# MICROWAVE DIELECTRIC PROPERTIES OF TISSUE

## SOME COMMENTS ON THE ROTATIONAL MOBILITY OF TISSUE WATER

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ABSTRACT Dielectric permittivity and conductivity data are reviewed for tissue over the frequency range of 0.1–10 GHz. The conductivity of muscle increases quadratically with frequency above 1 GHz, suggesting a Debye relaxation for tissue water centered at 20 GHz at room temperature, the same as for bulk water. Approximate mixture equations suggest that this "free" water accounts for about 70% of the tissue weight, showing that most of the tissue water has rotational mobilities similar to those in the bulk fluid.

In spite of much study, a generally accepted model for water in biological tissues has not emerged (1). While nuclear magnetic resonance (NMR) techniques can provide detailed information about the motional properties of this "biological" water, NMR data are subject to different interpretations, leading to divergent views about the nature of intracellular water. Dielectric measurements at frequencies above 100 MHz complement NMR studies in tissue, in that they explore water rotational properties over a time scale ($< 10^{-9}$ s) not directly accessible by NMR. This communication makes two observations. First, the high frequency dielectric properties of muscle predict that the tissue water exhibits a Debye dipolar absorption centered at 20 GHz at room temperature,[1] identical to that of pure water. Second, the increase in tissue conductivity above 1 GHz in muscle, skin, and liver, corresponds to a free water content of roughly 70% of the tissue weight, comparable to the known water content of these tissues. From a dielectric point of view, at these high frequencies the tissue is apparently equivalent to a suspension of nonconducting solid in ordinary "bulk" water, contradicting the hypothesis (2, 3) that most of the cell water has motional properties greatly different from those of the pure liquid. Although the dielectric data have long been available (4, 5), their significance to the debate about "biological" water has apparently not been appreciated.

### *Dielectric Properties*

The dielectric permittivity $\epsilon'$ and conductivity $\kappa$ of muscle tissue are summarized in Fig. 1. Also shown are the corresponding values for pure water. The experimental methods used to obtain these data are described in detail in a previous review (5); data

[1] 1 GHz = $10^9$ Hz.

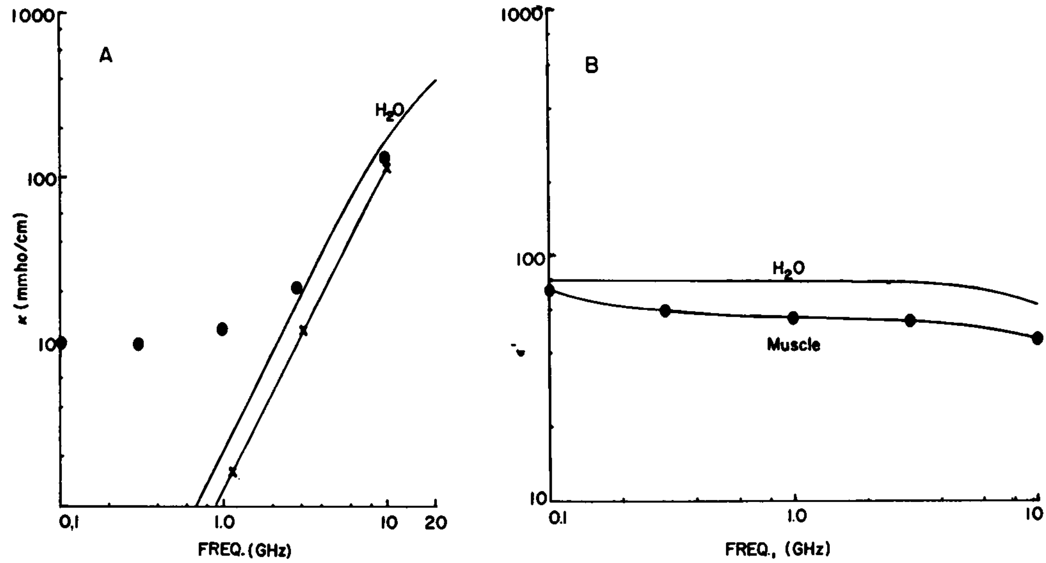


FIGURE 1 Dielectric properties of muscle tissue at 25°C vs. frequency. (A), conductivity $\kappa$, for muscle (●) and pure water (solid line). Also shown (x) is the frequency-dependent component of tissue conductivity, $\kappa - \kappa_0$, where $\kappa_0$ is taken to be 10 mmho/cm. (B) Dielectric permittivity $\epsilon'$ of muscle tissue (●) and pure water (solid line).

were taken from refs. 4 and 5. At frequencies below 0.1 GHz, the tissue conductivity somewhat decreases, and the permittivity greatly increases, primarily because of polarization effects associated with the charging of cell membranes (4). Note that the tissue conductivity rises dramatically at frequencies above 1 GHz, as does that of pure water. This increase in pure water occurs because of the rapid rotation of the water dipoles (6). Evidently, the tissue water retains much of the rotational freedom that it exhibits in bulk solution. From the limited data in Fig. 1, it is possible to deduce considerable information about the rotational mobility of this water.

*Rotational Time Constants for Pure and Tissue Water*

The dielectric properties of pure water or weak electrolyte solutions are well understood. To an excellent approximation (6, 7), they are described by the simple Debye equations:

$$\epsilon' = \epsilon'_\infty + \frac{\epsilon'_0 - \epsilon'_\infty}{1 + (f/f_c)^2}, \tag{1}$$

$$\kappa = \kappa_0 + \frac{(\kappa_\infty - \kappa_0)(f/f_c)^2}{1 + (f/f_c)^2}, \tag{2}$$

where $\kappa_0$ is the ionic contribution to the total conductivity (zero for pure water) and

$$\kappa_\infty = \kappa_0 + (\epsilon'_0 - \epsilon'_\infty) f_c / 1.8 \times 10^{12} \text{mho/cm}. \tag{3}$$

Here, $f_c = 1/(2\pi\tau)$ is the characteristic frequency of the dispersions in Eqs. 1 and 2 when $\tau$ is the rotational time constant. For pure water at 25°C, $\epsilon_0 = 78.3$, $\epsilon_\infty = 4.5$, and $f_c = 19.7$ GHz.

It appears that tissue dielectric properties can also be characterized by equations of the Debye type. Subtracting the ionic contribution to the tissue conductivity ($10^{-2}$ mho/cm), the conductivity increase in muscle tissue clearly parallels that of water (Fig. 1 A). Since the tissue data evidently do not extend past $f_c$, this parameter must be indirectly estimated. Combining Eqs. 2 and 3, we find for $f < f_c$,

$$f_c \cong \frac{(\epsilon_0' - \epsilon_\infty') \cdot 2\pi\epsilon_r f^2}{\kappa - \kappa_0} \tag{4}$$

where $\epsilon_r$ is the permittivity of free space. The "static" permittivity $\epsilon_0'$ is determined below the dispersion that begins near 1 GHz; it is not the direct current dielectric constant of tissue, which is very high because of the presence of several dielectric relaxation mechanisms at lower frequencies. From Fig. 1B, $\epsilon_0 = 54$. The high-frequency permittivity $\epsilon_0$ can be assumed to be 4.5 (the value for pure water; its value does not significantly affect our estimate of $f_c$). Using the measuring value of $\kappa$ for tissue at 10 GHz, we find that $f_c = 19.7$ GHz, identical to that of pure water at 25°C. This calculation assumes that the high frequency dispersion in muscle (beginning at 1 GHz in Fig. 1) is adequately described by the Debye equations (1 and 2), an assumption that appears valid, since the frequency dependences of $\kappa - \kappa_0$ for tissue and water in Fig. 1 B are the same.

### *Amount of "Normal" Tissue Water*

Note that the dipolar contribution to the tissue conductivity in Fig. 1 B is decreased from that of water. From the value of $\kappa - \kappa_0$ at 10 GHz, we can estimate the apparent tissue solid content responsible for this depression. While an exact mixture equation appropriate to tissue is not available, several theoretical calculations give some indication of the expected results. For a volume fraction $p$ of nonconducting spheres and fibers in an aqueous electrolyte solution of conductivity $\kappa_0$,

$$\frac{(\kappa - \kappa_0)_{\text{mixture}}}{(\kappa - \kappa_0)_{\text{solvent}}} = 1 - p \tag{5}$$

for fibers oriented parallel to the electric field lines;

$$\frac{(\kappa - \kappa_0)_{\text{mixture}}}{(\kappa - \kappa_0)_{\text{solvent}}} = \frac{1 - p}{1 + p/2} \tag{6}$$

for spheres (8), and

$$\frac{(\kappa - \kappa_0)_{\text{mixture}}}{(\kappa - \kappa_0)_{\text{solvent}}} = \frac{1 - p}{1 + p} \tag{7}$$

for fibers oriented perpendicular to the electric field lines (9). Eqs. 6 and 7 are the

TABLE I

CONDUCTIVITY DATA FROM CANINE TISSUE AND PURE WATER

| Sample | $\kappa$, 100 MHz | $\kappa$, microwave frequency |
|---|---|---|
| | *mmho/cm* | *mmho/cm* |
| Muscle (25°C) | 10.0 | 125.0 (10 GHz) |
| Skin (37°C) | 7.7 | 71.4 (8.5 GHz) |
| Liver (37°C) | 6.0 | 62.5 (8.5 GHz) |
| Water (25°C) | < 0.1 | 165.0 (10 GHz) |
| Water (37°C) | < 0.1 | 98.4 (8.5 GHz) |

Tissue data are from refs. 4 and 5; water data from refs. 6 and 7.

well-known Maxwell and Rayleigh equations; Eq. 5 is trivial. Eqs. 4 and 6 represent limiting cases of the theory of dielectric properties of suspensions; the "correct" expression for tissue probably is within these limits, and probably close to the Maxwell formula. Taking $\kappa$ and $\kappa_0$ to be, respectively, tissue conductivities at 0.1 and 10 GHz (Table I) and using known dielectric properties of water (6, 7), we estimate that the weight fraction of tissue water is of the order of 65–75% (Table II), in agreement with the water content of these tissues quoted in the literature (10).

Implicit in Eqs. 5–7 is the assumption that the particles in suspension do not affect the dielectric properties of the suspending water. Because of the strong interaction of tissue water molecules with charged sites and polar groups on protein surfaces, in tissue this assumption breaks down to an arguable extent (which is, of course, the essential issue in the "biological water" debate). Water significantly oriented or motionally hindered by interfaces in the tissue will not contribute substantially to the high-frequency electric polarizibility of the tissue, leading to an underestimate from Eqs. 5–7 in the tissue water content. Our results do indicate tissue water contents somewhat lower than literature values, but it is not clear how much of this discrepancy results from an approximate theory or from "bound" water. From other evidence (1), we expect that about 10% of the tissue water is in some way "bound" to macromolecules in tissue. Dielectric studies in hydrated hemoglobin (11) and lysozyme (12) show that "bound" water exhibits a dielectric relaxation in the frequency range between 100 and

TABLE II

CALCULATED AND MEASURED WATER CONTENT OF TISSUE

| Tissue | Mixture equation | | | Literature value |
|---|---|---|---|---|
| | Eq. 5 | Eq. 6 | Eq. 7 | |
| Muscle | 0.64 | 0.73 | 0.78 | 0.76 |
| Skin | 0.59 | 0.68 | 0.74 | 0.72 |
| Liver | 0.50 | 0.61 | 0.68 | 0.76 |

Tissue water contents are from ref. 10.

1,000 MHz, 20- to 200-fold lower than the bulk liquid. Application of Eq. 3 suggests that this "bound" water will not influence the frequency dependence of the tissue conductivity above 1,000 MHz, provided that it constitutes a minor fraction of the total tissue water. The variation of $\kappa - \kappa_0$ with the square of the frequency (Fig. 1 A) suggests that only the relaxation mechanisms found in normal water noticeably contribute to the microwave tissue conductivity. These dielectric measurements show, therefore, that most of the tissue water has rotational mobilities identical to those in the pure liquid.

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