where the intracellular and extracellular compartments are each taken to occupy the entire tissue space (see also Miller and Geselowitz, 1978). Clerc’s data can be converted to this form using his value of 30% for the volume fraction of extracellular space with the result: \( r_L = 160 \) ohm-cm, \( r_o = 423 \) ohm-cm, \( r_T = 574 \) ohm-cm, and \( r_i = 5170 \) ohm-cm.

In his paper, Clerc presents a model for the anisotropy of intracellular resistivity. With regard to extracellular anisotropy, he simply states that the ratio “being 2.7 may be explained by the tortuous pathway around tightly packed fibres encountered by transverse current.” The purpose of this note is to provide a theoretical basis for the ratio \( r_T/r_o \).

To calculate extracellular resistivity, the muscle can be modeled by an array of insulating circular cylinders in a suspending fluid of conductivity, \( \sigma_o \). For current flow in the longitudinal direction, the current path is parallel to the axes of the cylinders, and \( \sigma_L = (1 - p)\sigma_o \), where \( p \) is the volume fraction occupied by the cylinders. The analysis of transverse current flow is much more complex. Fortunately, this problem was solved by Lord Rayleigh (1892). His result is

\[
\frac{\sigma_T}{\sigma_o} = 1 - \frac{2p}{1 + p - 0.3058p^4 - \ldots}.
\]

Taking the value, \( p = 0.70 \), used by Clerc, we find \( r_T/r_o = \sigma_T/\sigma_o = 2.15 \), which is intermediate between the values reported by Clerc and Roberts et al.

The theory may be expected to underestimate the anisotropy ratio for several reasons. For one, the fiber packing order deviates from the ideal rectangular array analyzed by Rayleigh. For another, the volume fraction, 70%, is approaching the maximum possible value of 78.6% for a rectangular array. As the volume fraction increases, the Rayleigh approximation will deteriorate, and \( \sigma_T/\sigma_o \) may be expected to rise sharply. For example, Sperelakis and MacDonald (1974) measured the resistivity ratio for an array of glass rods in Ringer’s solution and found a value of 7 for a volume fraction of 76.5%, as compared with 3.0 predicted by the Rayleigh equation. Clerc’s experimental results would thus appear to be in closer agreement to those expected theoretically than would those of Roberts.

David B Geselowitz, Ph.D.
Bioengineering Program
Pennsylvania State University
University Park, Pennsylvania 16802

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D B Geselowitz

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