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The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz

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Abstract. Three experimental techniques based on automatic swept-frequency network and impedance analysers were used to measure the dielectric properties of tissue in the frequency range 10 Hz to 20 GHz. The technique used in conjunction with the impedance analyser is described. Results are given for a number of human and animal tissues, at body temperature, across the frequency range, demonstrating that good agreement was achieved between measurements using the three pieces of equipment. Moreover, the measured values fall well within the body of corresponding literature data.

1. Introduction

A recent review of the dielectric properties of biological tissues (Gabriel *et al* 1996a) showed that there is a large body of literature on the subject. By piecing together the data available, the main features of the dielectric spectrum of a biological tissue are revealed. However, the study exposed variability between data from different studies and gaps in our knowledge with respect to certain tissue types and, for most tissues, with respect to certain frequencies. An experimental study based on modern swept-frequency techniques may therefore consolidate our knowledge in this field.

In the present study three experimental techniques were used to measure the dielectric properties of tissue in the frequency range 10 Hz to 20 GHz. There is sufficient overlap among the three sets of measurements to demonstrate the extent of consistency between them. By superimposing the data from this measurement programme on the corresponding data from the literature it is possible to show that the experimental spectrum obtained in this study exhibits the same frequency-dependence and bridges the gaps that there are within the frequency range of the measurements.

A comparison was made between the dielectric properties of human tissue and its equivalent in one or more animal species. Comparisons were also made between measurement carried out *in vivo* on accessible parts of the body and *in vitro* on freshly excised tissue.

2. Measurement techniques

The dielectric measurements were performed using automatic swept-frequency network and impedance analysers. The frequency range 10 Hz to 10 MHz was covered by an HP4192A

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impedance analyser, an HP 8753C was used in the frequency range 300 kHz to 3 GHz and an HP8720 from 130 MHz to 20 GHz. Open-ended co-axial probes were used to interface the measuring equipment with the samples in all cases.

The technique used with the HP8700 series network analysers has been reported in detail elsewhere (Gabriel *et al* 1994) and will not be discussed further. The techniques used in conjunction with the impedance analyser will be briefly described.

A 50 Ω (impedance-matched conical co-axial probe (Gabriel and Grant 1989) was adapted to interface the sample to the HP4192A impedance analyser. The probe is characterized by a fringing capacitance C and conductance G which are functions of its physical dimension and can be measured with the impedance analyser. In addition there are stray capacitive and inductive elements that have to be normalized. The characteristic parameters of the probe, equivalent to its capacitance in air K, were calculated from measurements of the impedance components of the probe in air and in a standard sample (water or salt solution). In principle, the dielectric properties (permittivity ε' and conductivity σ) of an unknown sample could then be calculated from measurements of the impedance of the probe against an unknown sample using the following relationships, where ε_0 is the permittivity of free space:

$$\varepsilon' = C/K \qquad \sigma = G\varepsilon_0/K. \tag{1}$$

In practice, the measurement of conductive materials in the frequency range 10 Hz to 10 MHz is not so straightforward. Normalization of the measured capacitance and conductance against the parameters of the probe in air is not sufficient. The measurements are affected by two sources of systematic errors, electrode polarization and lead inductance errors, which become apparent at the lower and higher ends of the frequency range under consideration.

Electrode polarization is a manifestation of charge organization which occurs at the sample–electrode interface in the presence of water molecules and hydrated ions. In its simplest form, the phenomenon is equivalent to a frequency-dependent capacitor in series with a resistor. Both components can be approximated by negative power functions of frequency, that is their absolute values decrease with increasing frequency. The effect increases with increasing sample conductivity and its consequences are more pronounced on the capacitance than they are on the conductance of ionic solutions as well as biological samples (Schwan 1992). In the case of biological samples, the poorly conducting cells shield part of the electrode from the ionic current, thus reducing the polarization effects compared to an ionic solution equivalent in conductivity to the intracellular fluid (Schwan 1992).

The material of the electrode plays an important part in determining its polarization impedance. In the current study gold plated and sputtered platinum electrodes were tested and a choice was made in favour of the latter. The effect of the rough platinum surface was to shift the electrode polarization effect to lower frequencies and thus to reduce its contribution in the frequency range under consideration.

The inductance of the probe and connecting cable adds another series component to the measured impedance. It affects the measured capacitance and conductance of lossy media. Its value could be determined from measurements on standard salt solutions and applying an equivalent circuit analysis. For the present set-up the stray inductance was $L = 2 \times 10^{-7}$ Henry and the following equations were used to account for it:

$$\begin{aligned} C &= \frac{C_m + LG_m\omega^2 + LC_m^2}{(1+\omega^2 LC_m)^2 + (\omega LC_m)^2} \\ G &= \frac{G_m}{(1+\omega^2 LC_m)^2 + (\omega LC_m)^2} \end{aligned} \tag{2}$$

where C and G are the corrected capacitance and conductance expressed in terms of the measured values C_m and G_m, the lead inductance L and the angular frequency ω. The effect of the stray inductance increases with frequency and with sample conductivity.

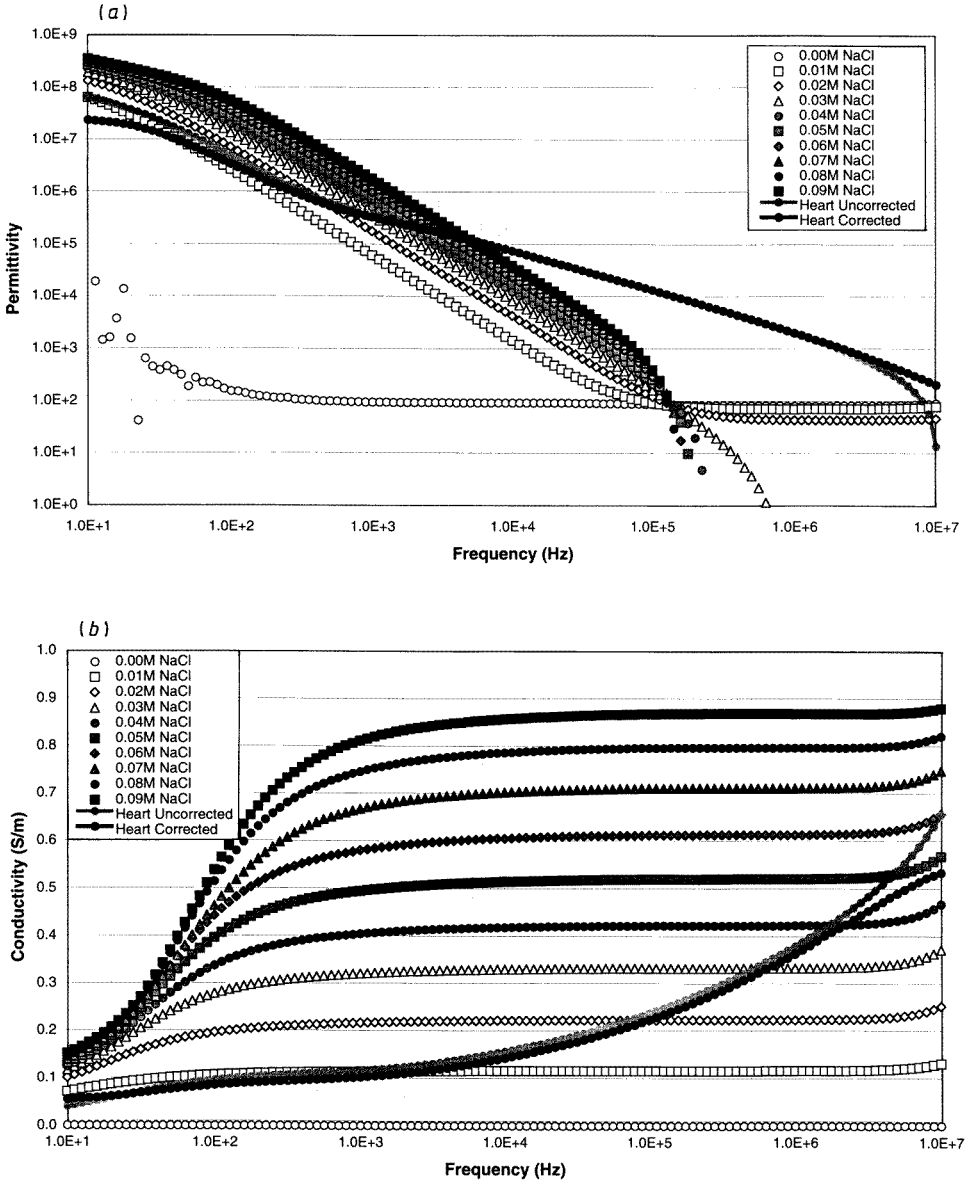


Figure 1. (*a*) Permittivity and (*b*) conductivity of a series of salt solutions. The data are uncorrected for electrode polarization and lead inductance errors. Also shown are corrected and uncorrected data for heart muscle tissue shown to illustrate the outcome of the correction procedure.

Figures 1(*a*) and (*b*) show the effects of electrode polarization and the stray inductance on the uncorrected permittivity and conductivity of a series of salt solutions ranging from

zero molar (de-ionized water) to 0.09 molar. The high permittivity values at low frequencies are a manifestation of electrode polarization whereas negative permittivity values at high frequency show the effect of the stray inductance. Superimposed on these data are the uncorrected permittivity and conductivity of a tissue sample (heart tissue). It can be seen that the low-frequency conductivity of the tissue is less than that of 0.01 molar salt solution. It is therefore reasonable to assume that the effect of electrode polarization on the tissue is also less than that exhibited by the 0.01 molar salt sample. A further observation indicates that the errors in the permittivity and conductivity of the sample are likely to be apparent below 1 kHz and significant below 100 Hz whereas the effect of inductance manifests itself above a few megahertz in the case of tissue samples.

To correct for electrode polarization and induction errors the capacitance and conductance of the tissue sample are evaluated in accordance with (2) and normalized with respect to a salt solution of similar low-frequency conductivity. The example in figures 1(*a*) and (*b*) was corrected with reference to a 0.005 molar salt solution; the corrected dielectric properties are shown for comparison purposes. All impedance analyser tissue measurements were treated in a similar manner.

3. Uncertainties

The measurement techniques and associated instrumentation used in this study give random reproducibility of about 1% across the frequency range. This statement is based on multiple measurements performed on standard samples of uniform composition. Biological tissues are inhomogeneous and show considerable variability in structure or composition and hence in dielectric properties. Such variations are natural and may be due to physiological processes or other functional requirements. The spread of values ranges from about ±5–10% above 100 MHz to ±15–25% at the lower end of the frequency scale.

Care has been taken to eliminate all known sources of systematic errors; however, in view of the assumptions made in correcting for electrode polarization, it is possible that the dielectric parameters below 1 kHz may be undercorrected. This source of errors may affect the permittivity values below 100 Hz by up to a factor of two or three.

4. Materials

Three sources of materials were used: (i) excised animal tissue, mostly ovine, some porcine, from freshly killed animals; (ii) human autopsy materials and (iii) human skin and tongue *in vivo*.

All animal tissues used were as fresh as possible, mostly within 2 h of the animal's death; human material was obtained 24 to 48 hours after death. The conical probe used in conjunction with the impedance analyser requires relatively large samples, at least a cube of 5 cm linear dimension. In view of this requirement not all samples could be measured at low frequencies.

5. Results

5.1. Measurements across the frequency range

Examples of measurements on the three experimental arrangements, across the frequency range, are given in figures 2(*a*)–(*k*). The agreement among measurements on the three machines was particularly good when the measurements were made on the same

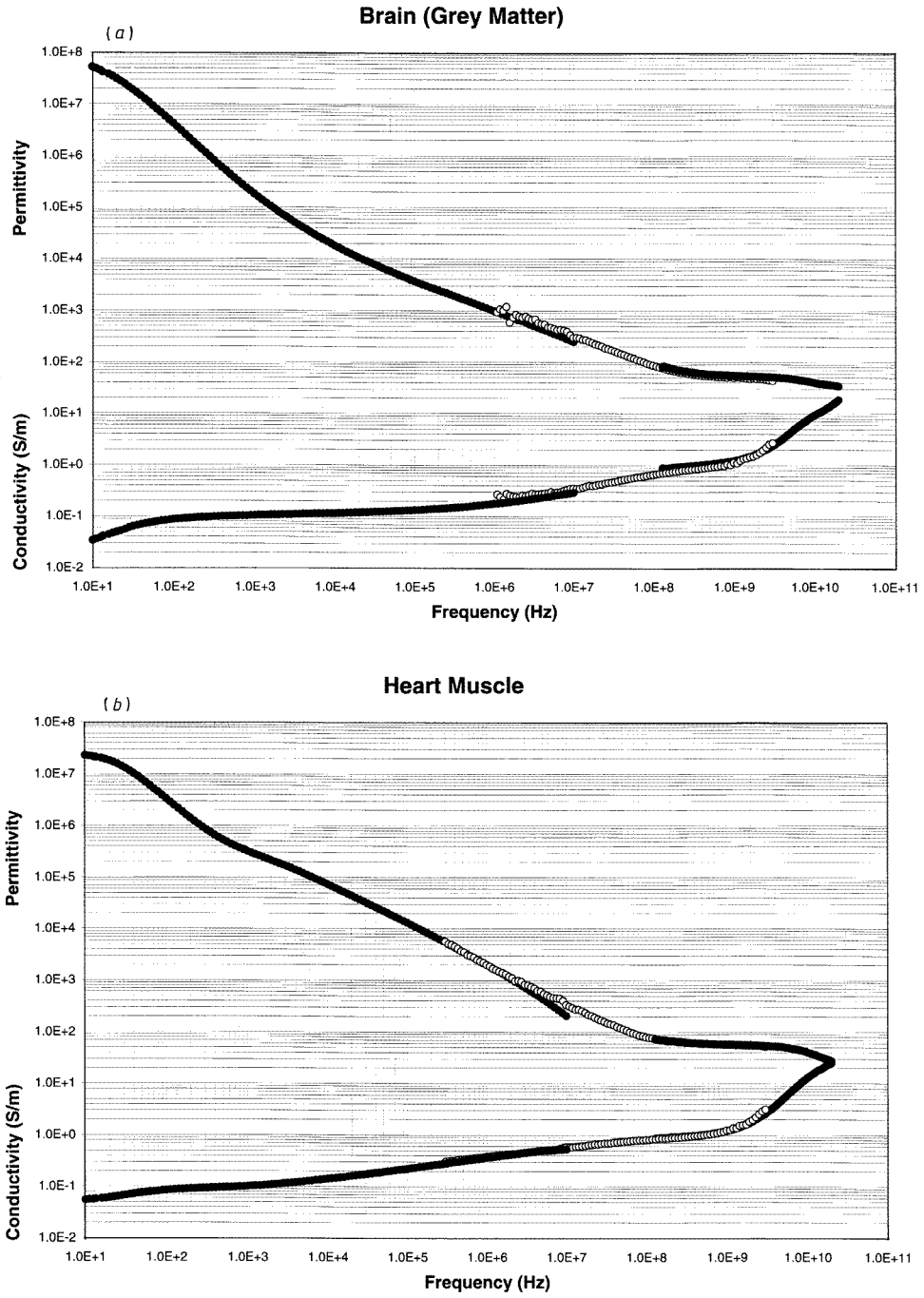
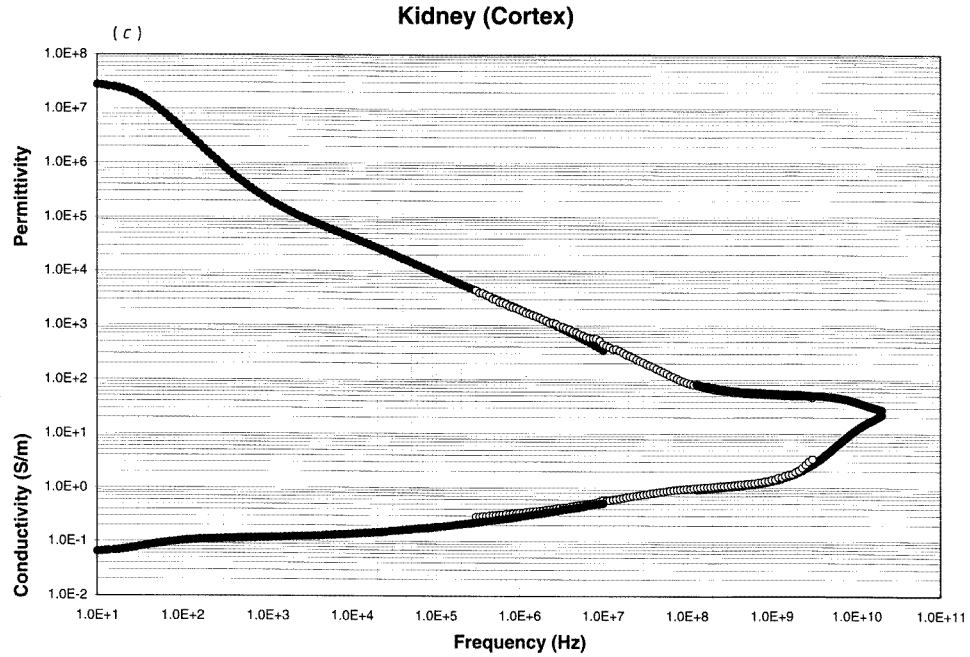
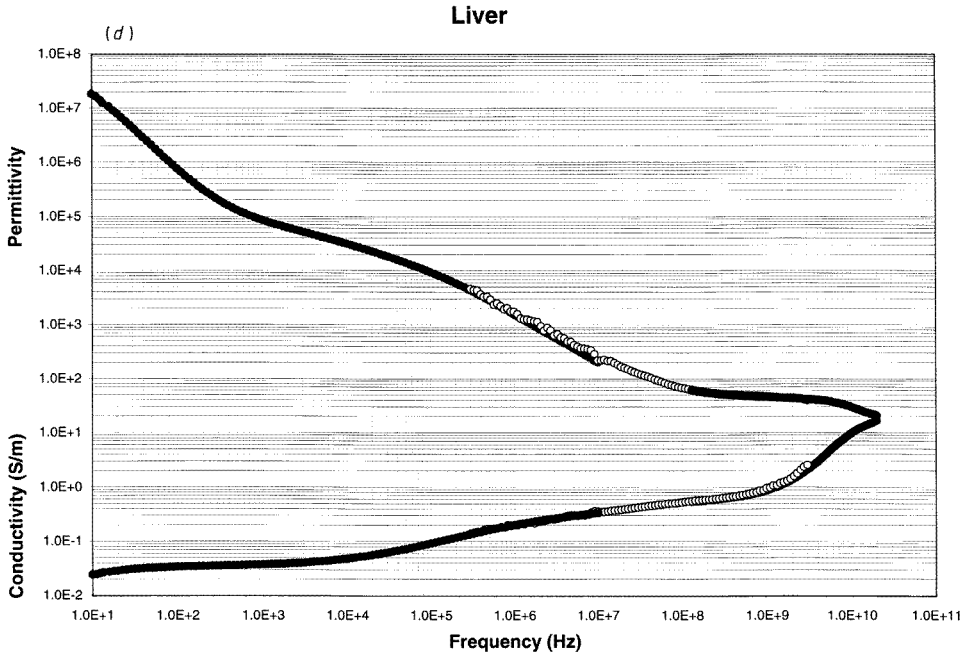


Figure 2. The permittivity and conductivity of various tissues from measurements on three experimental arrangements with overlapping frequency coverage. (*a*) brain (grey matter), (*b*) heart muscle, (*c*) kidney (cortex), (*d*) liver, (*e*) lung (inflated), (*f*) spleen, (*g*) muscle (paravertebral cut across the fibres), (*h*) muscle (paravertebral cut along the fibres), (*i*) uterus and (*j*) skin (ventral forearm). Tissues (*a*)–(*h*) are of bovine origin, (*i*) is from a human post-mortem sample and (*h*) is human *in vivo*. All measurements were at body temperature.





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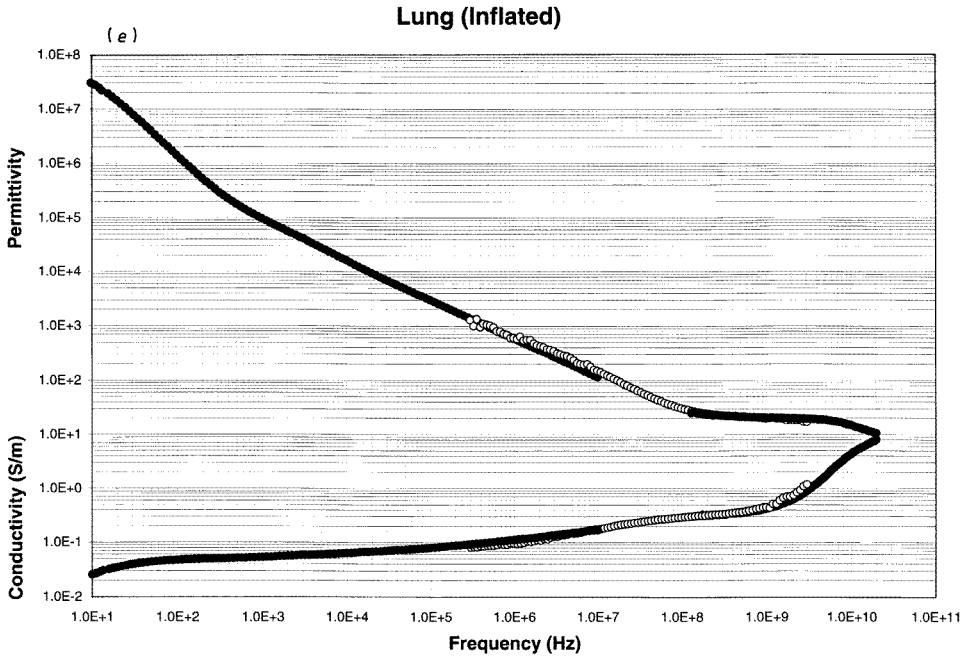

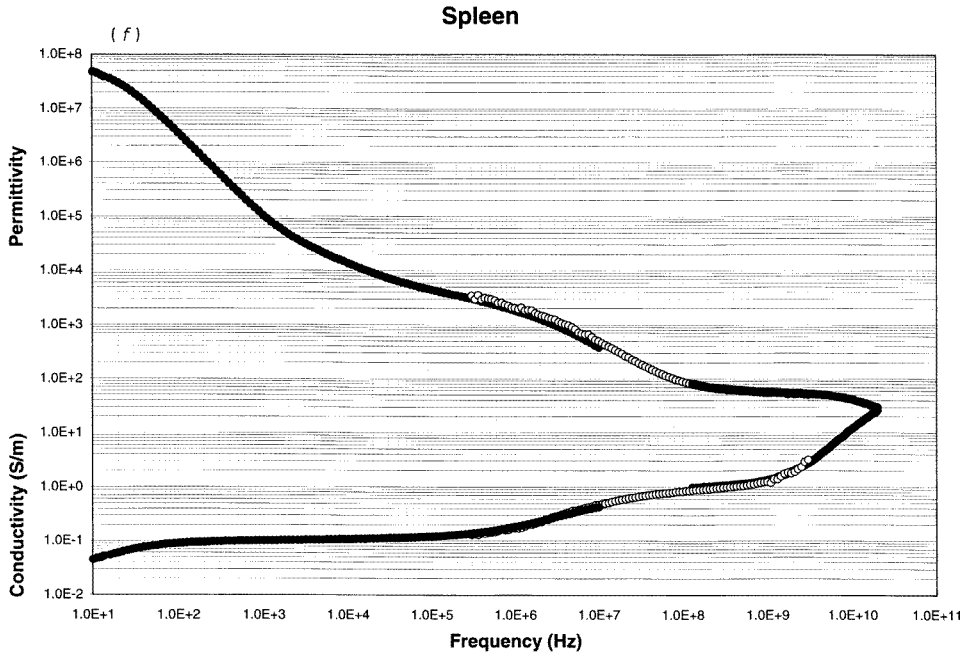

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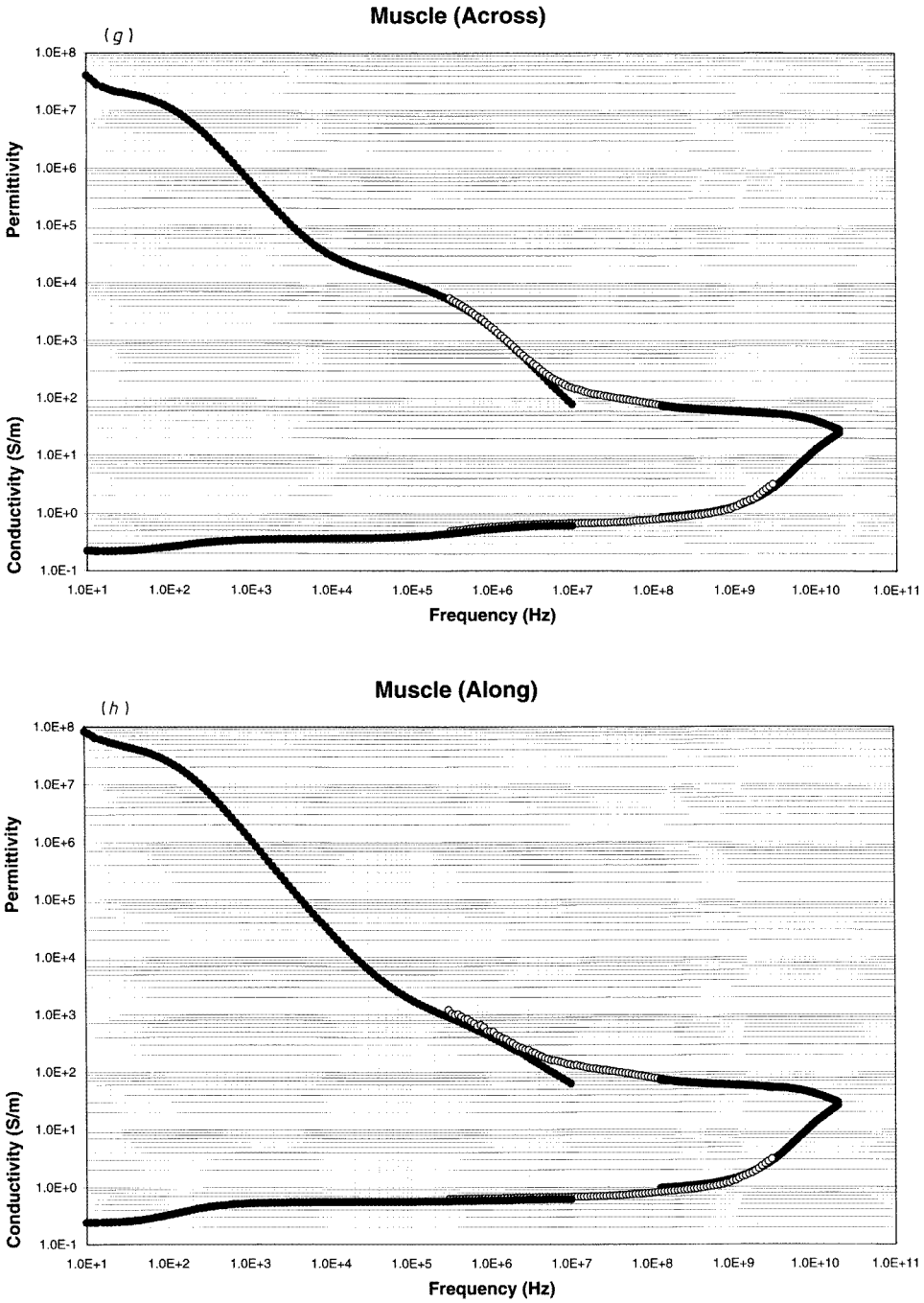

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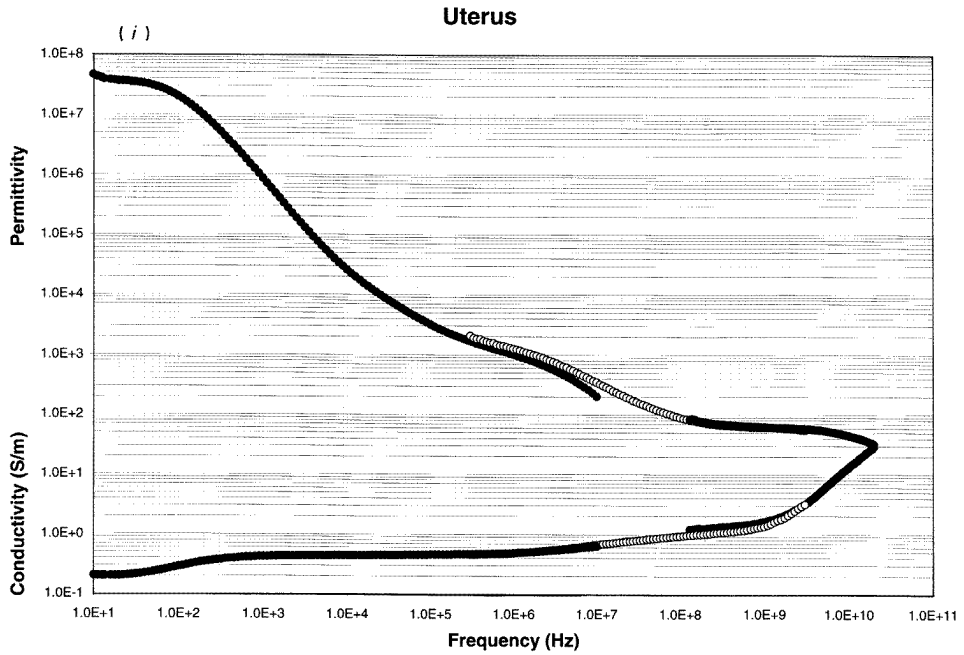

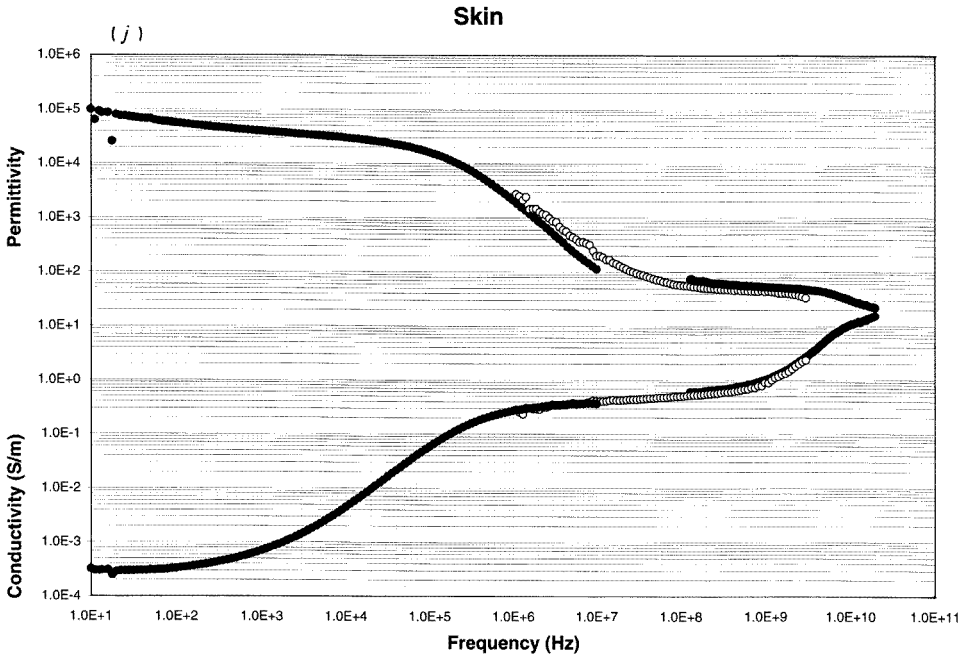

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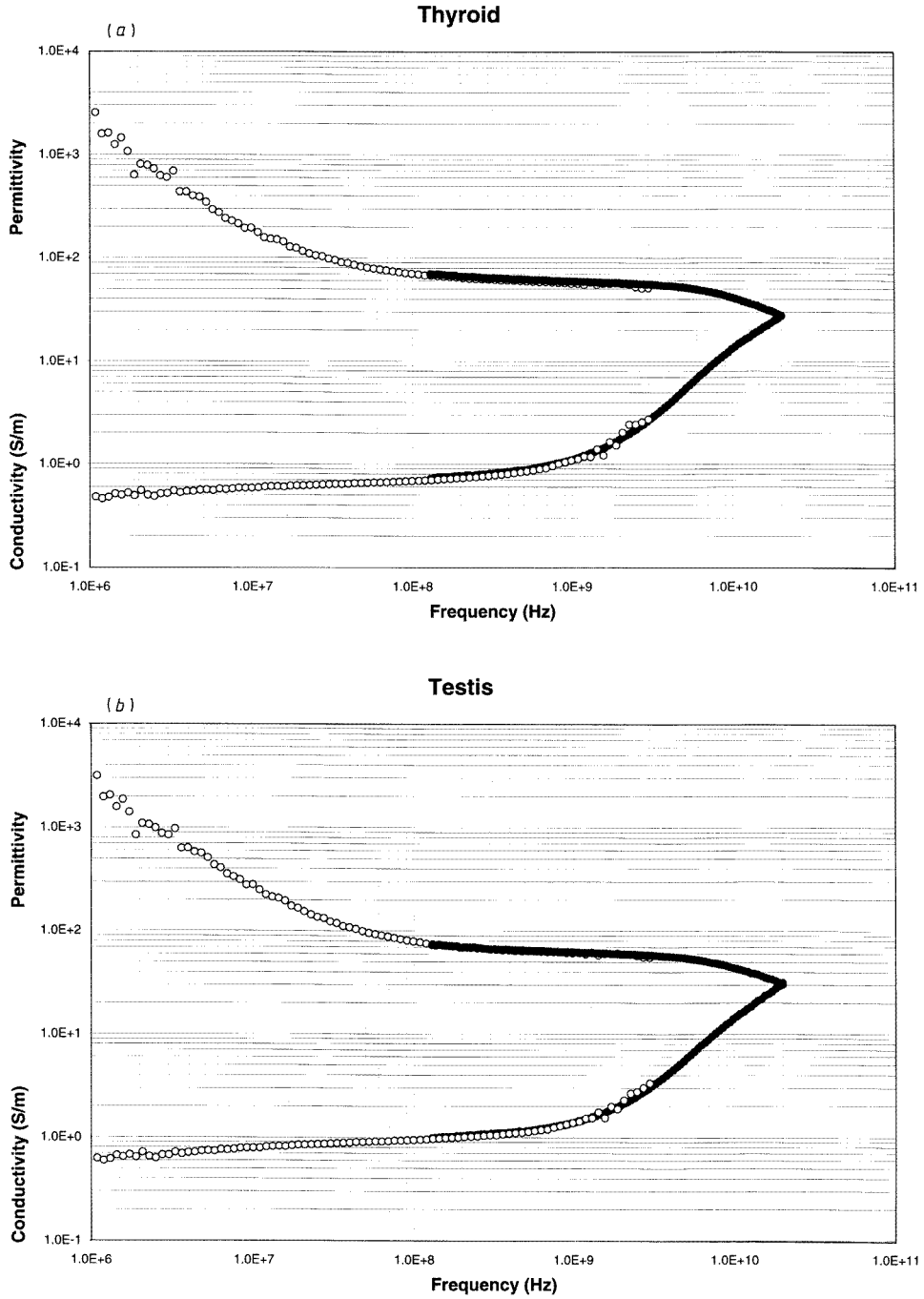
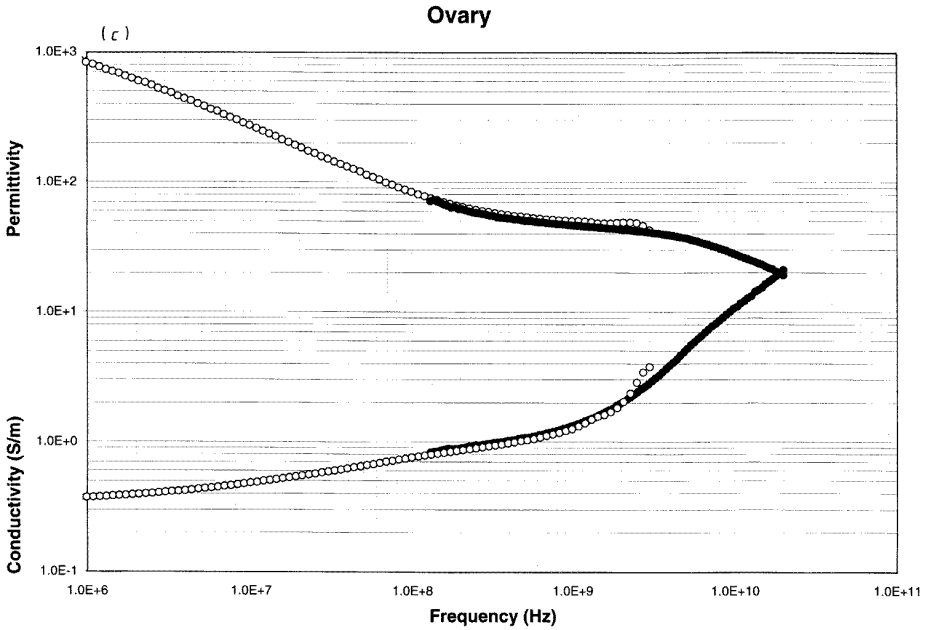
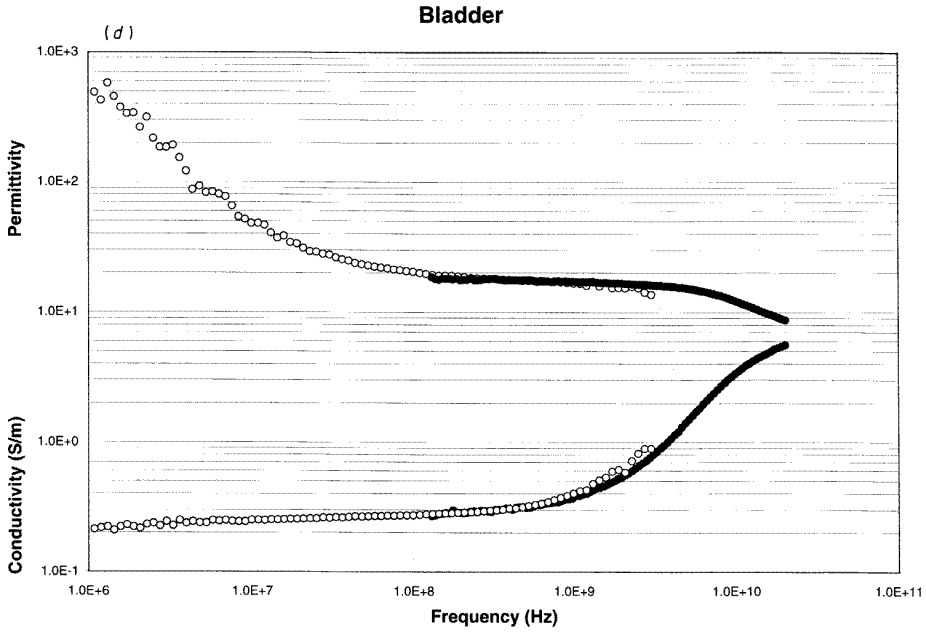


Figure 3. The permittivity and conductivity of tissues (human autopsy samples) from measurements on two experimental arrangements with overlapping frequency coverage: (*a*) thyroid, (*b*) testis, (*c*) ovary and (*d*) bladder. All measurements were at body temperature.





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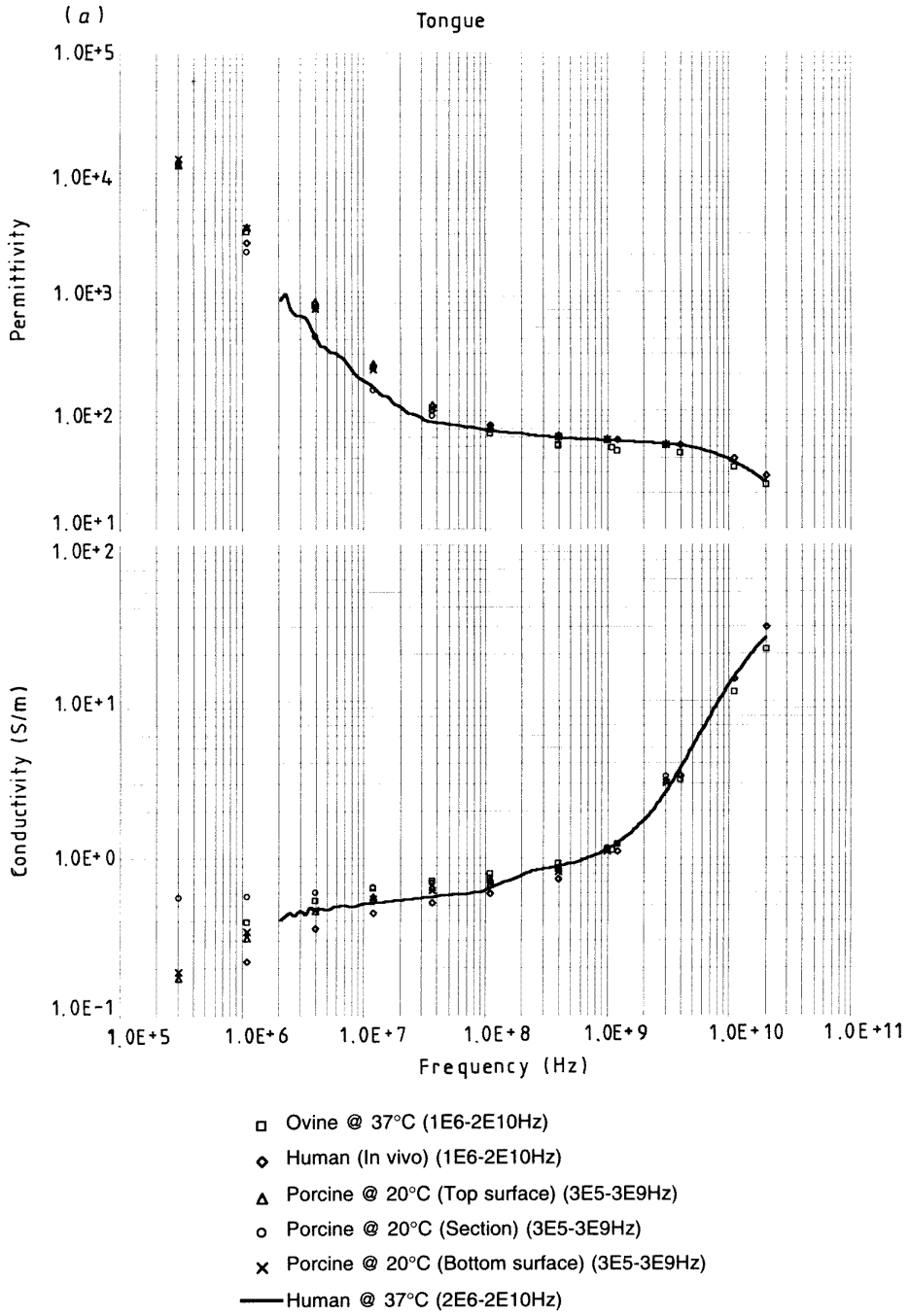
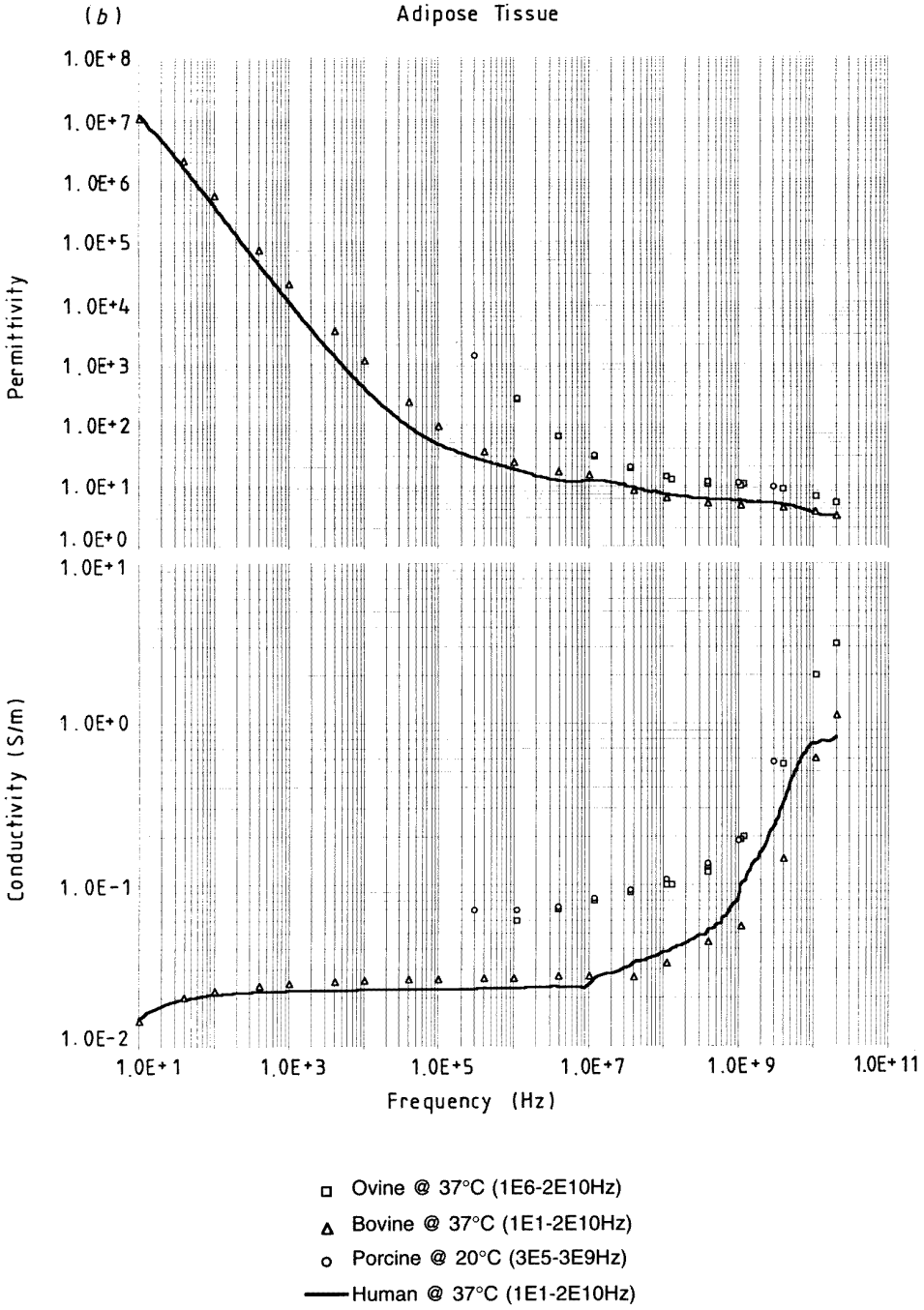


Figure 4. Comparisons between species and between *in vivo* and *in vitro* measurements: (*a*) tongue muscle, (*b*) adipose tissue, (*c*) cartilage and (*d*) cortical bone.



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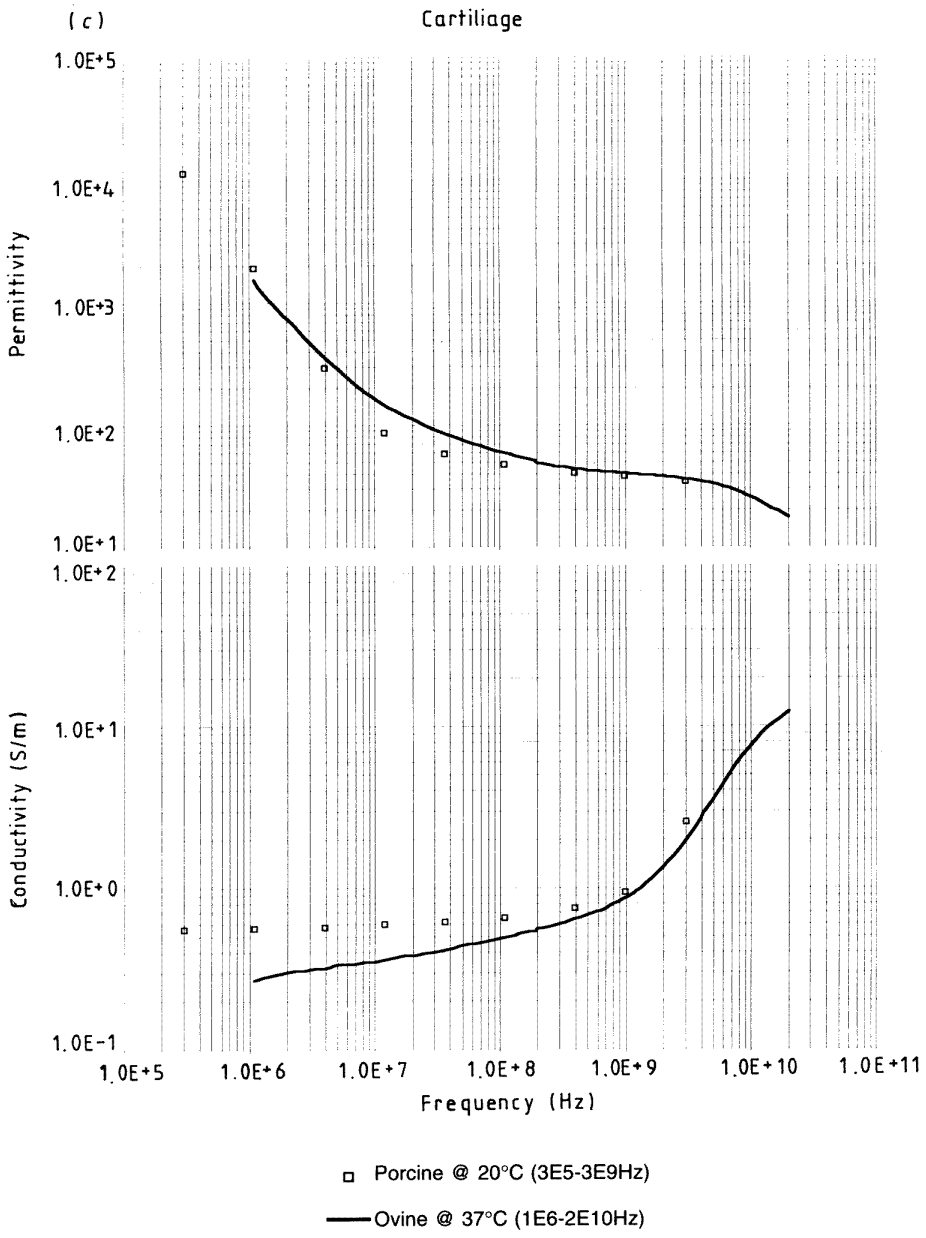

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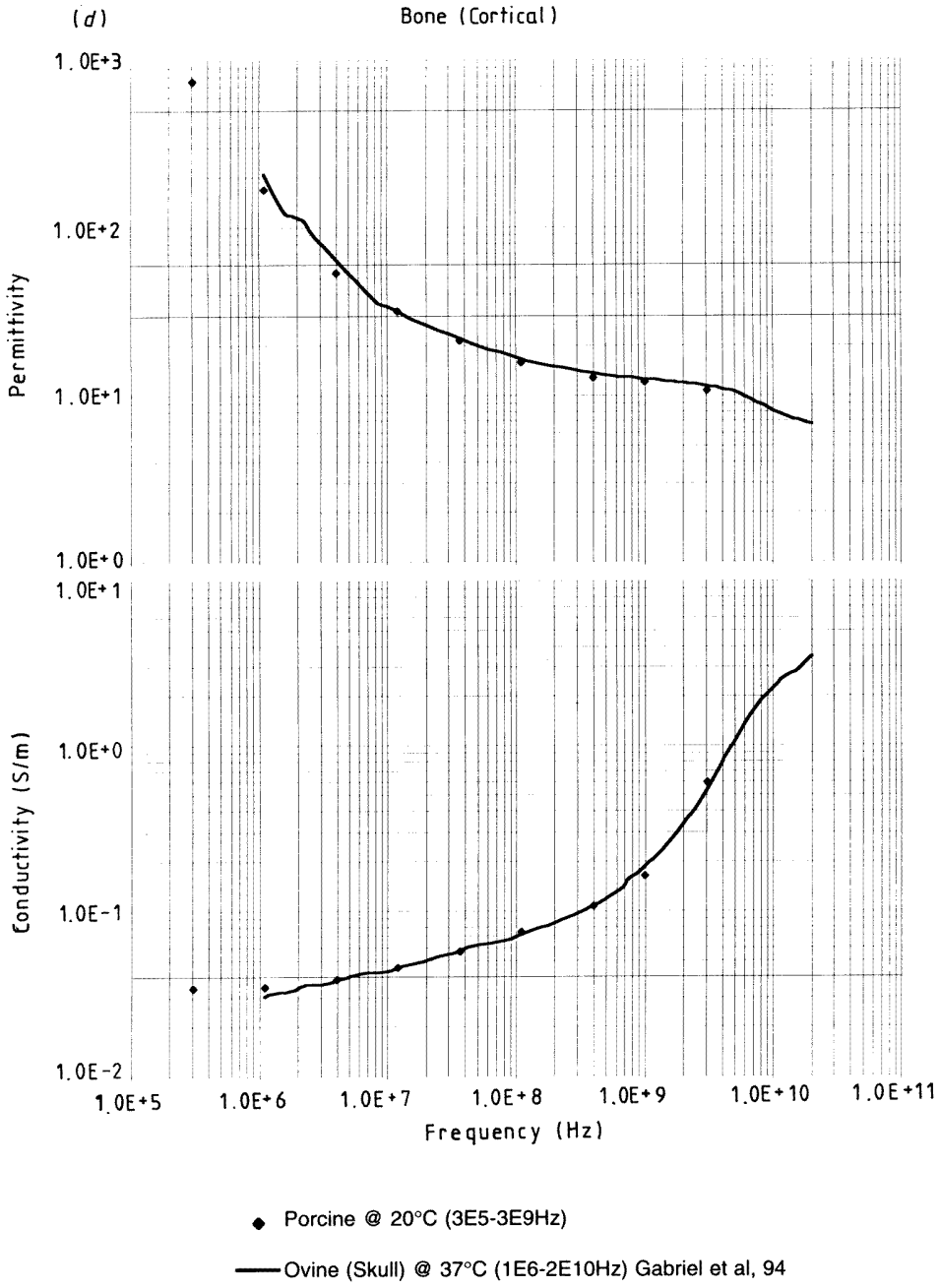

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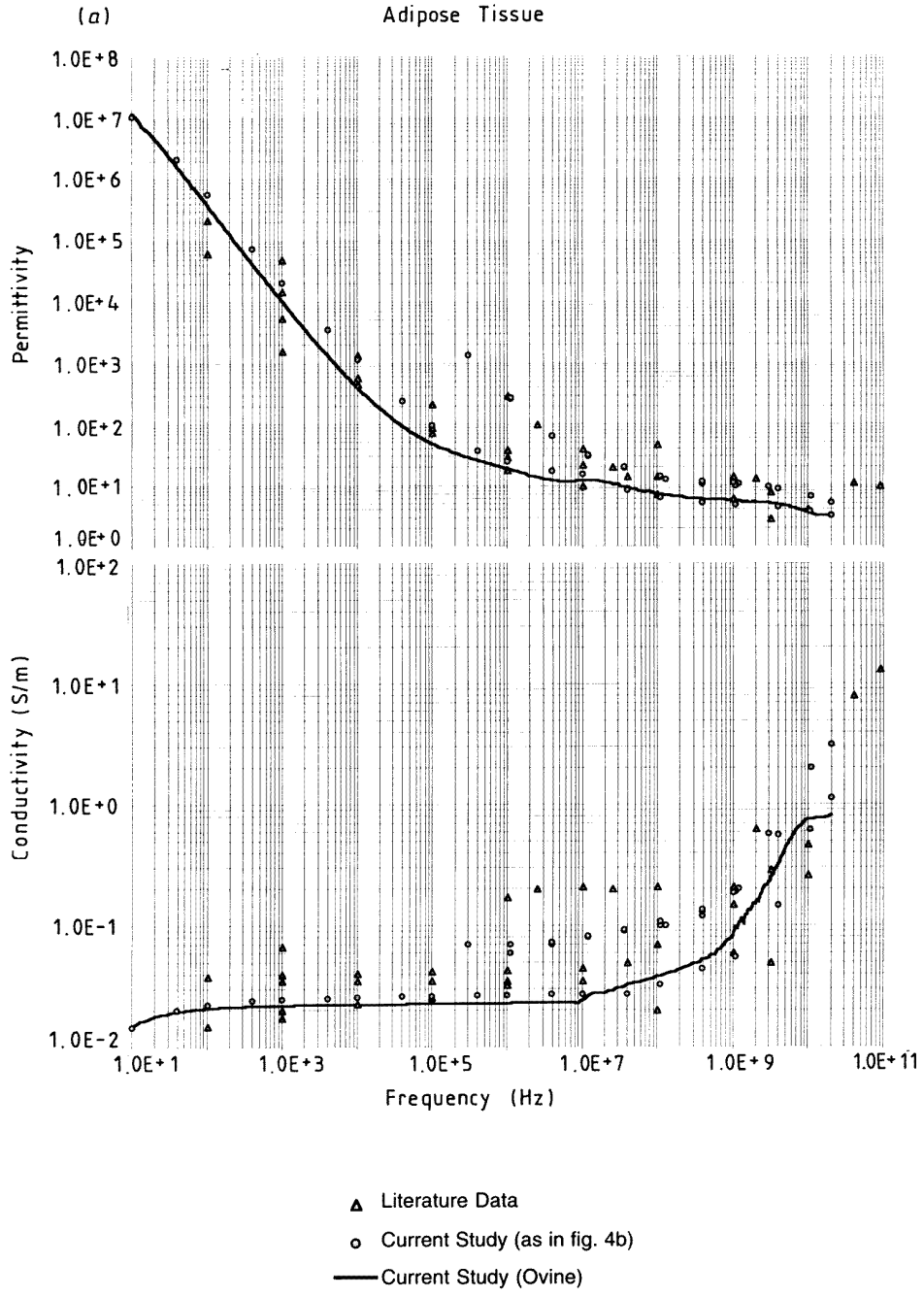

Figure 5. Dielectric data from the current study and corresponding data from the literature: (*a*) adipose tissue and (*b*) liver.

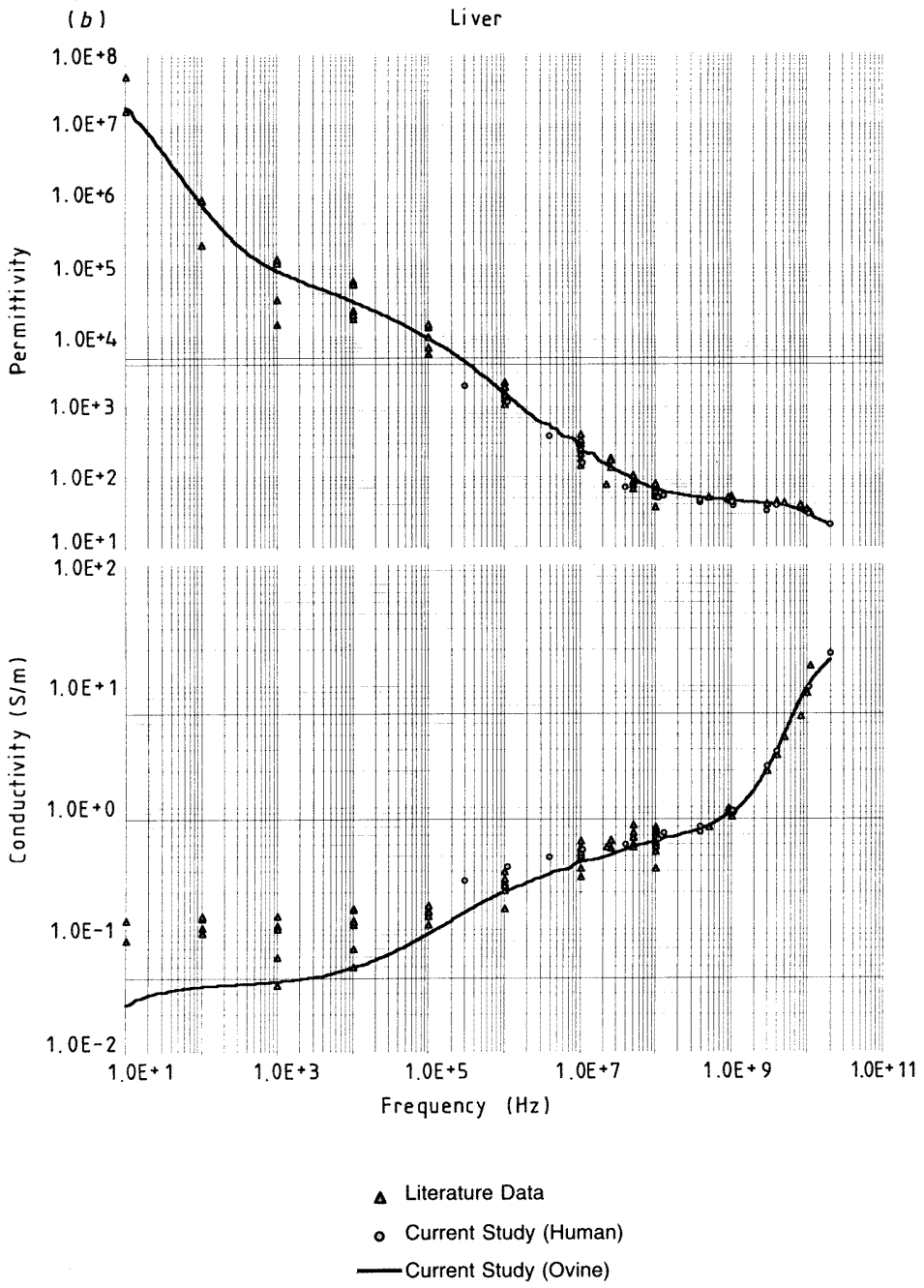

Figure 5. (Continued)

sample throughout. The impedance and network analysers were connected to an Intel Pentium processor-based personal computer through a GPIB bus. The equipment and the measurement procedures were controlled by software written in LabView™, a Windows-based graphics programming system. A common graphic user interface allowed measurements to be performed on all three machines in quick succession.

Small samples of human material were measured only in the frequency range above 1 MHz on the two network analysers. Examples of such measurements are given in figure 3(*a*)–(*d*).

5.2. Comparison between species and between measurements in vivo and in vitro

The differences in the dielectric properties between animal and human species are not systematic. The variation in tissue properties within a species may well exceed variations between species. Example of comparative measurements are given in figures 4(*a*)–(*d*). This result reinforces conclusions from other studies reported by Stuchly and Stuchly (1990). In figure 4(*a*) data for human tongue *in vivo* are compared to measurements *in vitro* on an autopsy sample. Data for samples of animal origin are not significantly different except at the low-frequency end, where the conductivity is higher for a longitudinal section. Figure 4(*b*) shows a wide spread of data for adipose tissue of human and animal origin. Closer inspection of the data shows that there are two limiting values corresponding to pure fatty tissue of low water content and little infiltration with blood, in contrast to the data corresponding to tissue of higher water content and more blood infiltration. Similar observations were made with respect to measurement on yellow bone marrow with high blood infiltration in the region closer to the bone in comparison to that in the centre. Figure 4(*c*) shows that the dielectric properties of cartilage are those of a high-water-content tissue, in agreement with reported values of 55–85% (ICRP 1992). Figure 4(*d*) shows data for cortical bone. The reported water content of this tissue is 12–15% (ICRP 1992).

5.3. Effect of relative field-cell orientation

The dielectric properties of muscle are known to be anisotropic (Epstein and Foster 1983). The data reported were obtained by measurement on the paravertebral muscle. The sample was measured twice, first with a transverse section against the probe (figure 2(*i*)) and then it was cut along the muscle fibre and re-measured (figure 2(*j*)). In view of the radial nature of the fringing field of the co-axial probe, these measurements do not represent the true limits of the dielectric properties with the field along and across the fibre. They show, however, the effect of fibre direction and the parts of the spectrum influenced by it.

5.4. Comparison with literature data

Comparison between the experimental data presented in this paper and corresponding data from the literature shows good agreement. The experimental spectrum exhibits the same frequency-dependence and falls well within the range of values reported in the literature (figures 5(*a*) and (*b*)). Analysis of the data in this manner was extended to other tissue with similar conclusions (Gabriel *et al* 1996b).

6. Comments and conclusions

An experimental investigation of dielectric properties of tissues was undertaken using three experimental techniques with overlapping frequency coverage extending from 10 Hz to 20 GHz. It was shown that, for measurement on the low-frequency experimental set-up, electrode polarization errors affect the results below 1 kHz and become significant below 100 Hz in the case of tissue samples. Appropriate corrections were made for electrode polarization and for the lead inductance effect. The corrected data fall well within the values in the literature. The results presented serve to consolidate existing knowledge of the dielectric behaviour of tissue, in particular they provide data at frequencies below 10 kHz, where previous knowledge had been limited.

Acknowledgments

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References

Epstein B R and Foster K R 1983 Anisotropy in the dielectric properties of skeletal muscle *Med. Biol. Eng. Computing* **21** 51–5

Gabriel C, Chan T Y A and Grant E H 1994 Admittance models for open ended coaxial probes and their place in dielectric spectroscopy *Phys. Med. Biol.* **39** 2183–200

Gabriel C, Gabriel S and Corhout E 1996a The dielectric properties of biological tissues: I. Literature survey *Phys. Med. Biol.* **41** 2231–49

Gabriel C and Grant E H 1989 Dielectric sensors for industrial microwave measurements and control *Microwellen HF Mag.* **15** 643–5

Gabriel S, Lau R W and Gabriel C 1996b The dielectric properties of biological tissues: III. Parametric models for the dielectric spectrum of tissues *Phys. Med. Biol.* **41** 2271–93

International Commission on Radiological protection (CRP) 1992 *Report of the Task Group on Reference Man* (Oxford: Pergamon)

Kraszewski A, Stuchly S S, Stuchly M A and Smith A M 1982 *In vivo* and *in vitro* dielectric properties on animal tissues at radio frequencies *Bioelectromagnetics* **3** 421–32

Schwan H P 1992 Linear and nonlinear electrode polarisation and biological materials *Ann. Biomed. Eng.* **20** 269–88

Stuchly M A and Stuchly S S 1990 Electrical properties of biological substances *Biological Effects and Medical Applications of Electromagnetic Energy* ed O P Gandhi (New Jersey: Prentice-Hall)