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ELECTRICAL PARAMETER VALUES OF SOME HUMAN TISSUES IN THE RADIOFREQUENCY RADIATION RANGE

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NOTICES

This interim report was submitted by personnel of the Biomathematics Modeling Branch, Data Sciences Division, USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks Air Force Base, Texas, under job order 7757-01-69.

This technical report has been reviewed and is approved for publication.

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This report is an attempt to consolidate electrical parameter values of some human body tissues for the radiofrequency radiation range: 10 - 10,000 MHz. The sources of the data were widely distributed in scientific journals, books, and technical reports and included data points secured by experimental techniques, by computations (Debye or modified Debye equations), and by curve fitting methods. Values extracted from the conductivity and dielectric constant curves provided in the report give reasonable estimates of the interrelationships

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20. ABSTRACT (continued)

between various tissues over the frequency range of interest. These values are important in the study of effects of radiofrequency radiation on living organisms.

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ELECTRICAL PARAMETER VALUES OF SOME HUMAN TISSUES IN THE RADIOFREQUENCY RADIATION RANGE

INTRODUCTION

Radiofrequency radiation can be absorbed by living organisms. The patterns of absorbed power distribution and the associated buildup of hot spots within living objects vary greatly with the frequency, direction, and strength of the impinging waves and with the size, shape, temperature, and internal structure of the body irradiated.

Researchers in the field of electromagnetic bioeffects are confronted with the problem of data scarcity on electrical parameters of living tissues. The conductivity (σ) and complex dielectric constant (ϵ) of each type of tissue are complicated functions of temperature, percent water content, electrolyte concentration, large protein molecule content, cell structure and cell wall properties of the tissue. Theories to explain the variation of σ and ϵ with frequency are well known (6, 8). In tissue, three S-shaped bends in the conductivity and dielectric curves can be seen. These occur in the low frequency, radiofrequency, and superhigh frequency ranges and are called α-, β-, and γ-dispersions, respectively (6).

In the study of human effects of radiofrequency radiation, the conductivity and the real part of the complex dielectric constant at 37°C for various human tissues are required. An attempt to determine these properties in the frequency range 10-10,000 MHz produced the results described in this report. The β-dispersion causes rapid changes in σ and ϵ at the low end of this frequency range, and the γ-dispersion causes rapid changes at the high end with relatively small changes in between.

The knowledge to be gleaned from this effort is directly related to the research effort of the Radiation Sciences Division at the School of Aerospace Medicine. Briefly, here studies are being currently conducted: (1) to determine radiofrequency radiation-induced effects in biological specimens, (2) to accurately determine the distribution of energy in the whole biological body or a particular organ, (3) to extrapolate response to radiation from the test animal to man in a meaningful manner, and (4) to contribute in the design of realistic safety standards with a sound scientific foundation.

ELECTRICAL PARAMETER DATA ON VARIOUS HUMAN BODY TISSUES

Schwan (8, 9, 10) has published much of the available data in this field. These data are published in various forms--in tables, in graphs drawn through available laboratory measurements, and in plots that appear to be based on equations derived from available data. On some graphs Schwan (8) shows the source of these measurements to be various studies dating from 1937 through 1956. Johnson and Guy (3) have published tables of values for (a) muscle, skin, and tissues of high water content and (b) fat, bone, and tissues of low water content, and state that tissues of intermediate water content will lie between the two listed groups. Other authors who print tables of values have used much of Schwan's data in addition to available new data from frequently unspecified sources.

Three methods are commonly used to obtain values of σ and ε for various tissues, as a function of frequency, from available data.

First, the available points can be plotted and a smooth curve drawn through the points. A table of values is then extracted from the curve and used for computing interpolated values at any frequency. This method yields the most accurate results, but for nearly all tissues investigated, the available points leave room for speculation in at least some parts of the frequency range.

A second method is to fit the available points to an equation. The equations utilized are derived from the work of Debye (1):

$$\sigma = a\left[\frac{1+b(f/f_o)^2}{1+(f/f_o)^2}\right]$$

$$\varepsilon = c\left[\frac{d+(f/f_o)^2}{1+(f/f_o)^2}\right]$$

where

f = frequency in GHz,

f_o = frequency in GHz associated with the high frequency inflection of the curve,

a, b, c, and d = constants for the tissue type.

Weil (12), Joines and Spiegel (4), some plots of Schwan (10), and local efforts show several disadvantages of this method. These equations attempt to fit data in the γ-dispersion area, and points in the frequency range 10-30 GHz are not available. The equations do not fit the observations well, but they are still useful in a narrow frequency range. From our experience with available data, this method seems to overemphasize the differences between tissues.

When only a few points in a narrow frequency range are available for a given tissue, a third method is used. A tissue for which values are available over the desired frequency range is selected as a base. The ratio of values for the base tissue to those for the tissue with few values is calculated for the frequencies measured. This ratio and the base curve are then used to calculate data at other frequencies. In our experience this method underestimates the differences between tissue types. Johnson and Guy (3) and Lin et al. (5) use this technique.

Data for the following discussion of electrical properties were gathered from the References and, after eliminating duplicated values, coded by the number of the source in the Reference List. In most cases the originator of the measurements is unknown. Some of the data were read from plots. Where a range of measured values, from one or several studies, was found in one reference, the midpoint of the range was recorded.

Primarily due to water content of the samples tested, the variations in measurements are less than 10% for most tissues; fat is a notable exception.

Muscle is the tissue with the most recorded data and the least variable data. The measured points and estimated mean curves for σ and ϵ of muscle are shown in Figures 1 and 2 respectively. These curves probably furnish the best base curves for estimating the electrical property values of other tissues with medium to high water content when sufficient laboratory measurements are missing.

Figures 3 and 4 show the measured points for skin. Johnson and Guy (3) print one table for muscle, skin, and tissue of high water content. Data from other sources indicated that σ and ϵ for skin are lower than for muscle. The curves drawn on these plots are 0.9 times values on the curves for muscle. Tinga and Nelson (11) show values for skin from different parts of the human anatomy. It is alleged that dura has properties similar to skin (7, 12), but no values for dura alone were found.

The available values for brain tissue in Figures 5 and 6 are too few in number and too scattered to define an adequate curve. Lin et al. (5) print new data for ϵ of the brain that are lower in value than the older data found. The plotted curves are for 0.658 times muscle values. This is consistent with the newer values of ϵ for brain tissues. Mathematical models of the human head show that small changes in these brain parameters cause large changes in the hot spots calculated. Schwan (9) states that red bone marrow has electrical properties similar to those of the brain, but no data for this tissue were ever found.

The electrical properties of whole blood, shown in Figures 7 and 8, are quite high since whole blood has a high water content. These properties vary with the cell counts for the blood sample tested. The curves plotted are 1.2 times muscle values for σ and 1.1 times muscle values for ϵ. The frequency response curves for blood are obviously different from those for muscle; however, the available points do not clearly define the correct curve at the ends of the frequency range.

Cerebrospinal fluid (CSF), Figures 9 and 10, is about 99% water and therefore has very high values for any frequency. The only values found are those published by Shapiro et al. (7) at 3,000 MHz and by Weil (12) at 1,000 MHz. CSF should have electrical properties similar to those of a physiological saline solution and those of the vitreous humor; the scanty data available for these substances do not help in establishing curves for CSF.

Of human tissues with low water content, fat and bone are of the greatest interest. Bone samples vary very little in water content and in values of σ and ϵ. Fat samples vary greatly in water content and therefore in electrical properties. The conductivity of fat varies much more than the dielectric constant--up to 5 to 1 ratio for different samples. Average values for fat and bone are very similar. Most references print one set of values for the two tissue types. Figures 11 and 12 show the values found and curves drawn through these points. These curves are well defined except at the low end of the frequency range. Schwan (10) states that yellow bone marrow has the lowest values σ and ϵ of all body tissues. The few values found do not differ significantly from the values for bone and fat.

Available values for the electrical properties of heart muscle, liver, spleen, kidney, and lung were examined and found to be insufficient for the development of the frequency response curves over the range discussed.

CONCLUSIONS

In summary, a study of the open literature in search of electrical parameter values of various body tissues yielded a few values that had to undergo careful scrutiny. The useful data gleaned was employed as input to a computer plotting routine. After many trials of data processing, a set of graphs, consisting of two graphs per human body tissue providing conductivities and dielectric constants, eventually emerged. The range of the frequency covered is 10-100,000 MHz. Because of the scarcity of measured values, particularly at the high and low ends of the frequency range where σ and ϵ vary rapidly, the curves for tissues of medium or high water content were drawn proportional to the curves for muscle, for which relatively extensive data exists. Values extracted from these curves give reasonable estimates of the interrelationships between various tissues over the frequency range of interest. Table 1 is an example of tissue difference at 800 MHz. As additional measurements become available, the electrical property tissue curves will be refined.

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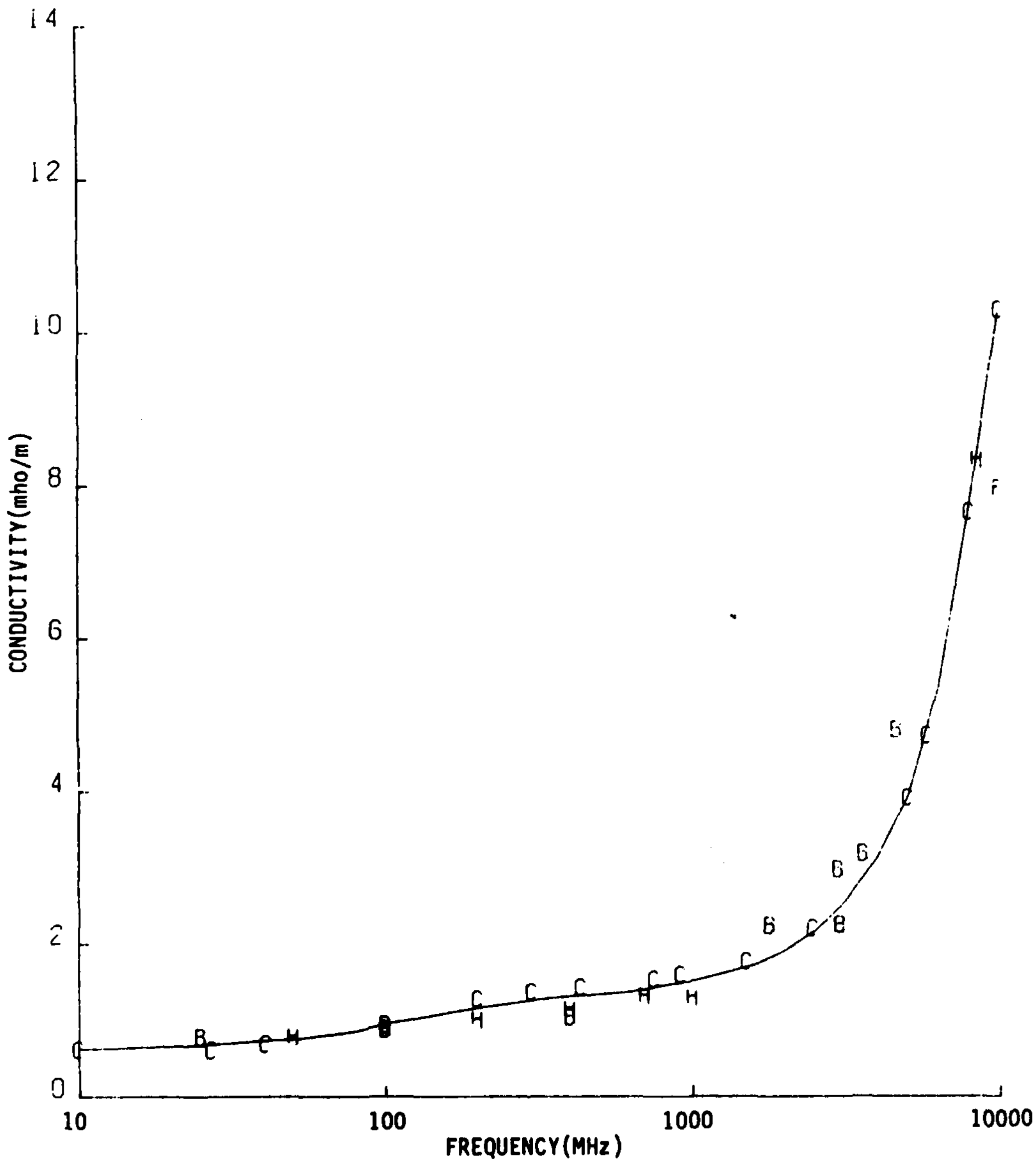

Figure 1. Conductivity of muscle as function of frequency. Temperature 37°C. Symbols B, C, F, and H refer to References 2, 3, 6, and 8, respectively.

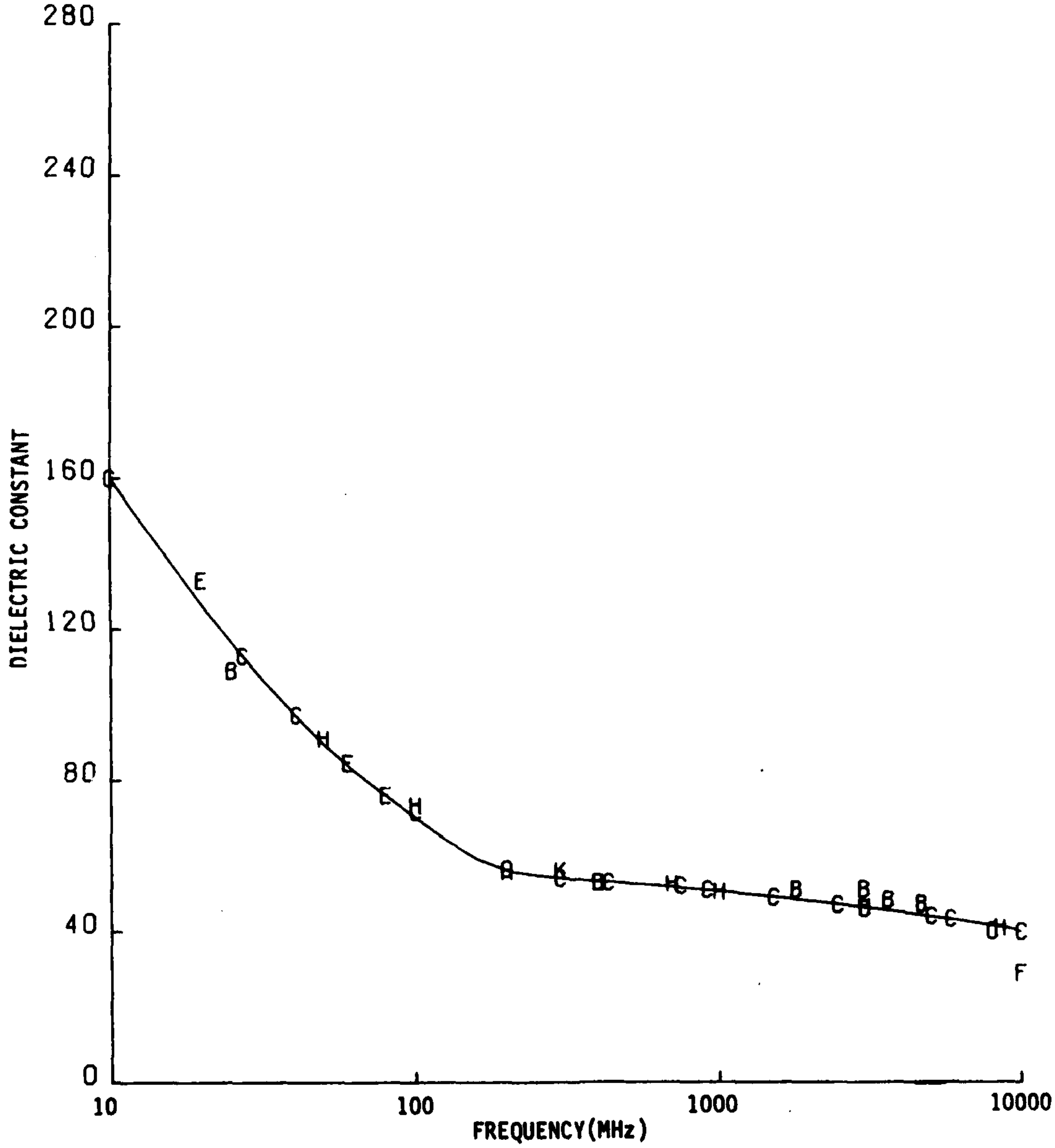

Figure 2. Dielectric constant of muscle as function of frequency. Temperature 37°C. Symbols B, C, E, H, and K refer to References 2, 3, 5, 8, and 11, respectively.

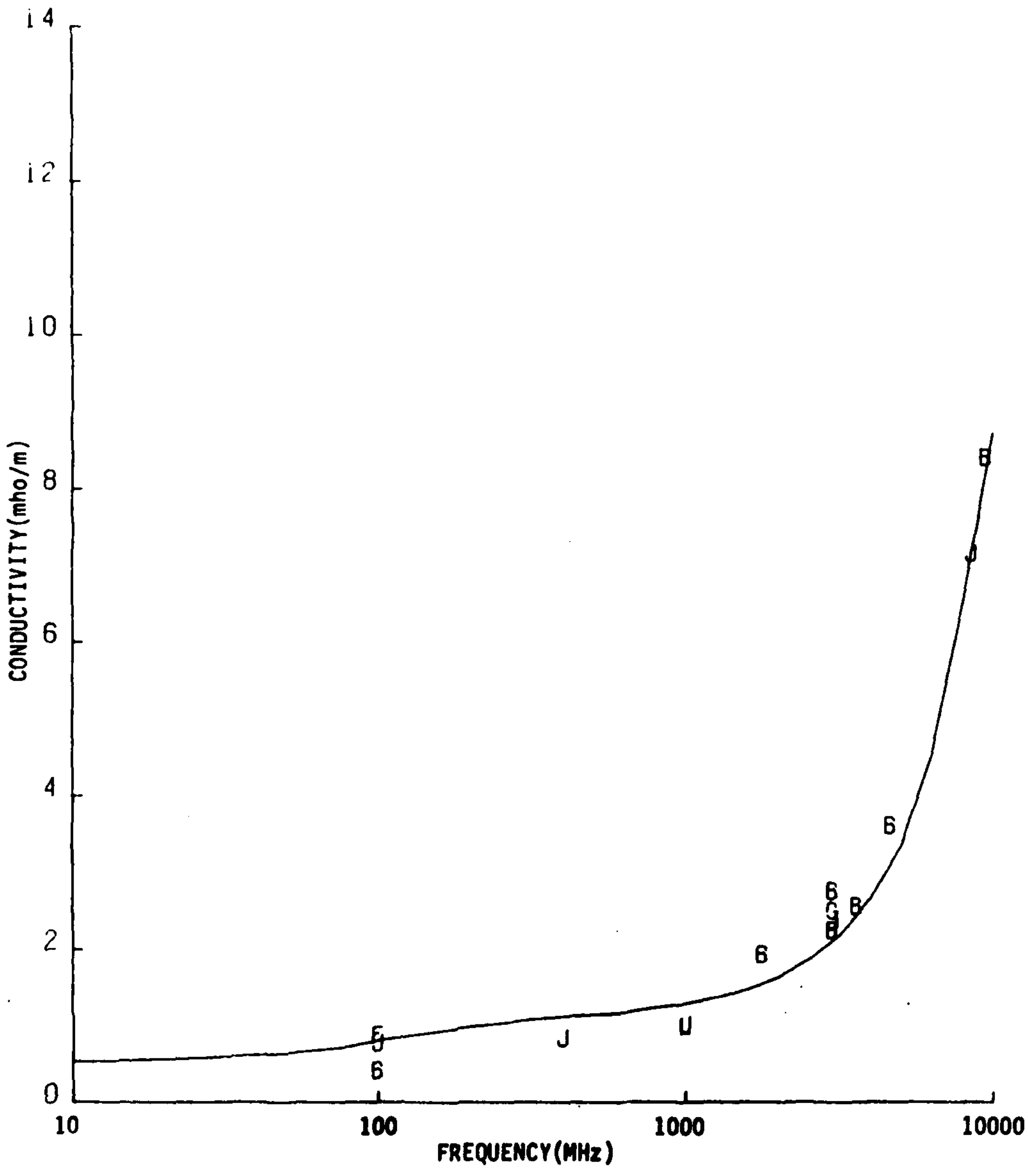

Figure 3. Conductivity of skin-dura as function of frequency. Temperature 37°C. Symbols B, F, G, J, and L refer to References 2, 6, 7, 10, and 12, respectively.

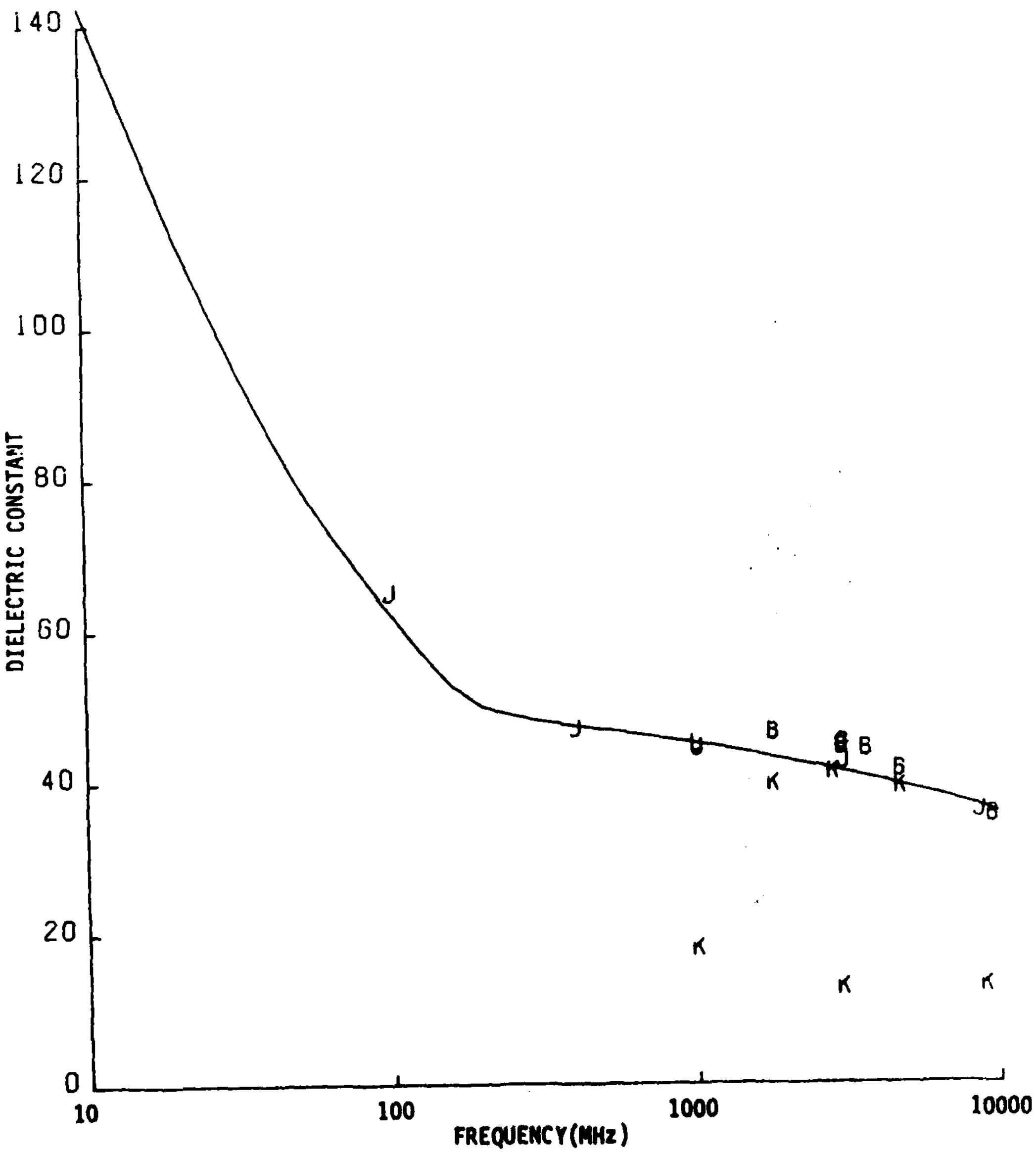

Figure 4. Dielectric constant of skin-dura as function of frequency. Temperature 37°C. Symbols B, G, J, K, and L refer to References 2, 7, 10, 11, and 12, respectively.

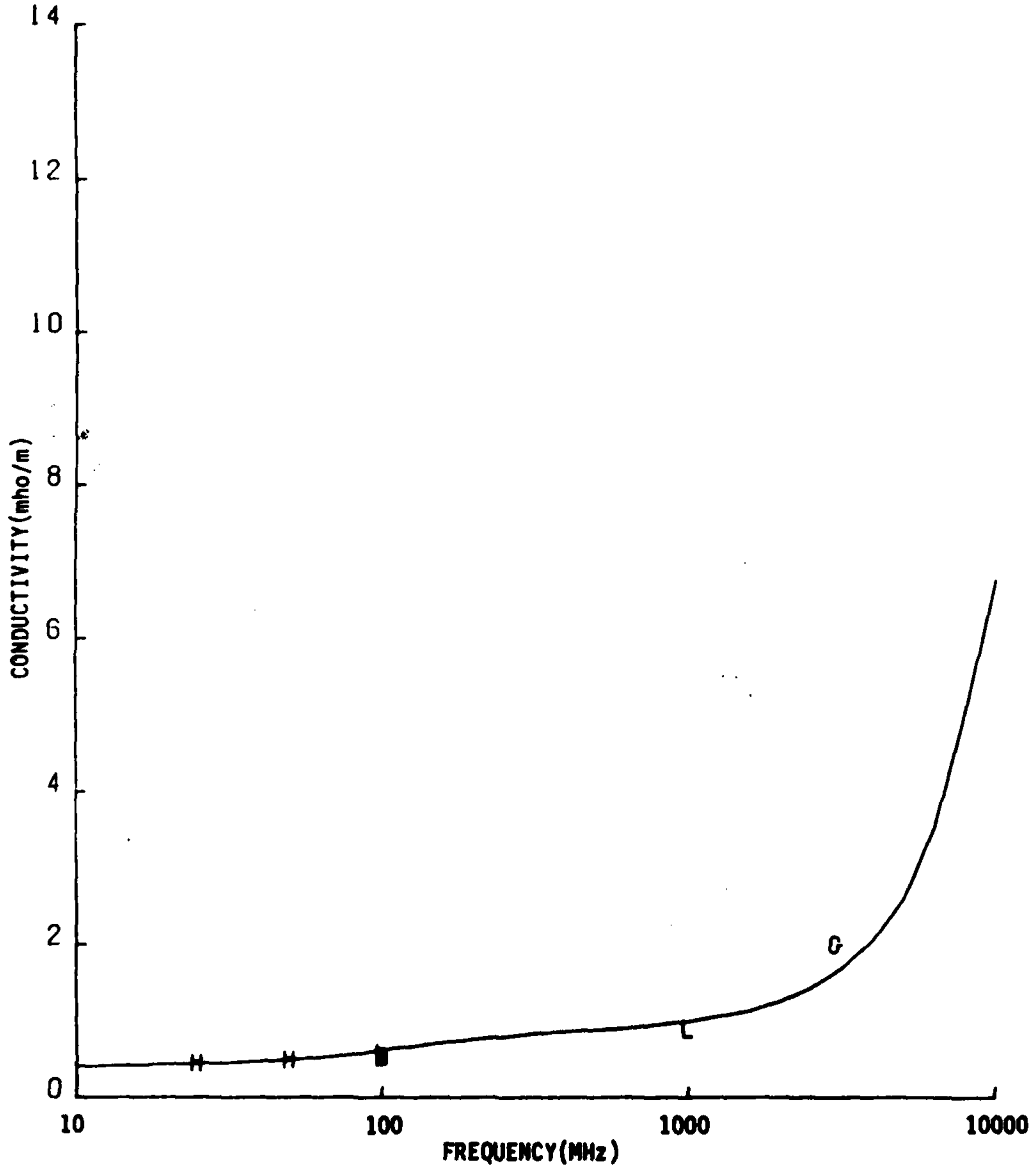

Figure 5. Conductivity of brain as function of frequency. Temperature 37°C. Symbols B, G, H, and L refer to References 2, 7, 8, and 12, respectively.

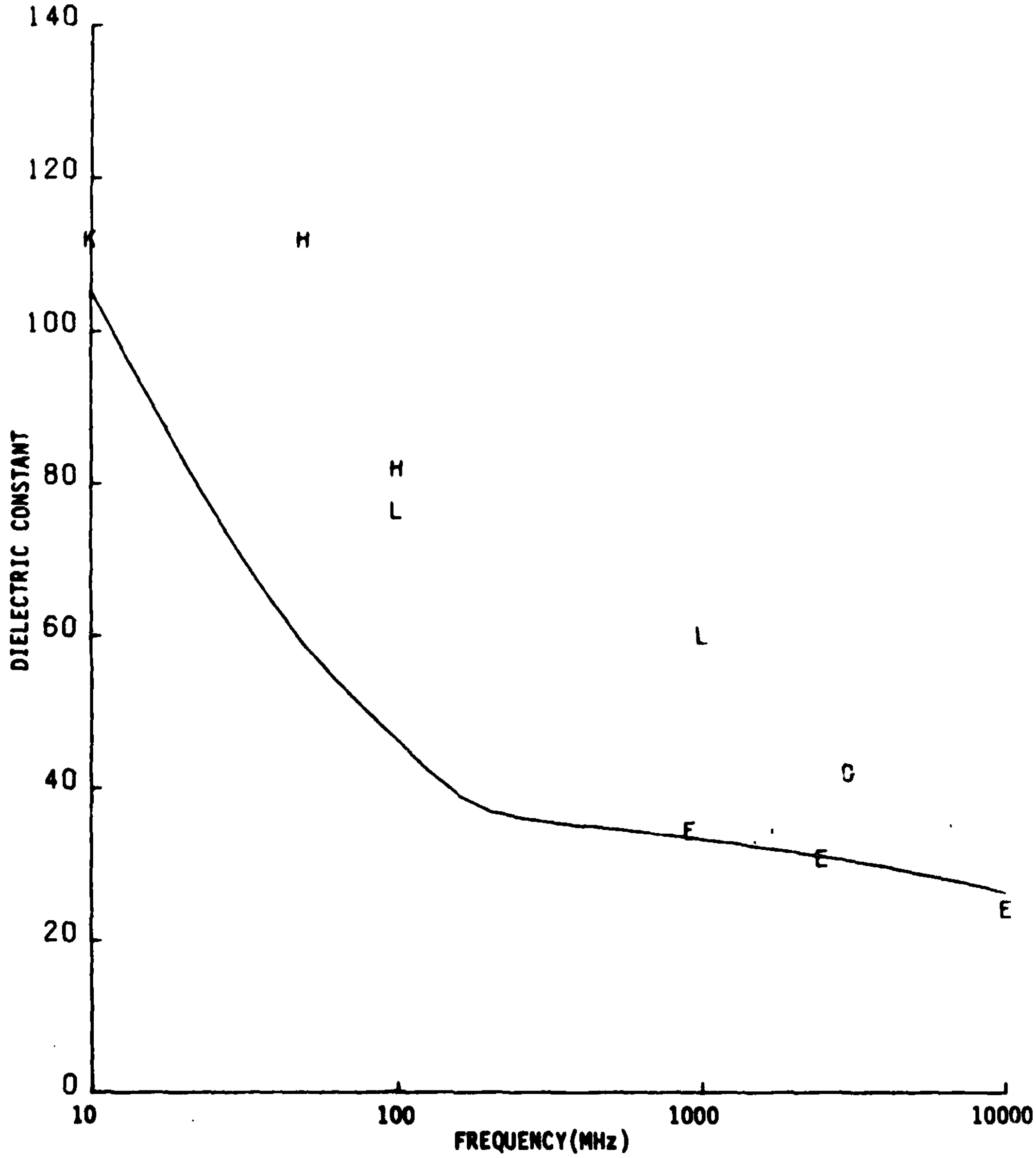

Figure 6. Dielectric constant of brain as function of frequency. Temperature 37°C. Symbols E, G, H, and L refer to References 5, 7, 8, and 12, respectively.

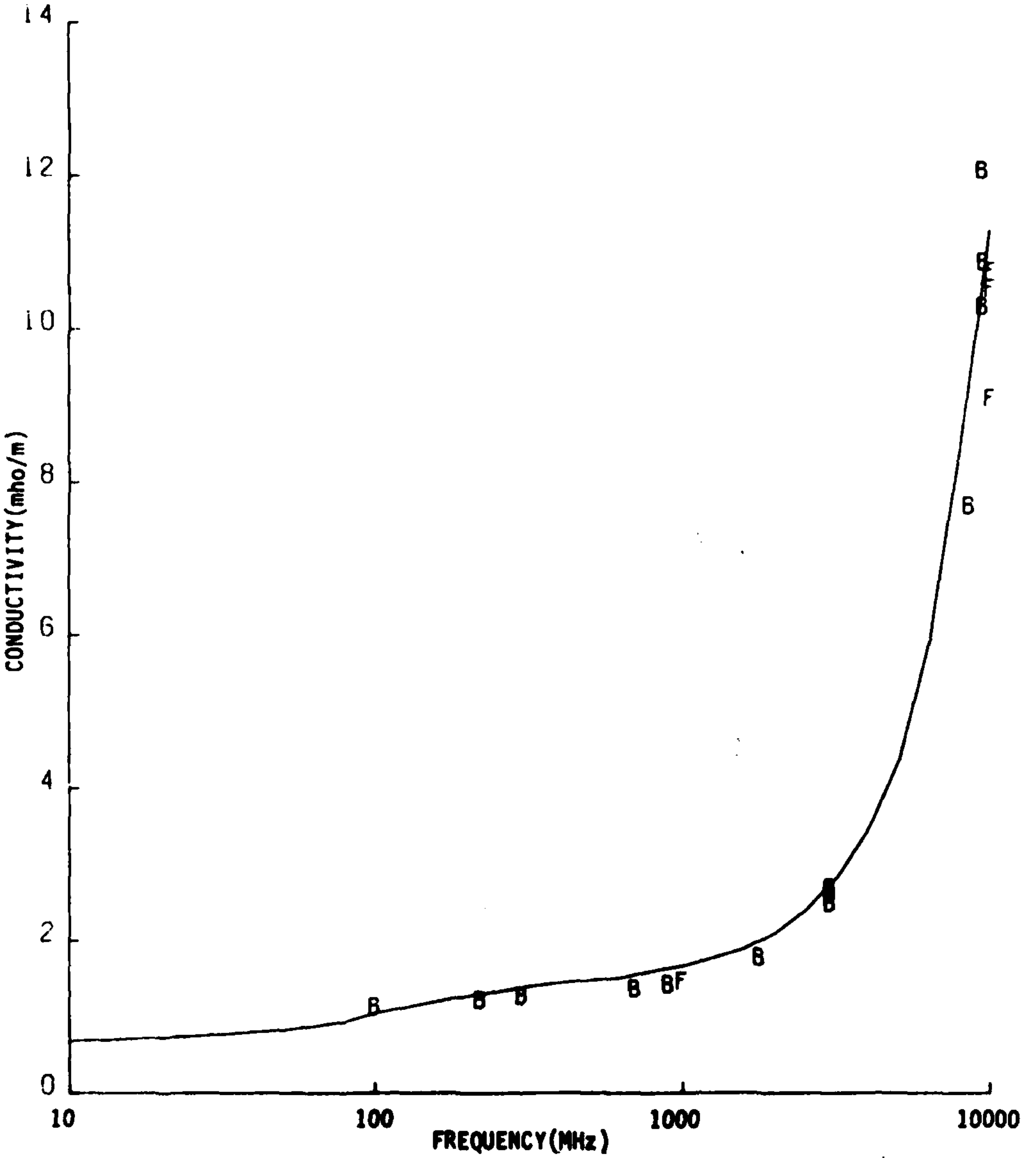

Figure 7. Conductivity of blood as function of frequency. Temperature 37°C. Symbols B and F refer to References 2 and 6, respectively.

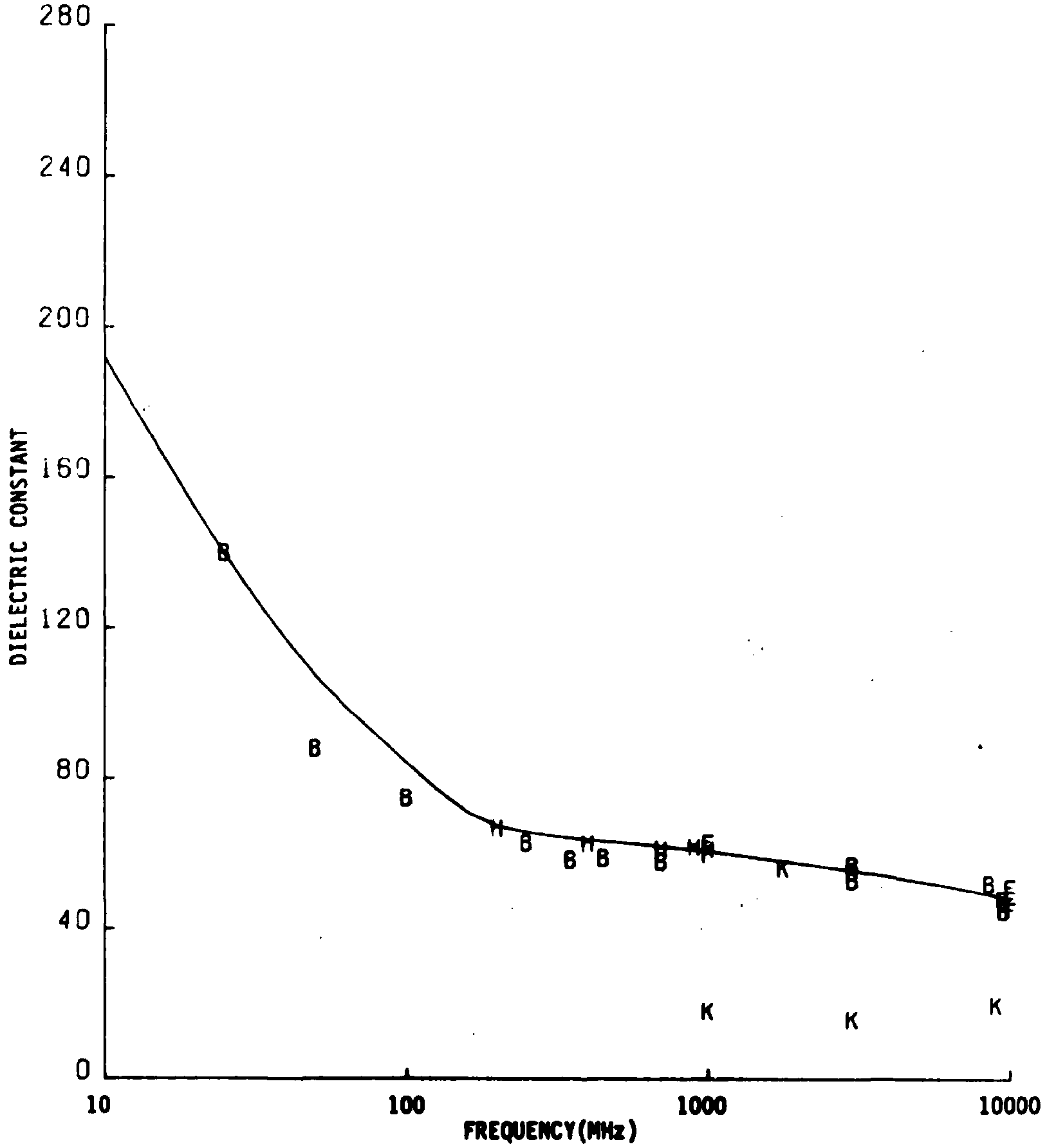

Figure 8. Dielectric constant of blood as function of frequency. Temperature 37°C. Symbols B, E, H, and K refer to References 2, 5, 8, and 11 respectively.

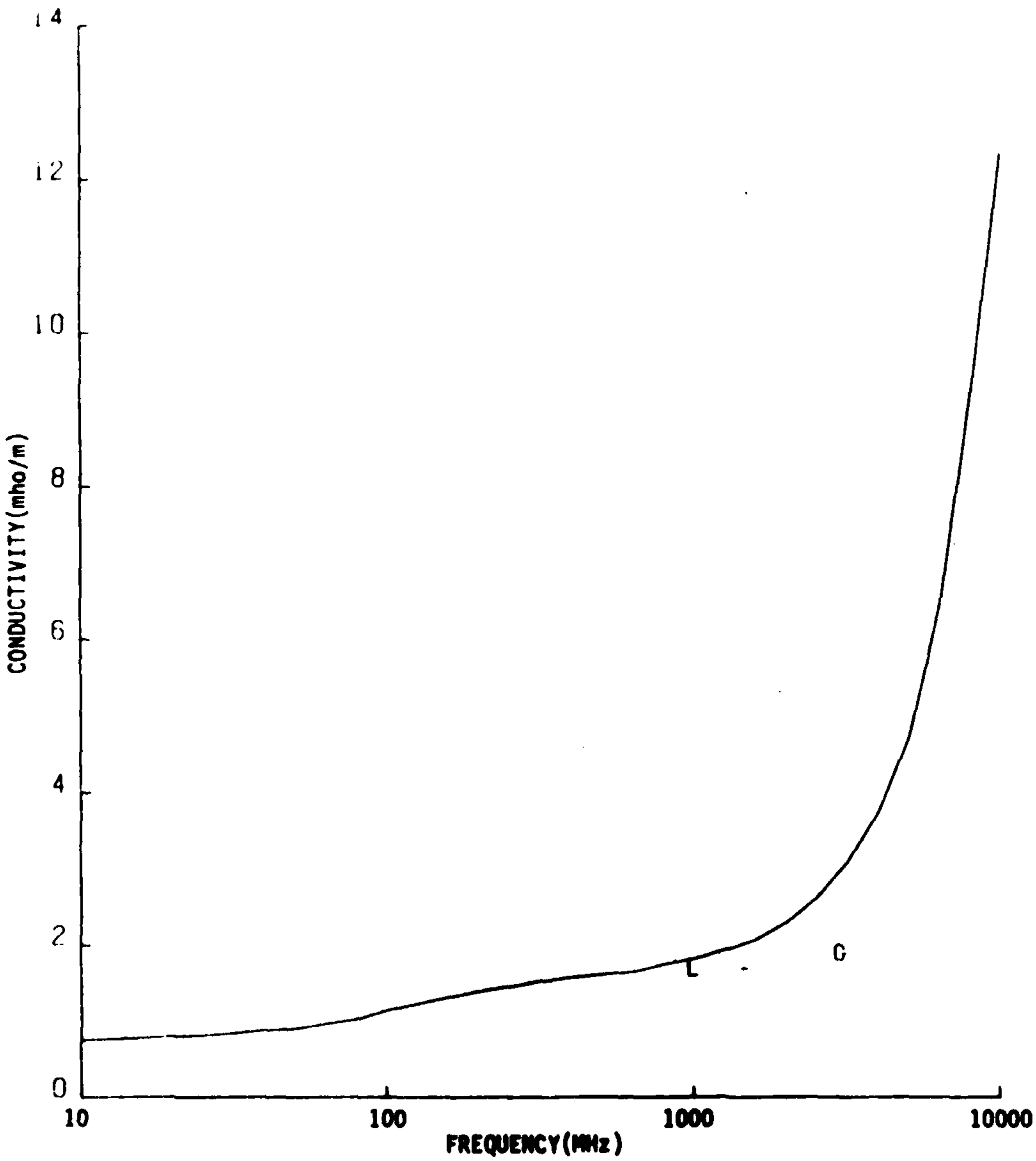

Figure 9. Conductivity of cerebrospinal fluid (CSF) as function of frequency. Temperature 37°C. Symbols G and L refer to References 7 and 12, respectively.

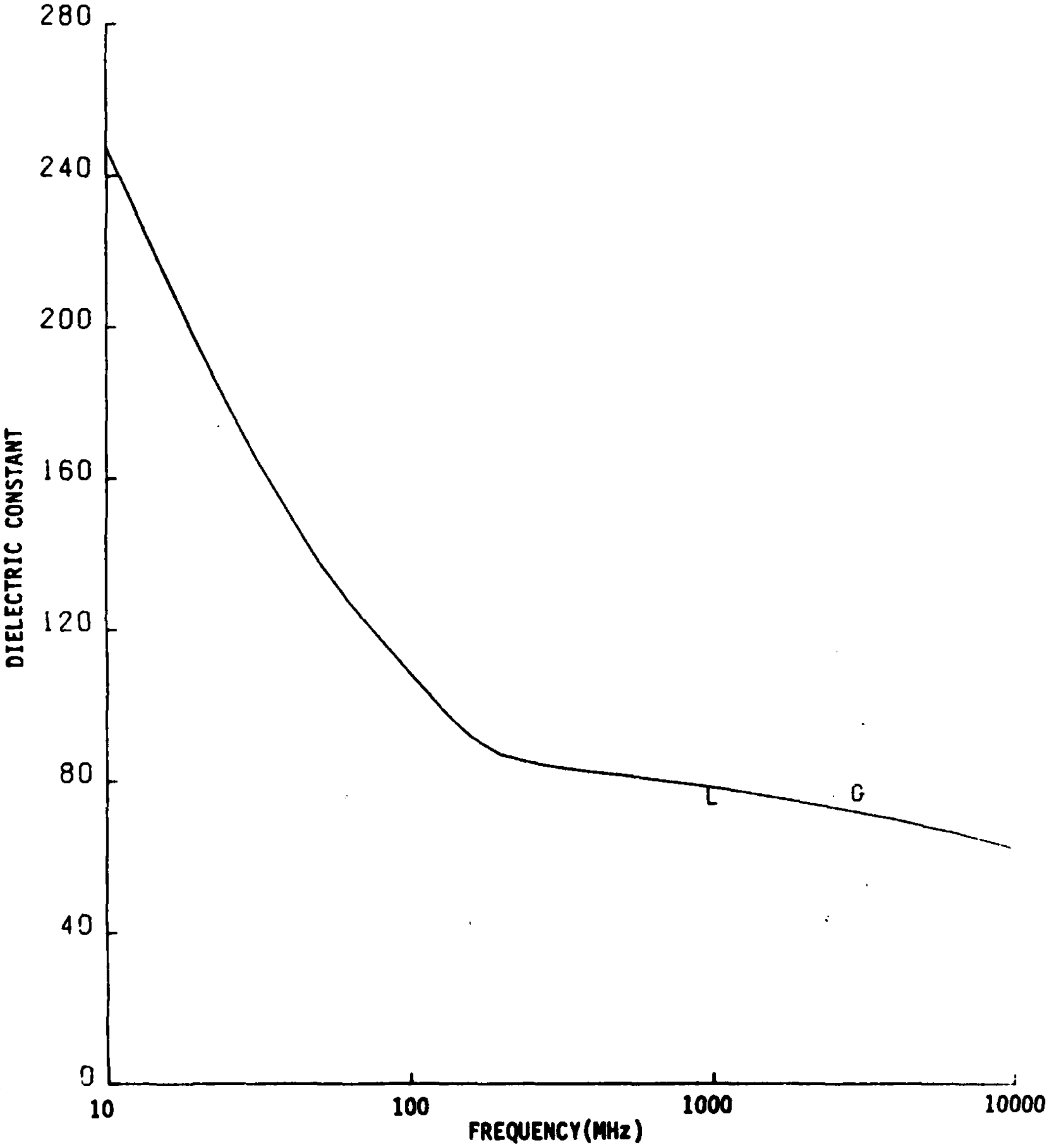

Figure 10. Dielectric constant of cerebrospinal fluid (CSF) as function of frequency. Temperature 37°C. Symbols G and L refer to References 7 and 12, respectively.

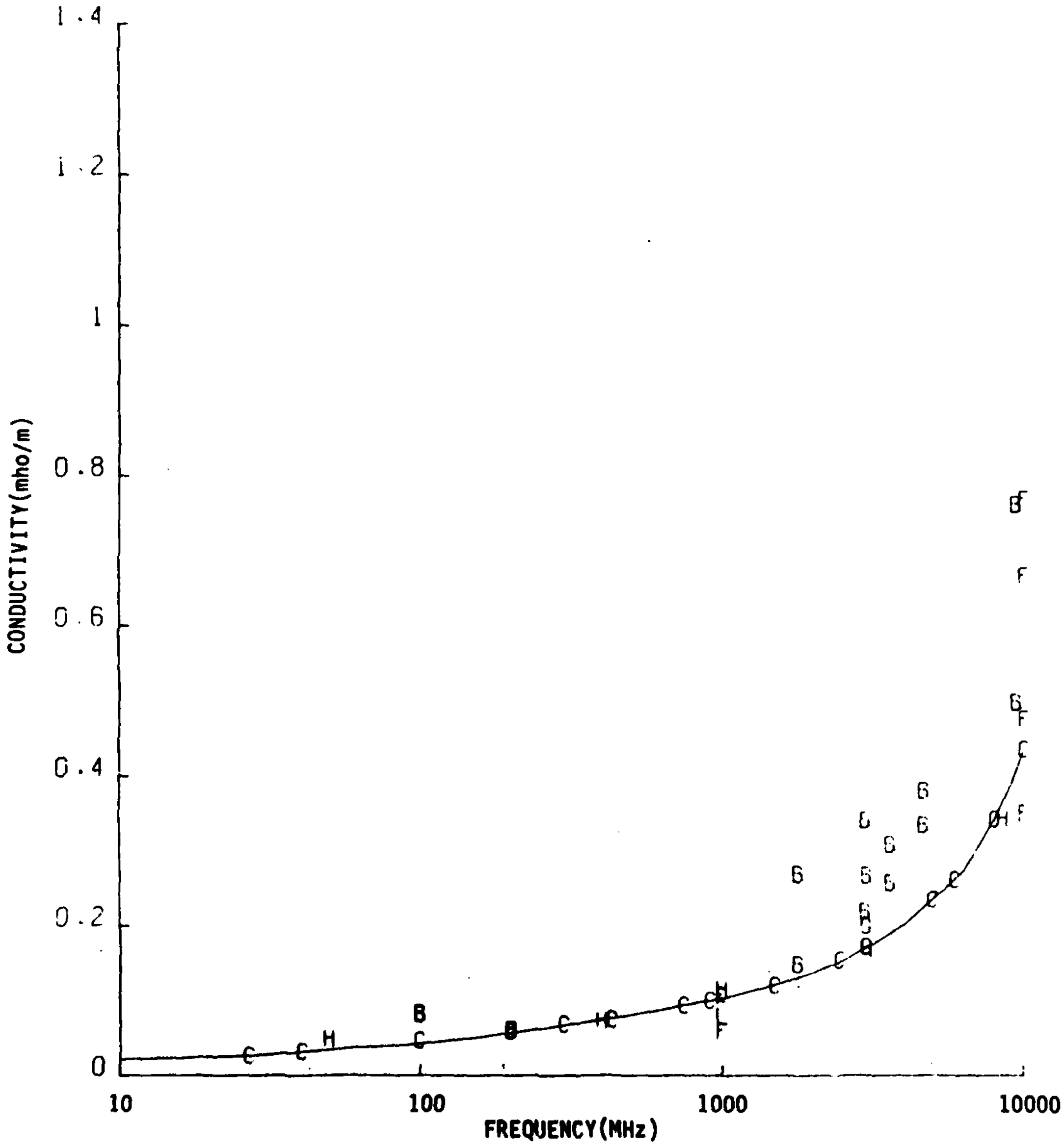

Figure 11. Conductivity of fat-bone-yellow bone marrow as function of frequency. Temperature 37°C. Symbols B, C, E, F, H, and L refer to References 2, 3, 5, 6, 8, and 12, respectively.

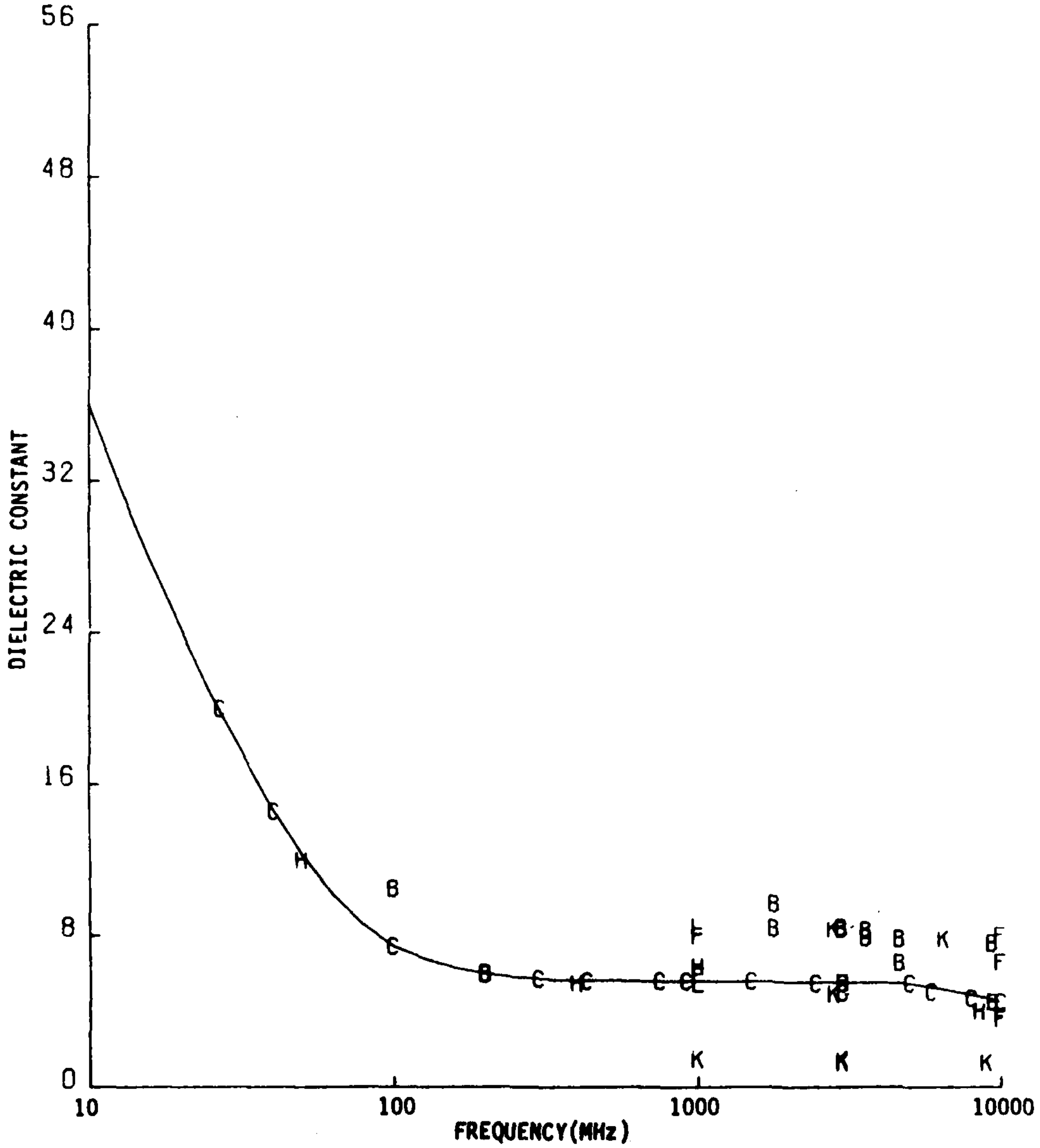

Figure 12. Dielectric constant of fat-bone yellow bone marrow as function of frequency. Temperature 37°C. Symbols B, C, F, H, K, and L refer to References 2, 3, 6, 8, 11, and 12, respectively.

TABLE 1. VALUES OF ELECTRICAL PARAMETERS OF HUMAN TISSUES EXTRACTED FROM APPROPRIATE CURVES

Tissue	Conductivity* σ (mho/m)	Dielectric Constant ε
Brain	0.96	33.76
CSF	1.74	79.47
Dura	1.23	45.64
Bone	0.096	5.61
Fat	0.096	5.61
Skin	1.23	45.64
Muscle	1.45	51.27
Blood	1.60	61.52
Yellow bone marrow	0.096	5.61

*At frequency 800 MHz and temperature 37°C.