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COMPILATION OF THE DIELECTRIC PROPERTIES OF BODY TISSUES AT RF AND MICROWAVE FREQUENCIES

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This report has been reviewed and is approved for publication.

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13. ABSTRACT *(Maximum 200 words)*

A database of dielectric properties of tissues has been compiled for use by the scientific community in solving electromagetic interaction problems. This has been achieved in the frequency rang 1 MHz to 20 GHz. Work is currently underway to extend it lower in frequency. During the course of the study new data have been obtained corresponding to bone and cartilage tissue. An analysis of a subsection of the data showed that it can be used to gain an insight into the nature of water in tissue.

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INTRODUCTION

At the onset of this project we had already achieved the following:

- Developed a dielectric measurement technique and established that its associated errors do not exceed 1% for standard liquids.

- Used the technique to perform dielectric measurements on muscle tissue and established a good agreement with the literature values in the frequency range 1 MHz to 20 GHz.

- Reviewed the significant literature on dielectric data and concluded that there remain gaps in our knowledge with respect of certain tissue types and, for most materials, with respect to certain frequencies.

In planning this project, it was thought worthwhile to measure most of the body tissues including those for which there are data. The literature values will provide a useful basis for comparison and analysis.

The following has been achieved in the period covered by this report:

- Over 25 tissue-types have been measured in the frequency range 1 MHz to 20 GHz. Most of the these were measurements on animal tissues carried out in vitro, at 20 and 37°C. Measurements were also made, *in vivo*, on accessible parts of the human body such as palm, sole and forearm skin. The data have been organised in a database in graphical and table form.

- A low frequency measurement technique has been adapted to accommodate tissue measurement. When implemented it extends the low frequency coverage down to 10 Hz.

- An in-depth analysis has been carried out on the dielectric properties of cortical and cancellous bone.

- An analysis has been carried out to characterise the high frequency response of the various tissues. Its conclusions allow the prediction of the dielectric properties at frequencies beyond the high frequency measurement limit.

A brief summary of these results are presented in this report.

EXAMPLES FROM THE DATABASE

The Dielectric Properties of Skin

These properties are important because skin is the interface through which physiological potentials can be monitored and the barrier through which external fields couple to the body.

The measurements reported here were all performed *in vivo* on the same subject. An important consideration in measuring the skin is the type of skin-electrode contact to be used. In previously reported work (Gabriel et al 1986) we used a smear of high conductivity gel to ensure a good contact. A dry contact was not favoured mainly because of its dependence on the pressure applied. This concern had to be balanced against the need for both dry and wet skin measurements in solving problems of external fields coupling.

Measurements reported correspond for the ventral forearm, the palm of the hand and the sole of the foot. Figure 1a and b show the permittivity and conductivity of the dry skin while the data for the wet skin are given in Figures 2a and b. The data for dry and wet skin from the forearm are compared in Figures 3a and b together with corresponding data from the literature. All the literature data pertain to human samples, The measurements of Cook (1951) and England (1950) were made on excised post-mortem tissue, the data of Schwan (1965) and Yamamoto and Yamamoto (1976) were obtained *in vivo*. The latter data correspond to the dielectric parameters of the stratum corneum and to the deeper granular layer.

The three dry skin-types investigated exhibit well defined RF and microwave dispersions centred in the megahertz and gigahertz regions respectively. In the case of palm and sole the dispersions are broader than those for the forearm skin, but they remain well defined. Wetting the skin results in a marked shift of the RF dispersion to lower frequencies and an increase in the magnitude of both dispersions. This is an interesting result that will be investigated further when the results are extended to lower frequencies.

There is one main problem concerning the measurement of skin at lower frequencies. Such measurements would require the use of a probe of similar design but larger than the one used at the higher frequencies. When measuring laminar samples, two probes of different sizes may not sample the same material unless their sampling volume falls largely within the same layer. We are currently modifying the design of the probe to accommodate this requirement.

The Dielectric Properties of Bone and Cartilage

A preliminary study of the dielectric properties of bone and cartilage established that, at microwave frequencies, their dielectric properties are higher than the values reported in the literature (Durney et al., 1986). Measurements on cartilage showed that it behaves almost as a soft tissues whereas it was previously assumed to be like bone (Sullivan et al., 1988).

Data on the dielectric properties of bone were first reported by England (1950) and Cook (1951). Both sets of measurements pertain to unspecified human samples obtained post-mortem or post-operative and machined to fit into a measurement cell. Altogether, the two studies report 6 measurements in the frequency range between 1 and 23 GHz.

The literature on bone was very thin in the 60's and early 70's (Marino et al. 1967, Lakes et al. 1977) until the increasing use of electrical stimulation in treating nonunion bones and the revelation of their piezoelectric nature led to a revival in interest in their dielectric properties (Reinish and Nowick, 1979, Chakkalakal et al., 1980, Kosterich et al, 1983 and 84, Reddy and Saha, 1984, de Mercato G. and F.J.Garcia-Sánchez, 1988, Saha S. and Williams, 1992). Most of these studies cover the kHz range, a few extend to 1 MHz or beyond.

These low frequency studies can be grouped into two categories on account of the treatment to which the bone samples are subjected to prior to measurements. In one type of study, the samples are allowed to dry and then rehydrate under controlled conditions (Marino et al. 1967, Lakes et al. 1977, Reinish and Nowick, 1979). In the second type, the dielectric properties of fluid saturated bone were measured. To maintain the fluid saturation the samples are either soaked in a physiological buffer (Kosterich et al, 1983, Reddy and Saha, 1984, and Saha S. and Williams, 1992) or drained of their natural fluid first then soaked in a buffer or salt solution.

These studies were inspired by the need to understand the role of electrical stimulation in bone healing, consequently they were all carried out on samples of cortical bone from animal or human limbs. Skull bone is very different, being triple laminar in structure and made from two types of bone, compact and cancellous, the dielectric properties of which have never been reported.

Figure 4 shows measurements made on the surface of skull and jaw bones. The surfaces were prepared for measurement by removing all membranes. A naturally flat region was selected to ensure contact with the probe. Good contact was maintained by applying constant pressure at the probe sample interface. No wetting agent was used. The high frequency probe, being under 3 mm in diameter, was relatively easy to use compared to the 7 mm probe used for the low frequency measurements which requires a larger flat area so that there were fewer regions from which such samples could be obtained. As previously discussed, two probes of different sizes may not sample the same representative of the laminar bone material unless their sampling volume falls largely within the same layer, the matter is further complicated by a frequency dependence of such a volume. In practice, however, this condition would be largely fulfilled if the cortical layer is 2 to 3 mm thick.

It is interesting to compare the results for cortical bone to the values reported in the literature surveyed. The results of Kosterich (1983) were described as having been obtained under "near normal physiological conditions", the samples were immersed and measured in either Hank's solution or in normal saline, the results extend to 8 MHz and generally agree with the other studies on wet bone that were carried out at and below 1 MHz only. The data from Kosterich et al (1984) are included to illustrate the properties of fluid saturated bone where the bone fluid was replaced by salt solutions of different concentrations. The latter results (Figure 4) are characteristic of their type and illustrate the conclusions drawn by the authors that the conductivity of the fluid dominates the dielectric properties of the bone samples so treated. The data from Mercato and Garcia-Sanchez (1988) are also shown at 1 MHz, they pertain to cortical and cancellous samples from bovine femur and are therefore of sufficient interest to include in this comparison. Finally, the results of England (1950) and Cook (1951) are also shown in Figure 4. From 2 to 5 GHz (Cook 1951) the permittivity values are lower than our measurements, it should however be noted that Cook's values are based on just one sample. The two points at higher frequencies (England 1950) are in good agreement with our measurements. The corresponding conductivity values are significantly lower than our measurements. This may well be due to a discordance in their data as noted by Cook (1951) with respect to his and England's results.

In conclusion, the data in Figures 4a and b confirm our preliminary findings on the dielectric properties of bone. The new data agree satisfactorily with the existing literature at higher and lower frequencies when the type of bone and the treatment it has undergone are taken into consideration. The data for cortical and cancellous bone are given in Figures 5a and b.

Although there are no literature data to compare it with, measurements across the frequency range on tissues from three animals confirmed our original findings that cartilage behaves as a high water content tissue (Figure 6).

Dielectric Properties of Liver and Kidney Tissue

It is our intention to extend the measurement of the dielectric properties of tissue to frequencies below our current limit of 1 MHz. This will be carried out on an impedance analyzer with a nominal frequency range of 10 Hz to 10 MHz. Measurements over the whole frequency range have been carried on some tissues. The results for liver and kidney tissues are given in Figures 7 and 8 in the frequency range 100 Hz to 20 GHz. These results were selected to exemplify some of the outstanding problems in interfacing the data obtained using two different experimental techniques in the frequency range 1 and 10 MHz. It should, however be noted that these results are in fairly good agreement with the corresponding values in the literature.

DATA ANALYSIS

The Dielectric Dispersion of water in Tissue

One of the aims of this project is to derive models for the frequency dependence of the dielectric properties of the tissues investigated. The basis of the analysis will be the well known dispersions in the dielectric spectrum of biological materials and their expression as a summation of terms corresponding to the main polarisation mechanisms. The spectrum extends from Hz to GHz and the full analysis will be carried out when the low frequencies measurements are completed. The data available so far enabled us to carry out a preliminary study of the high frequency dispersion.

At frequencies in excess of a few hundred MHz, the dipolar orientation of the water molecules is the dominant polarisation mechanism. The frequency dependence of the complex permittivity may be expressed as

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{1-\alpha}} + \frac{\sigma}{j\omega\varepsilon_0}$$

which is the well known Cole-Cole equation where $j = \sqrt{-1}$, ε_∞ is the permittivity at field frequencies such that $\omega\tau >> 1$, and ε_s the permittivity at $\omega\tau << 1$ and α is the distribution parameter, σ is the ionic conductivity and ε_0 is the permittivity of free space.

Some of the data at 37 and 20°C were fitted to the above equation to yield the parameter in Tables 1 and 2 respectively. For all tissues the value of ε_∞ is determined by the response at frequencies in excess of those reported here. For the purpose of this analysis the ε_∞ was given an estimated value of 2.5 for bone and 3.5 for all other tissues. The parameters for pure deionised water have been included in the table for comparison purpose.

It can be seen from Tables 1 and 2 that the value of the distribution parameter α is significant for most tissues and negligible for body fluids (as exemplified by aqueous humour). The relaxation time τ is generally longer than the corresponding value for water indicating a decrease in the rotational ability of tissue water molecules due to the organic environment and its interaction with tissue water. This effect is not manifested in body fluids in view of their low organic content.

Such analysis will serve as a basis to study the nature of water tissues and particularly bone cartilage because they have not been sufficiently investigated.

CONCLUSIONS

The main purpose of this project is to compile a database of dielectric properties of tissues for use by the scientific community in solving electromagnetic interaction problems. This has now been achieved in the frequency range 1 MHz to 20 GHz. Work is currently underway to extend it lower frequencies.

During the course of the study new data have been obtained corresponding to bone and cartilage tissue.

An analysis of a subsection of the data showed that it can be used to gain an insight into nature of water in tissue. This is still an undefined matter despite being a much studied subject. A comprehensive study based on a large number of tissues as in this project is bound to shed new light on the matter.

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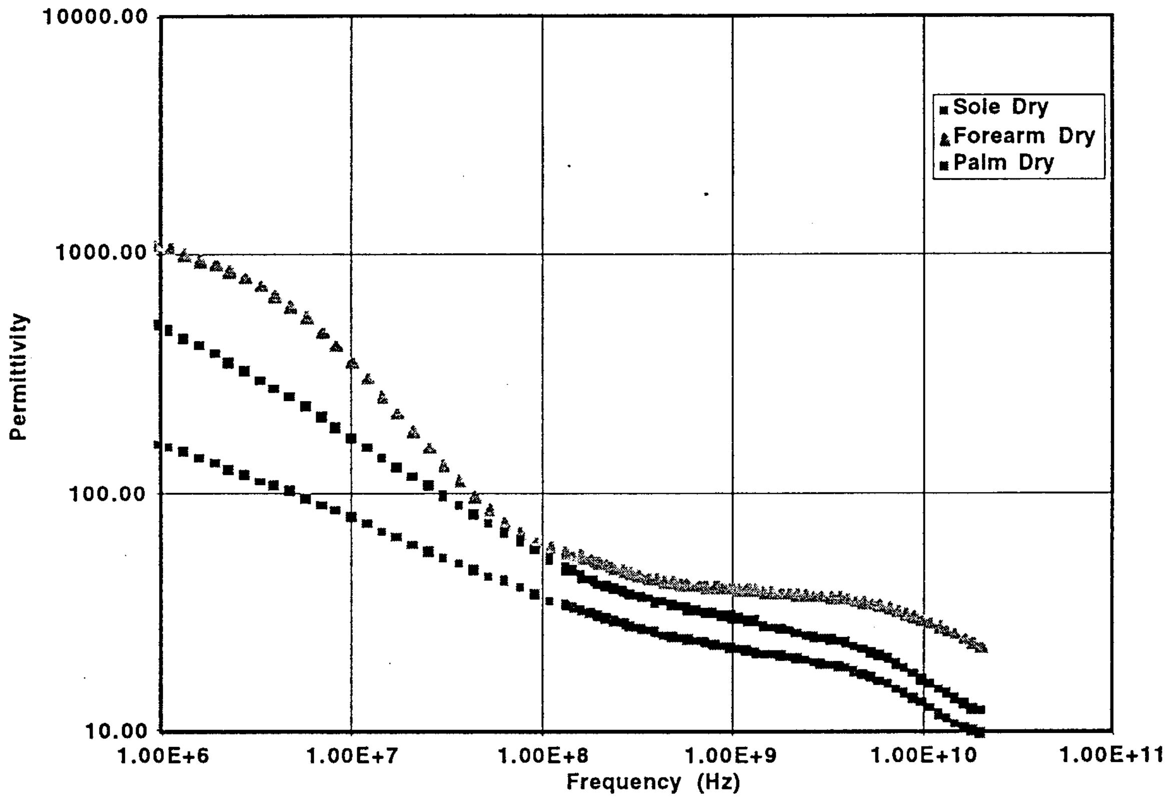


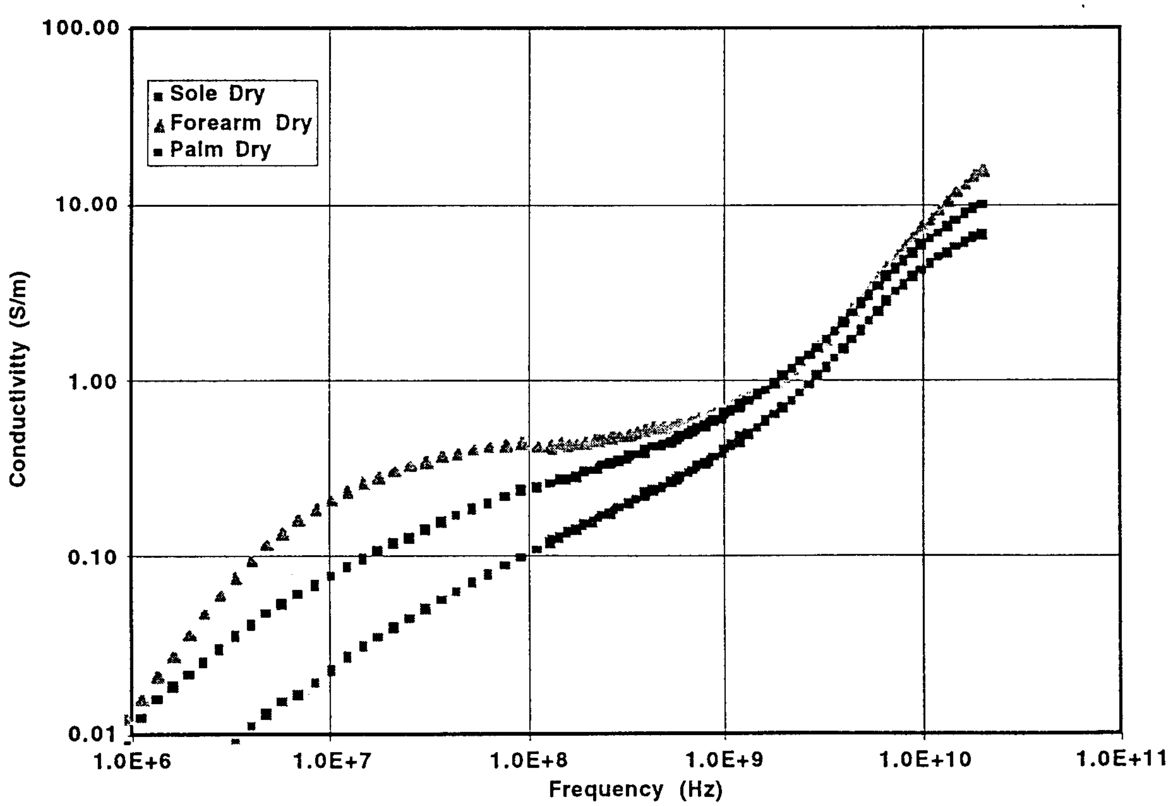


Figure 1 The permittivity and conductivity of dry skin measured *in vivo*.

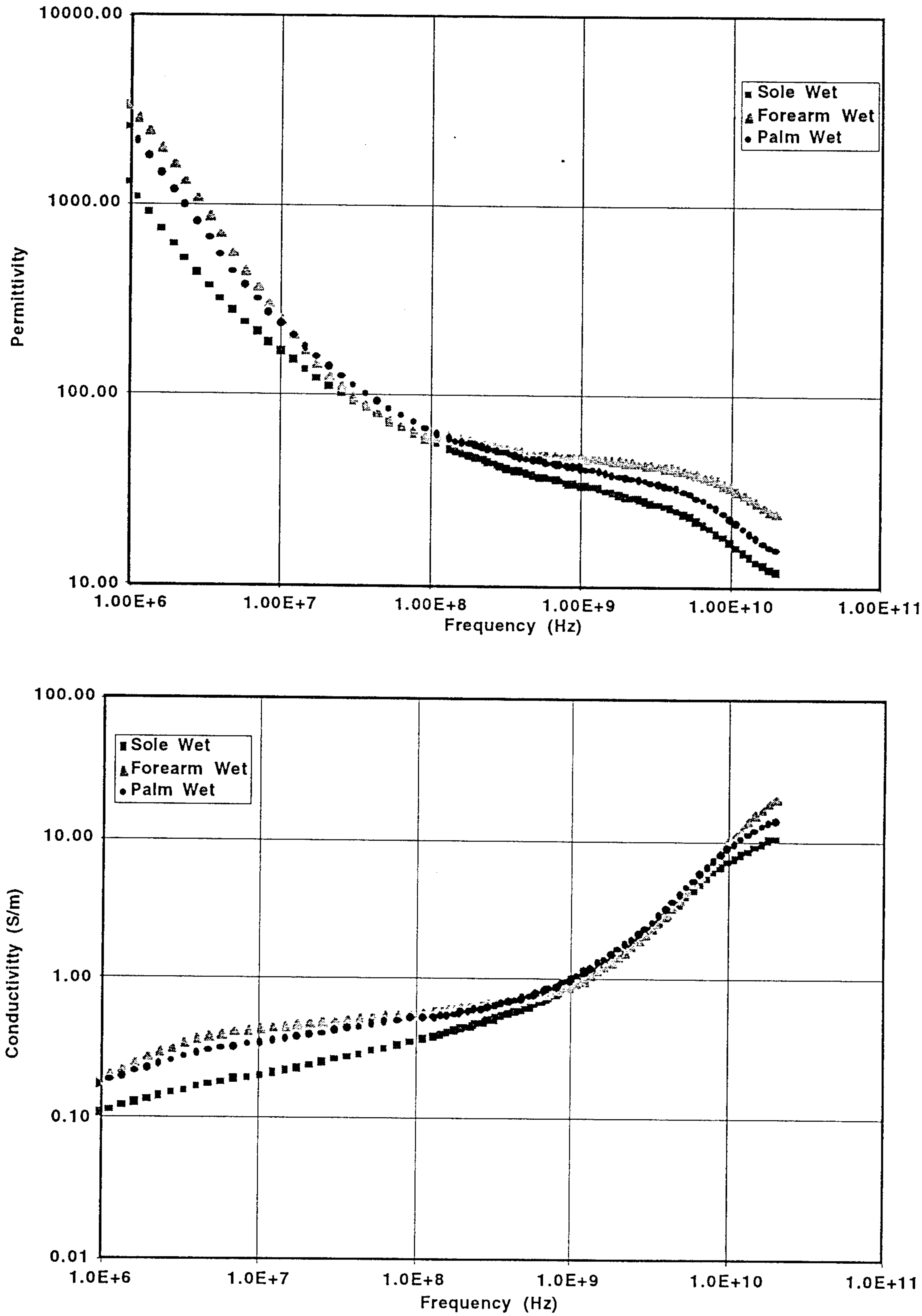
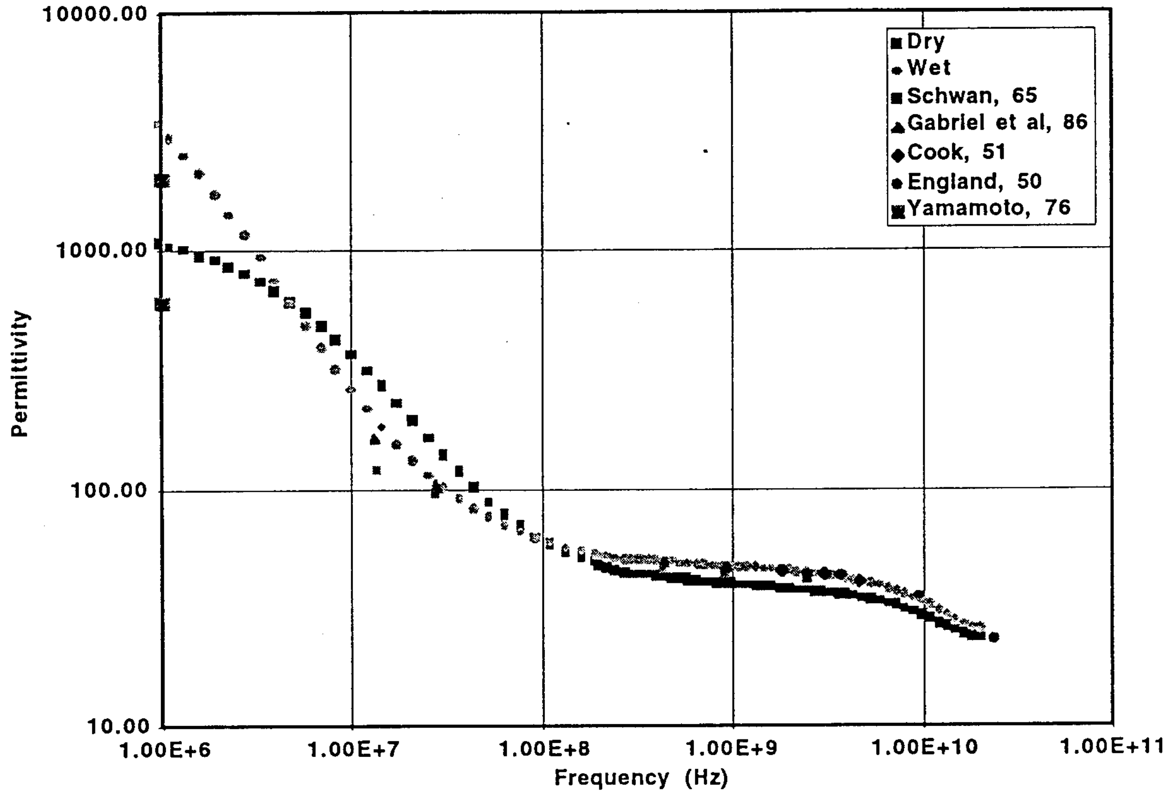


Figure 2. The permittivity and conductivity of wet skin measured *in vivo*..



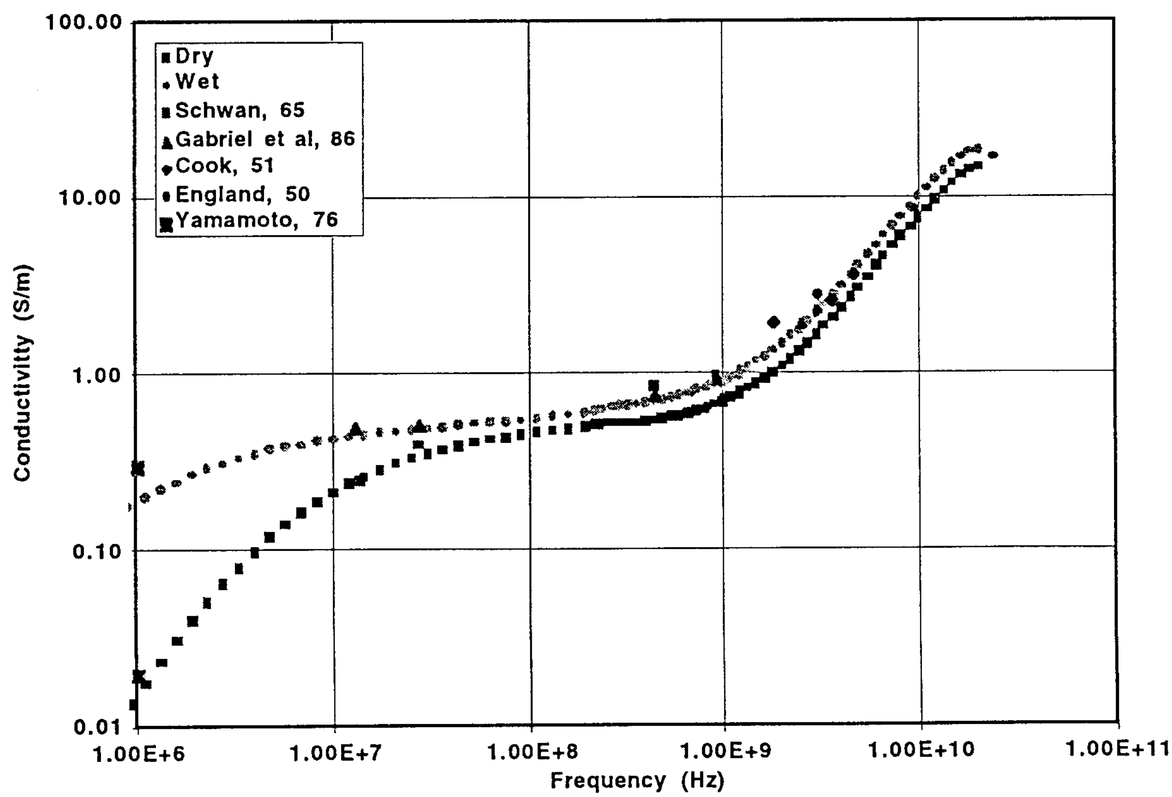
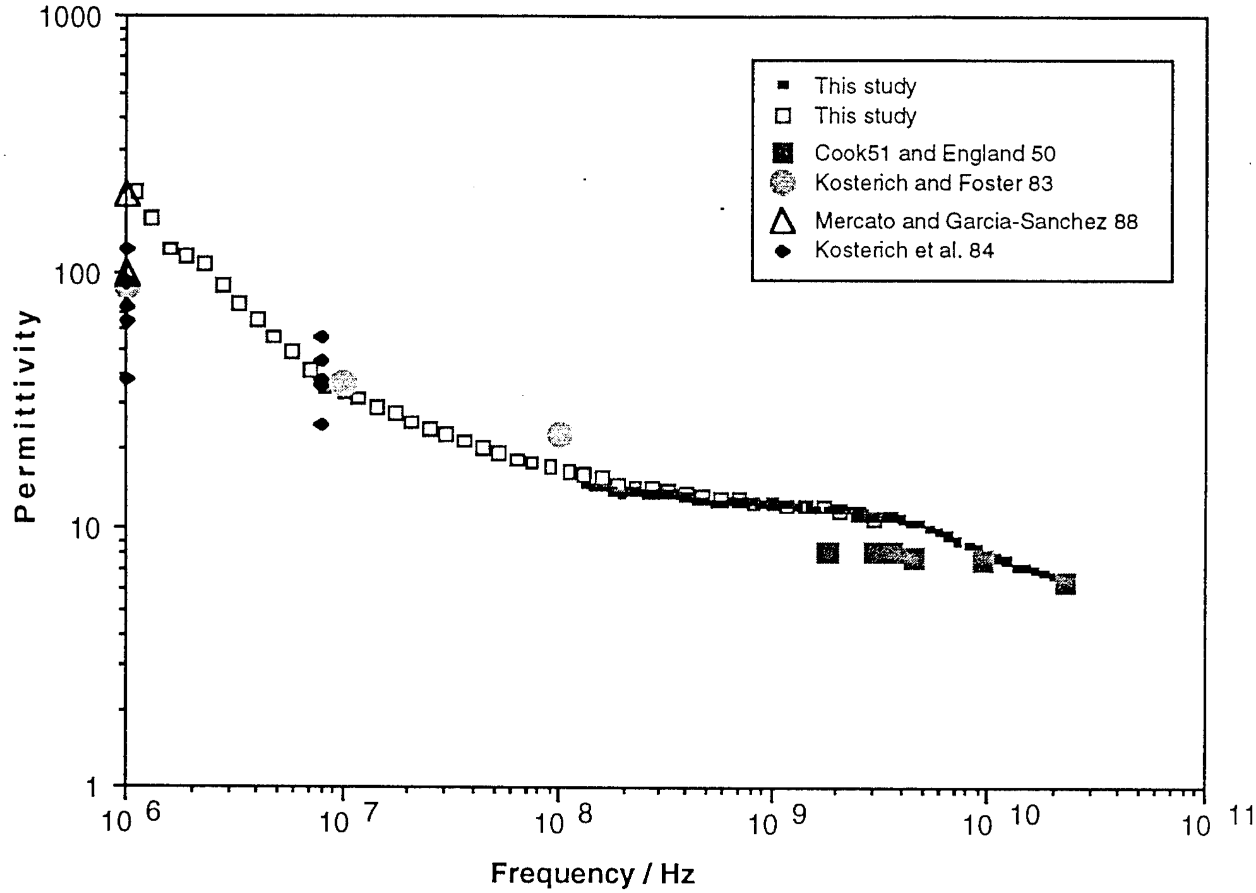


Figure 3. The permittivity and conductivity of dry and wet skin from the forearm compared to values from the literature.



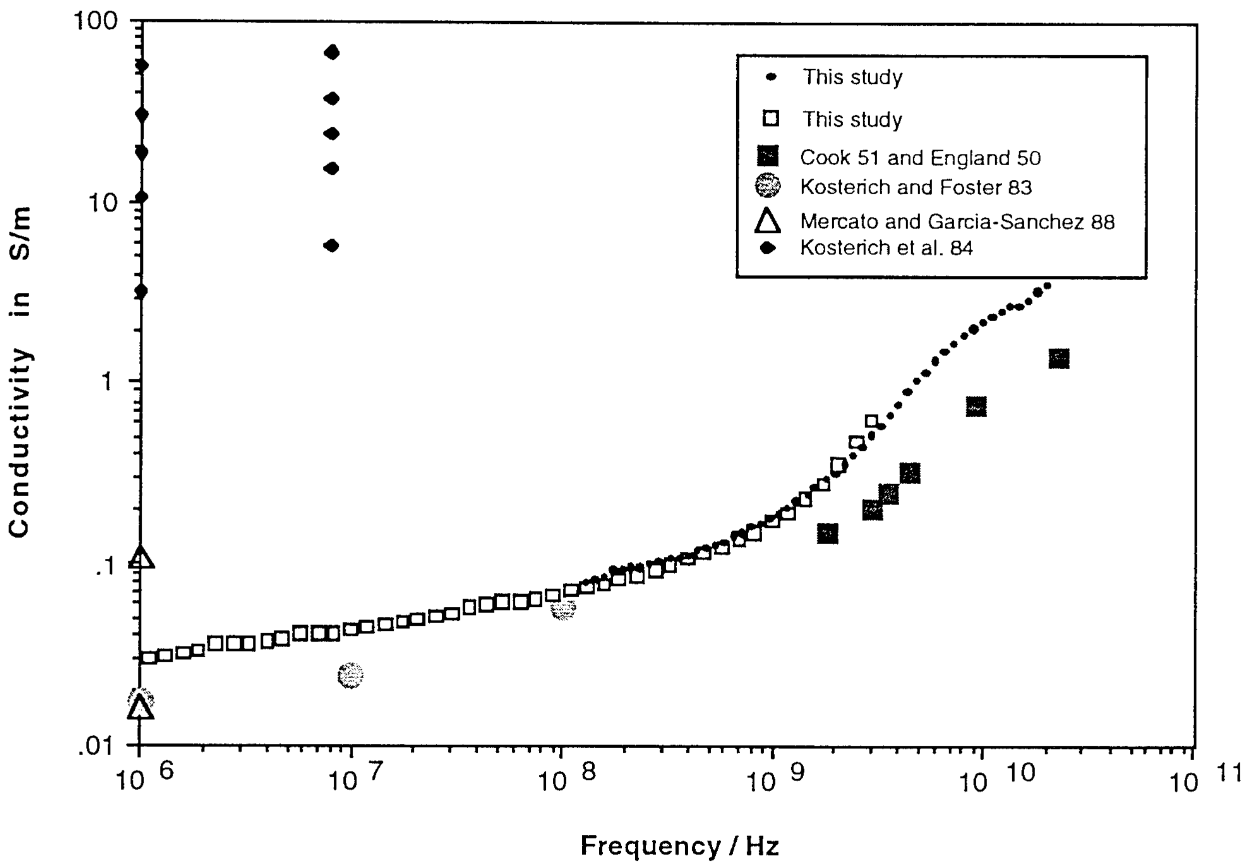


Figure 4. The permittivity and conductivity of cortical skull bone .

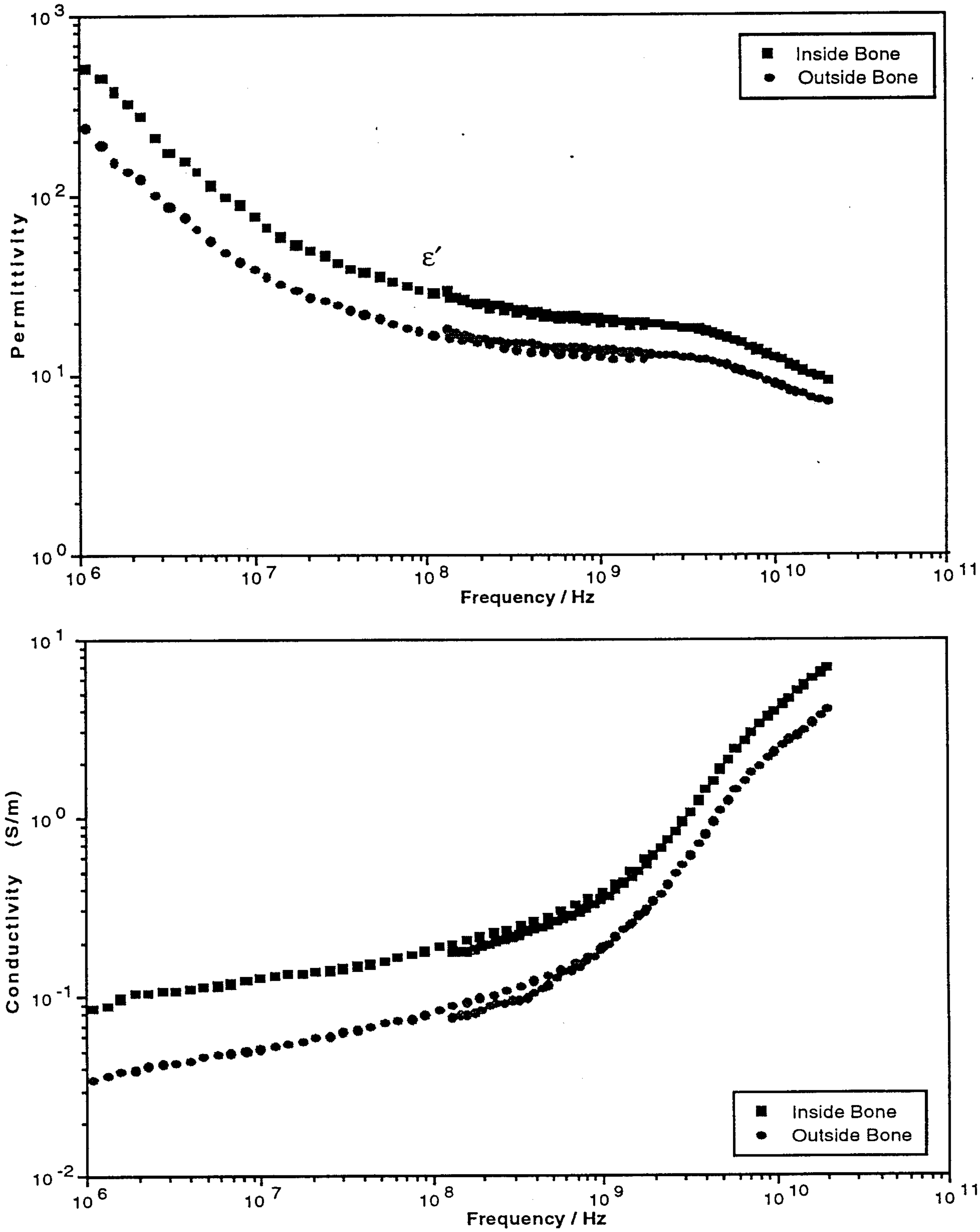


Figure 5. The permittivity and conductivity of cortical and cancellous skull bone.

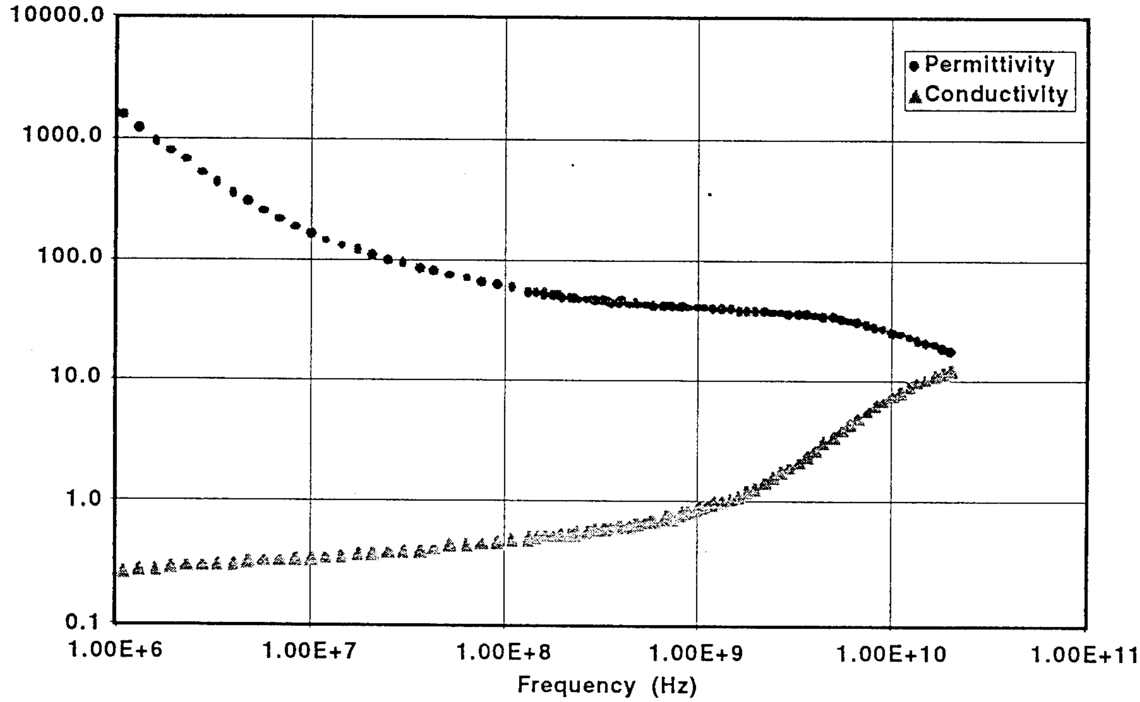


Figure 6. The permittivity and conductivity of cartilage from the septum of the nose.

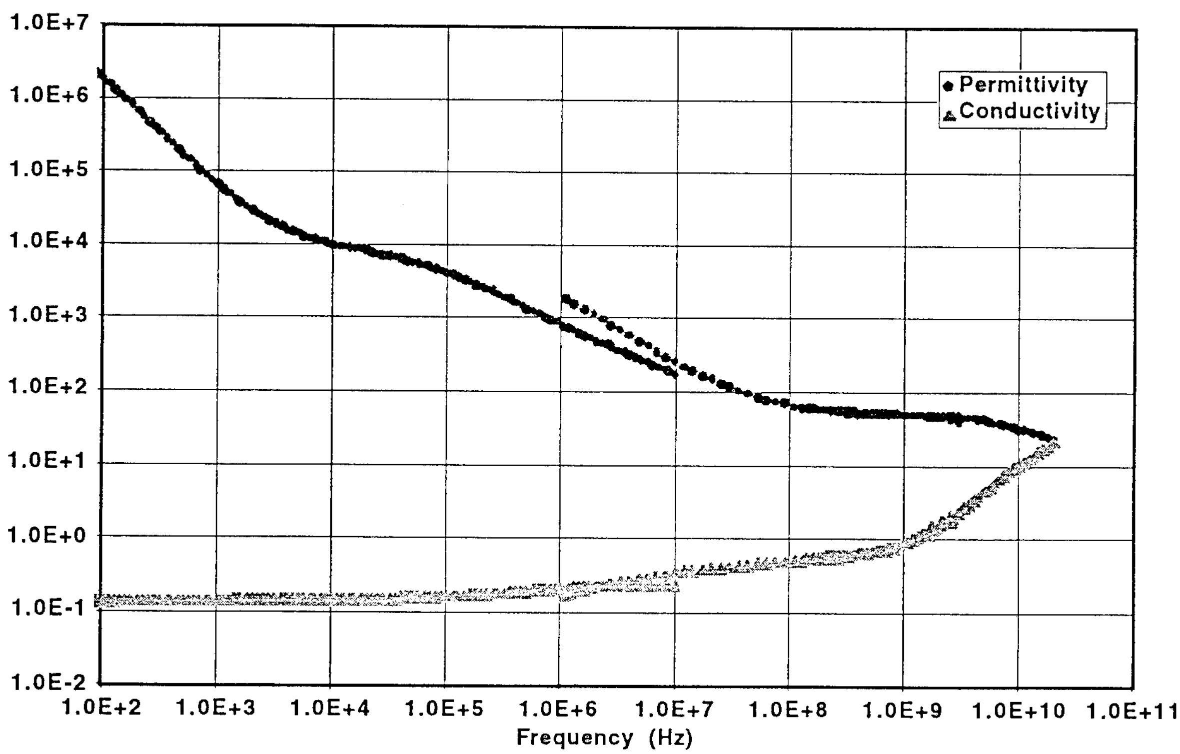


Figure 7. Permittivity and conductivity of liver tissue over the whole experimental frequency range

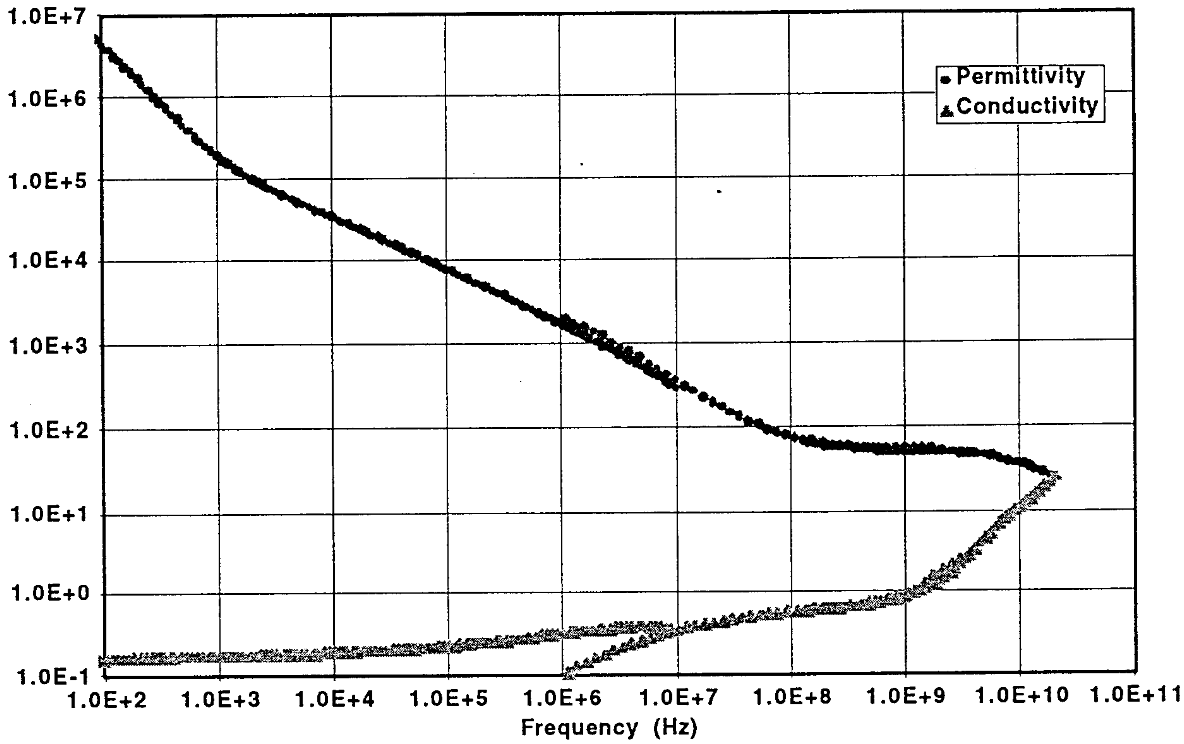


Figure 8. Permittivity and conductivity of kidney tissue over the whole experimental frequency range

TABLE 1. Dielectric parameters of water dispersion in tissues obtained by analysis of the experimental results at 37°C. The Δ terms correspond to the 95% confidence interval.

Tissue	ε_S	$\Delta\varepsilon_S$	τ (ps)	$\Delta\tau$ (ps)	α	$\Delta\alpha$	σ (Sm^{-1})	$\Delta\sigma$ (Sm^{-1})
Bone (cortex)	14.9	0.16	13.8	0.48	0.26	0.01	0.092	0.005
Bone (section)	22.1	0.17	14.4	0.33	0.22	0.01	0.208	0.005
Cartilage	43.6	0.63	12.8	0.55	0.27	0.02	0.58	0.02
Cornea	53.0	0.45	8.72	0.17	0.13	0.01	1.05	0.02
Lens (cortex)	52.1	0.32	9.18	0.16	0.11	0.01	0.72	0.01
Lens (nucleus)	38.1	0.26	11.3	0.22	0.20	0.01	0.33	0.01
Retina	67.3	0.33	7.25	0.08	0.05	0.01	1.42	0.02
Brain (grey)	55.5	0.50	7.76	0.15	0.12	0.02	1.03	0.02
Brain (white)	37.0	0.29	8.04	0.21	0.24	0.01	0.47	0.01
Cerebellum	50.2	0.41	8.52	0.21	0.09	0.02	0.89	0.02
Dura	49.2	0.46	9.63	0.26	0.14	0.02	0.77	0.02
Brain stem	34.6	0.26	8.45	0.21	0.20	0.01	0.47	0.01
Tongue (*in vivo*)	57.7	0.43	9.12	0.20	0.08	0.01	0.63	0.02
Aq. humour	74.2	0.30	6.81	0.08	0.01	0.01	1.83	0.01
Water	74.1		6.2		0.0		>0.0001	

TABLE 2. Dielectric parameters of water dispersion in tissues obtained by analysis of the experimental results at 20°C. The Δ terms correspond to the 95% confidence interval.

Tissue	ε_S	$\Delta\varepsilon_S$	τ (ps)	$\Delta\tau$ (ps)	α	$\Delta\alpha$	σ (Sm^{-1})	$\Delta\sigma$ (Sm^{-1})
Bone (cortex)	15.3	0.25	12.7	0.98	0.31	0.02	0.093	0.006
Cornea	62.6	0.26	10.8	0.11	0.09	0.01	1.00	0.01
Lens (cortex)	55.6	0.34	10.9	0.21	0.10	0.01	0.73	0.14
Lens (nucleus)	39.1	0.24	13.4	0.02	0.16	0.01	0.31	0.01
Retina	67.6	0.34	8.74	0.12	0.09	0.01	1.33	0.01
Brain (grey)	58.3	0.55	9.73	0.24	0.18	0.01	1.13	0.02
Brain (white)	45.13	0.45	9.49	0.27	0.22	0.02	0.78	0.01
Cerebellum	59.2	0.44	9.74	0.18	0.15	0.01	1.24	0.02
Dura	52.4	0.40	11.7	0.21	0.15	0.01	0.76	0.01
Aq. humour	78.2	0.09	8.71	0.02	0.02	0.002	1.43	0.004
Water	80.1		9.2		0.0		>0.0001	