Phys. Med. Biol. **41** (1996) 2231–2249. Printed in the UK

The dielectric properties of biological tissues: I. Literature survey

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Received 2 April 1996

Abstract. The dielectric properties of tissues have been extracted from the literature of the past five decades and presented in a graphical format. The purpose is to assess the current state of knowledge, expose the gaps there are and provide a basis for the evaluation and analysis of corresponding data from an on-going measurement programme.

1. Introduction

The study of the dielectric properties of tissues belongs to basic as well as applied science. The theoretical aspects and the main findings in this subject have been widely reviewed (Schwan 1957, Schwan and Foster 1980, Pethig 1984, Pethig and Kell 1987, Foster and Schwan 1989 and Stuchly and Stuchly 1980). Foster and Schwan reflect on the historical perspective provided by over 100 years of interest in the electrical properties of tissues, and review the basic concepts of dielectric phenomena in biological materials and their interpretation in terms of interactions at the cellular level. Pethig and Kell cover similar ground and provide an overview of theories formulated to explain the dielectric properties in terms of the underlying molecular processes. Common to all papers is a more or less extensive tabulation of dielectric properties of tissues selected to illustrate the theoretical deliberations provided by the authors. More extensive literature reviews of dielectric properties have been provided by Geddes and Baker (1967), who summarized the early reports on the specific resistance of tissues; Stuchly and Stuchly (1980), who tabulated the dielectric properties of tissues in the frequency range 10 kHz to 10 GHz; and Duck (1990), who extended the survey by including more recent data.

The purpose of this survey is to assess the current state of knowledge in terms of dielectric properties of tissues over ten frequency decades, expose the gaps there are and provide a basis for the evaluation and analysis of the data from an on-going measurement programme (Gabriel *et al* 1996a, b).

The present study was instigated by the need for such information in electromagnetic (em) dosimetry. This area of science deals with the simulation of em exposure situations and the calculation of internal fields within exposed structures. Recent developments in this field have produced high-resolution, anatomically correct man and animal models from medical imaging data (Dimbylow 1996). The level of detail is such that over 30 tissue types can be identified. The use of such models for em dosimetry require that dielectric

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properties be allocated to the various tissues at all the frequencies to which the model is exposed. There is, as yet, no consensus on the dielectric data. This paper is a first step towards achieving this objective.

2. Overview of dielectric properties: terms and definitions

The dielectric properties of materials are obtained from their measured complex relative permittivity, $\hat{\varepsilon}$ expressed as

$$\hat{\varepsilon} = \varepsilon' - j\varepsilon''$$

where ε' is the relative permittivity of the material and ε'' the out-of-phase loss factor associated with it such that

$$\varepsilon'' = \sigma/\varepsilon_0\omega.$$

σ is the total conductivity of the material which, depending on the nature of the sample, may include a contribution from a frequency-independent ionic conductivity, σ_i. In this expression, ε_0 is the permittivity of free space and ω the angular frequency of the field. The SI unit of conductivity is siemens per metre (S m^{-1}) which presumes that in the above expression ε_0 is expressed in farads per metre (F m^{-1}) and ω in radians per second. The dielectric properties are determined as ε' and ε'' values, or ε' and σ values, as a function of frequency.

The dielectric properties of a biological tissue result from the interaction of electromagnetic radiation with its constituents at the cellular and molecular level. The mechanisms of the interaction are well understood and discussed in the review articles mentioned in the previous section. Very briefly, the main features of the dielectric spectrum of a biological tissue are as follows:

- The relative permittivity of a tissue may reach values of up to 10^6 or 10^7 at frequencies below 100 Hz.
- It decreases at high frequencies in three main steps known as the α, β and γ dispersions. Other dispersions may also be present.
- The γ dispersion, in the gigahertz region, is due to the polarization of water molecules.
- The β dispersion, in the hundreds of kilohertz region, is due mainly to the polarization of cellular membranes which act as barriers to the flow of ions between the intra and extra cellular media. Other contributions to the β dispersion come from the polarization of protein and other organic macromolecules.
- The low frequency α dispersion is associated with ionic diffusion processes at the site of the cellular membrane.
- Tissues have finite ionic conductivities commensurate with the nature and extent of their ionic content and ionic mobility.

3. Review of the dielectric properties of tissues

Reports of dielectric properties of tissues prior to 1950 are difficult to get hold of; they are of more historical than practical interest and, with the exception of Osswald (1937), are not reported in this article. The literature in the 1950s and 1960s is dominated by the work of Schwan and his collaborators and has been extensively reviewed and tabulated by Durney *et al* (1986).

The data reported are those that correspond more closely to living human tissues. Consequently, human tissue and *in vivo* measurements were selected in preference to animal tissue and *in vitro*. For *in vitro* measurements, data obtained at temperatures closest to that of the body and nearest to the time after death were used when available.

Most of the literature data were in graphical rather than tabular form, and in a logarithmic rather than linear format. Such data were retrieved for each decade. When tables were available, a more extensive frequency range was often provided. The data were translated from the various authors' preferred set of parameters and units to relative permittivity and conductivity expressed in S m^{-1}.

Data obtained at temperatures as low as 20 °C are included in this survey. It was not considered advisable to translate them to body temperature. The temperature coefficients, for both permittivity and conductivity, are tissue-type and frequency dependent. Information on these coefficients is scarce and not sufficiently robust to warrant generalization and extrapolation. Moreover, the coefficients are highest ($\sim$ 1–2% $^\circ C^{-1}$) at low frequencies where the uncertainties and the scatter in the data are also high.

4. Presentation of data

The data are presented in a graphical format in order to highlight the information with respect to the frequency coverage and the scatter in the data. Details of the tissue, measurement temperature and the reference are included in the legend. To facilitate the comparison, the same scale is used for all tissues except where the conductivity of the tissue falls below 10^{-2} S m^{-1}.

The plot for blood (figure 1(*a*)) benefits from recent high frequency data extending to 90 GHz (Alison and Sheppard 1993). The two types of bone: cancellous (figure 1(*b*)) and cortical (figure 1(*c*)) were treated separately; some authors reported measurement in the longitudinal, transverse and radial directions; in such cases the average is reported. There are large systematic differences between data for fat from various origins (figure 1(*d*)); there are almost certainly due to naturally wide variations in sample composition leading certain authors to publish a range of values rather than an average (Schwan 1955, Land and Campbell 1992). Both the grey and white matter of the brain have been widely studied in the frequency range above 10 kHz (figures 1(*e*) and (*f*)). This is also the case for kidney (figure 1(*g*)) and spleen (figure 1(*h*)). By contrast, the few data sets for heart (figure 1(*i*)) are spread across ten frequency decades. The data for liver (figure 1(*j*)) extend over the same frequency range. The dielectric properties of lung tissue (figure 1(*k*)) depend on the degree of inflation and therefore vary with the physical state. In the case of muscle tissue, the dielectric properties are known to be anisotropic at frequencies below 10 MHz; the literature data reflect this property. Figure 1(*l*) shows all the data for muscle tissue including those for which no orientation is specified. Skin (figure 1(*m*)) is a laminar tissue in which the uppermost layer, the stratum corneum, is significantly less hydrated than the deeper granular tissue. The dielectric properties of composite skin would fall within the bounds formed by the two components.

5. Comments

The review includes all the main tissues for which there are three or more literature reports. The list is much shorter than what is needed to provide data for state-of-the-art voxel models used in theoretical dosimetry, in which many more tissues are identified. Among the tissues

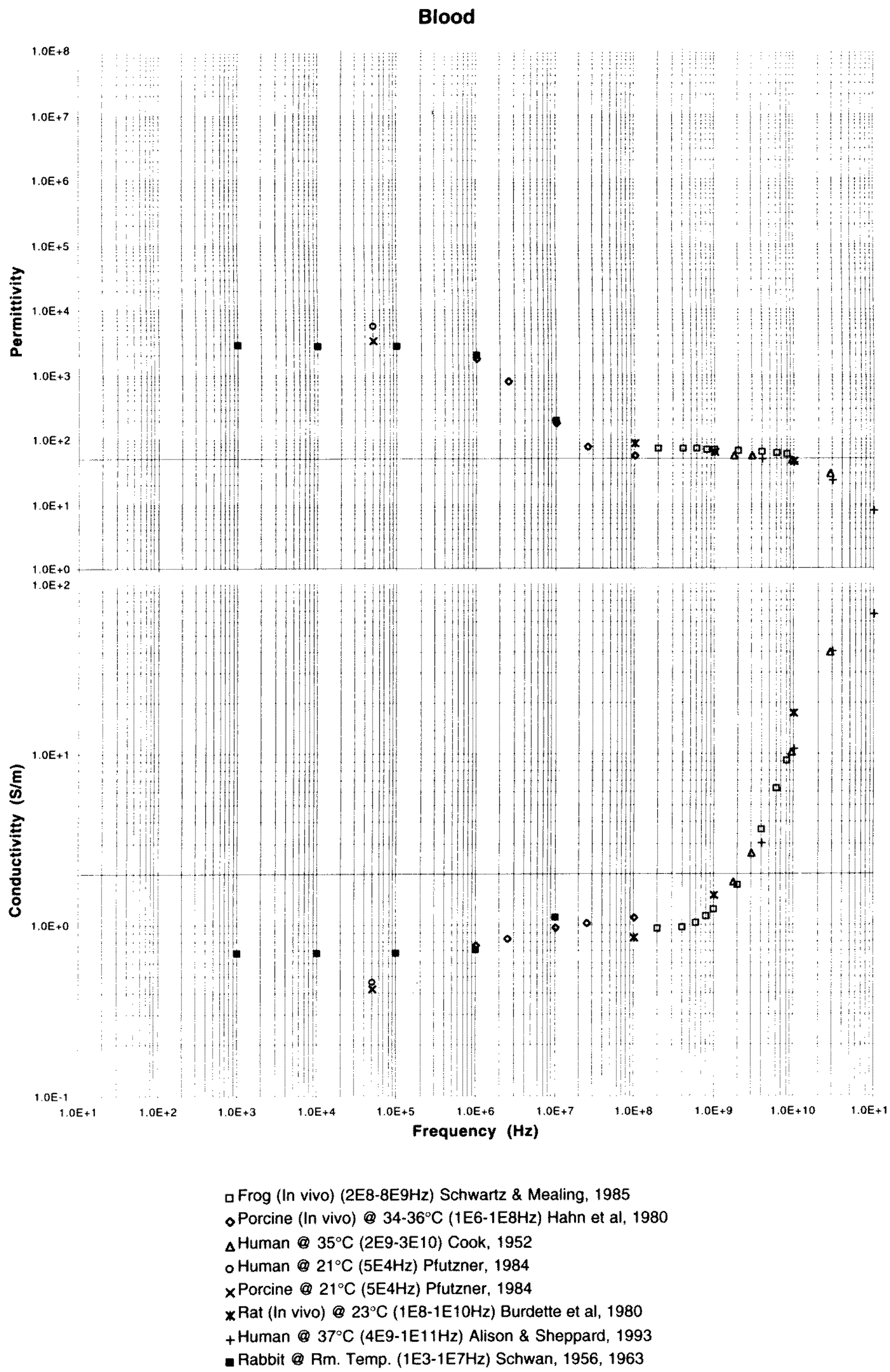


Figure 1. Survey of permittivity and conductivity of tissues in the frequency range 10 Hz to 100 GHz. (*a*) Blood.

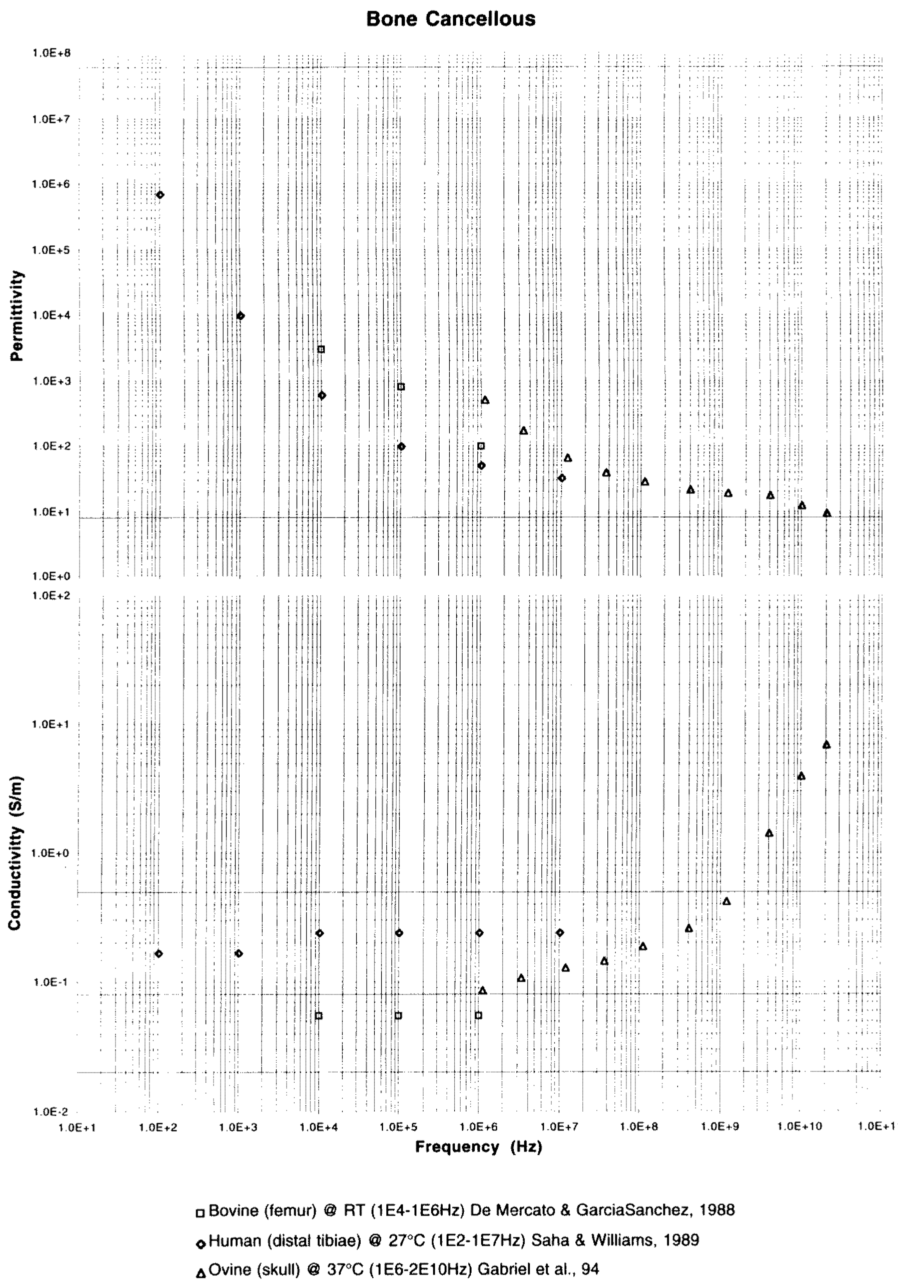


Figure 1. (*b*) Bone cancellous.

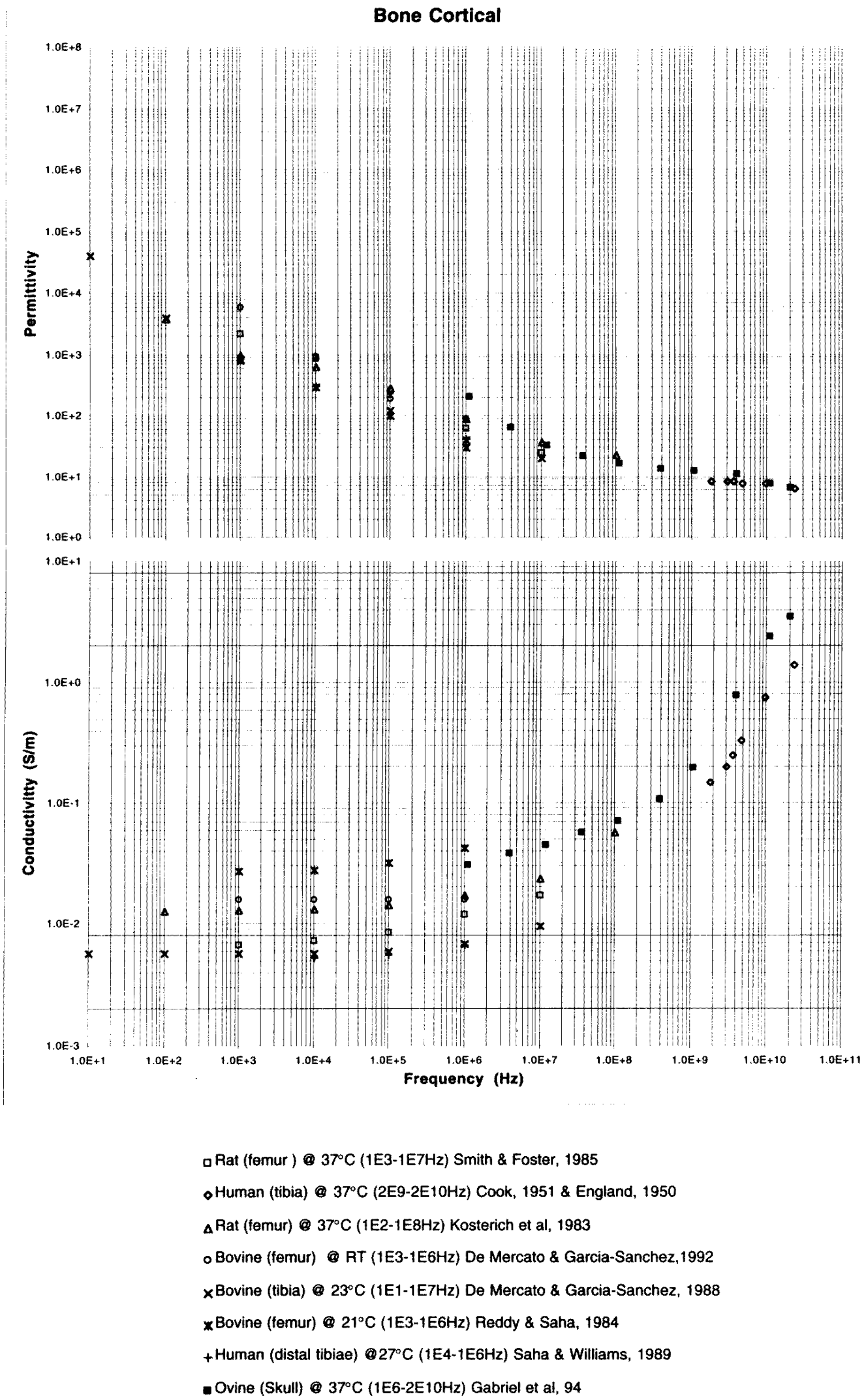


Figure 1. (*c*) Bone cortical.

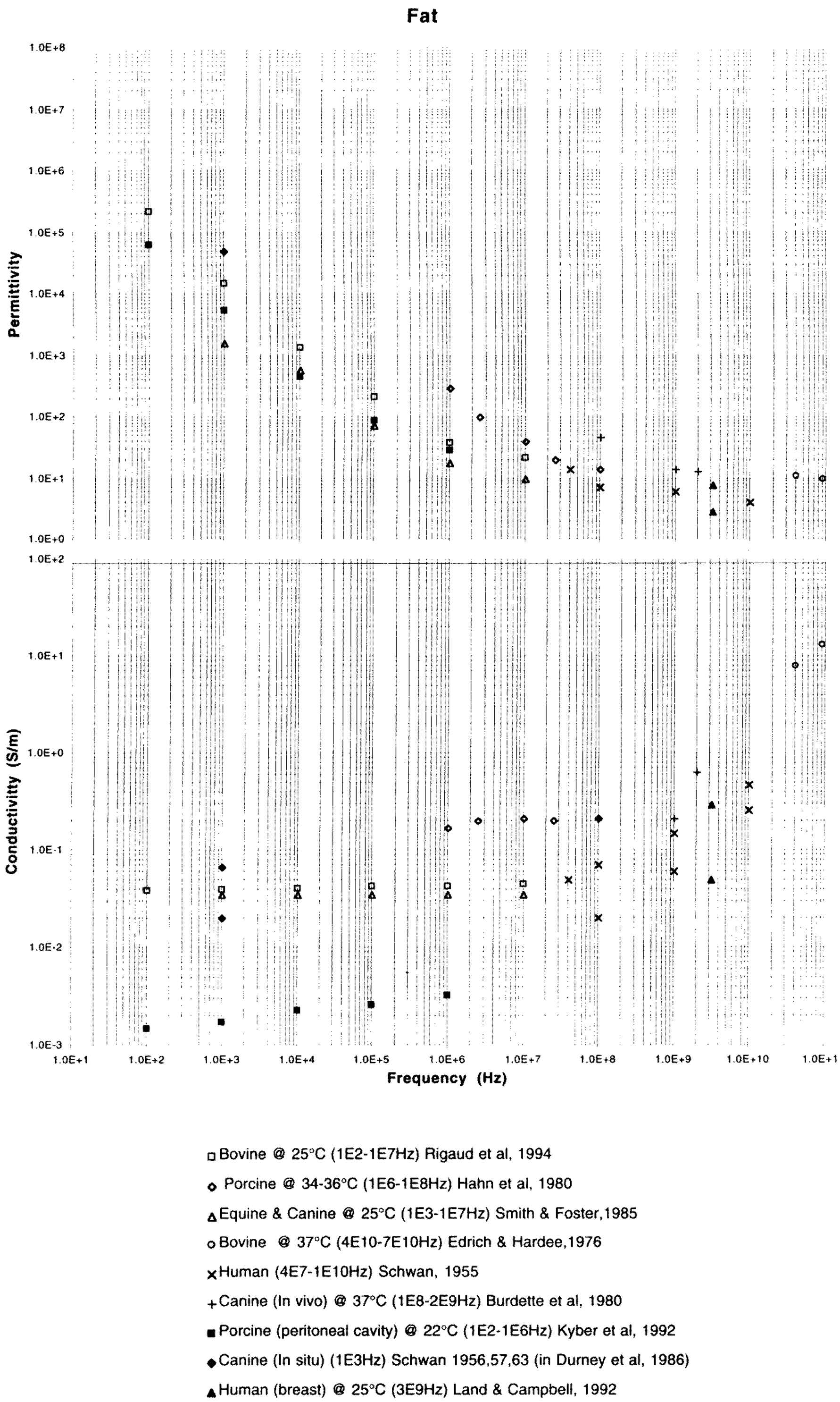


Figure 1. (*d*) Fat.

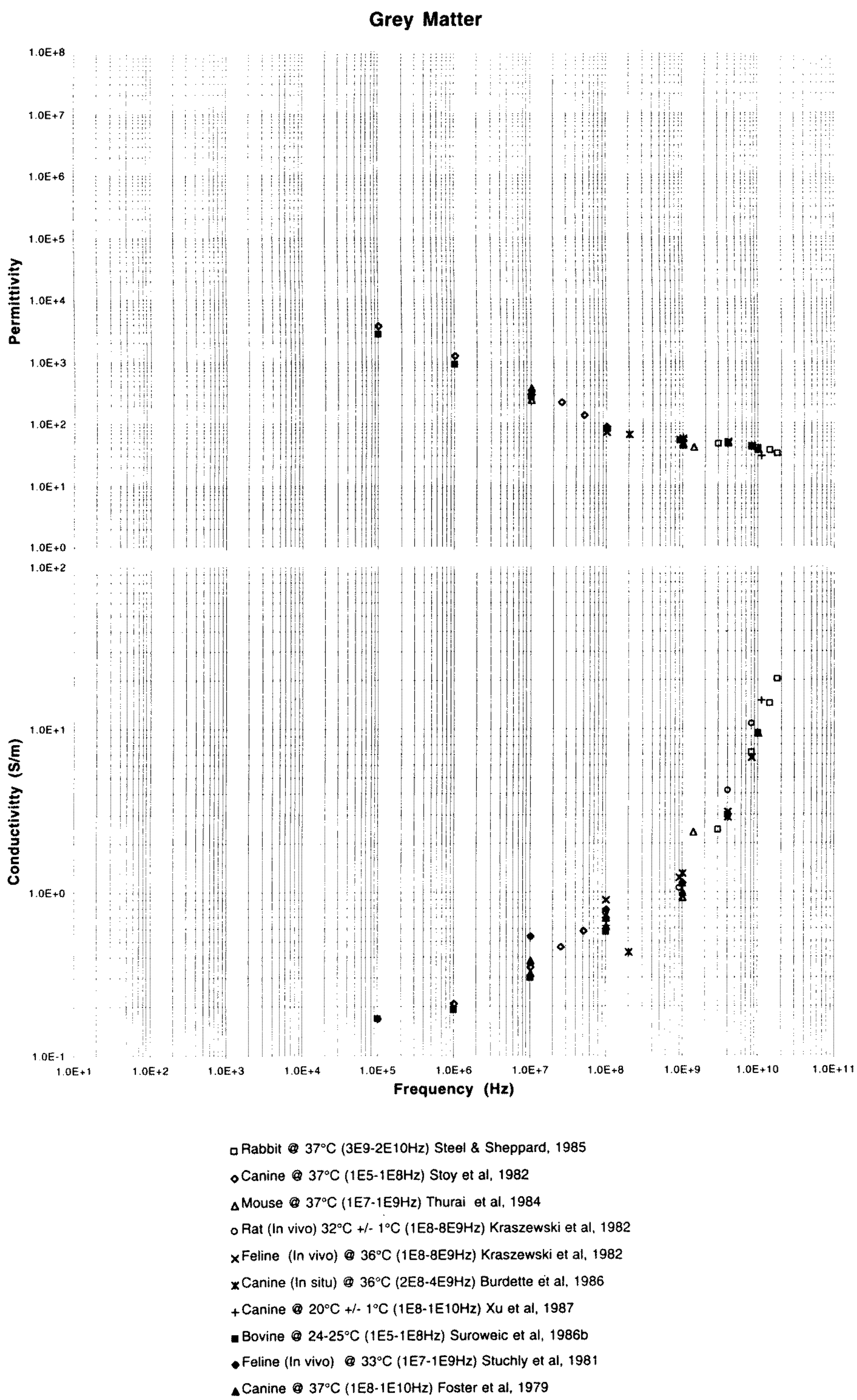


Figure 1. (*e*) Grey matter.

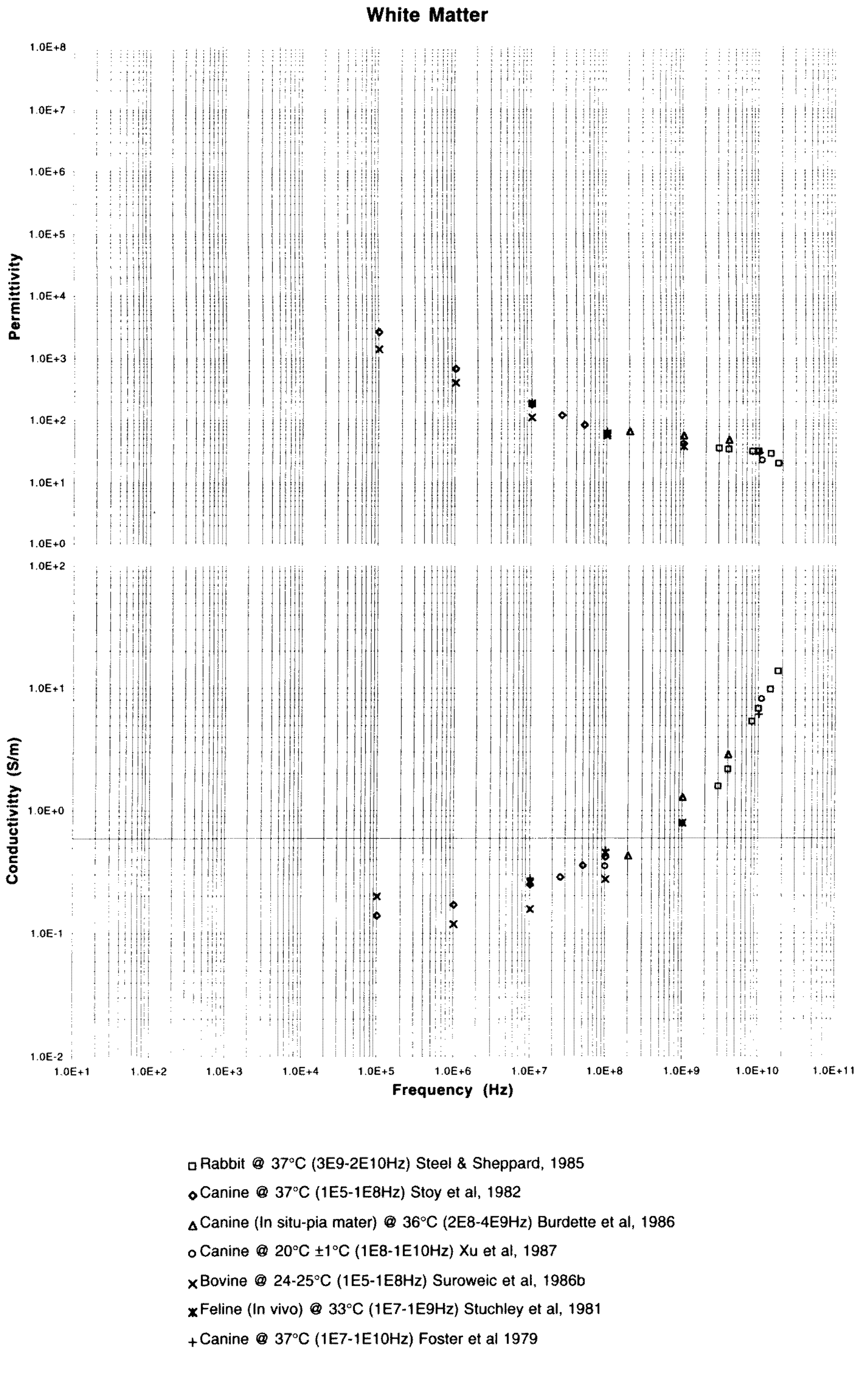


Figure 1. (*f*) White matter.

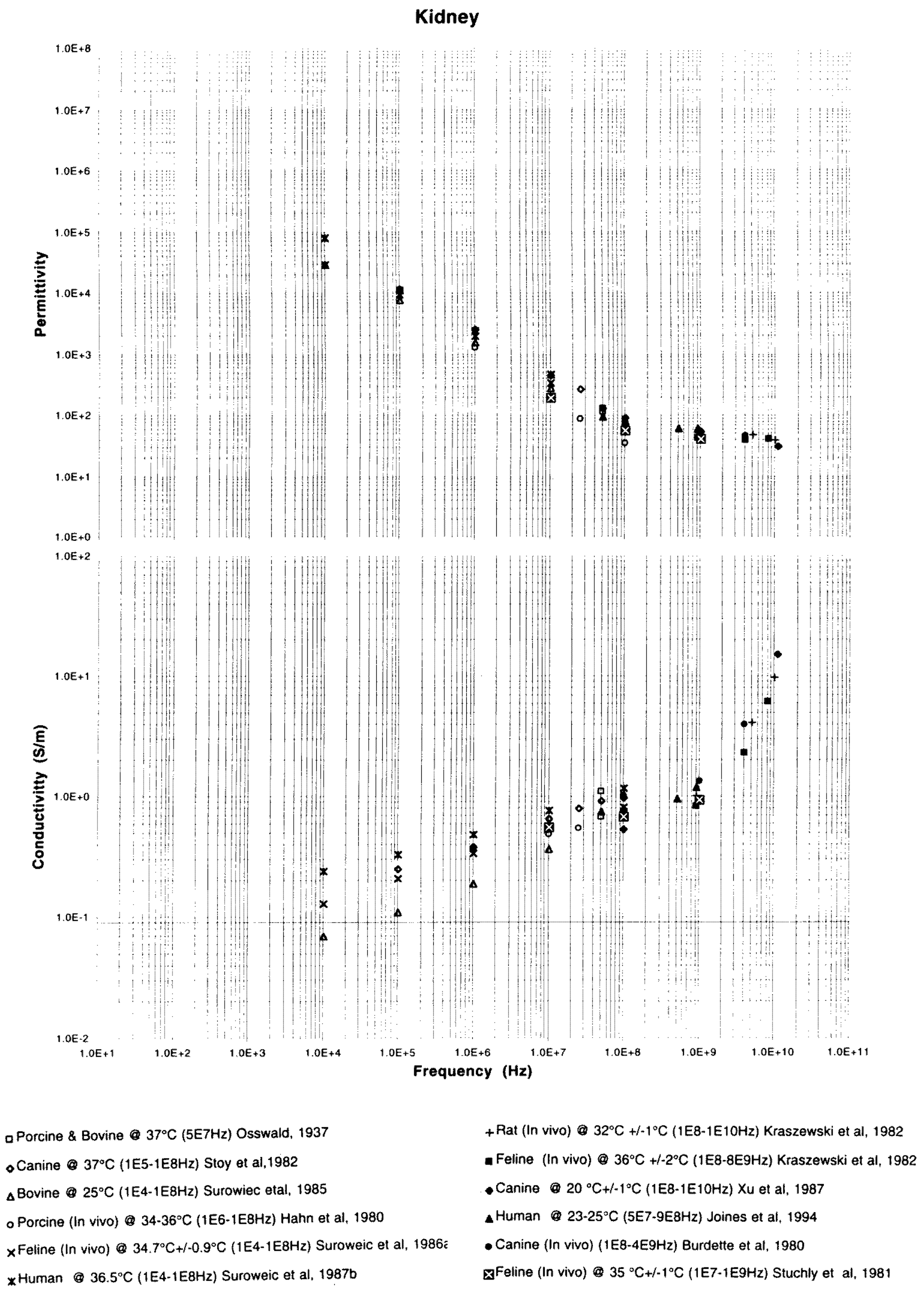


Figure 1. (*g*) Kidney.

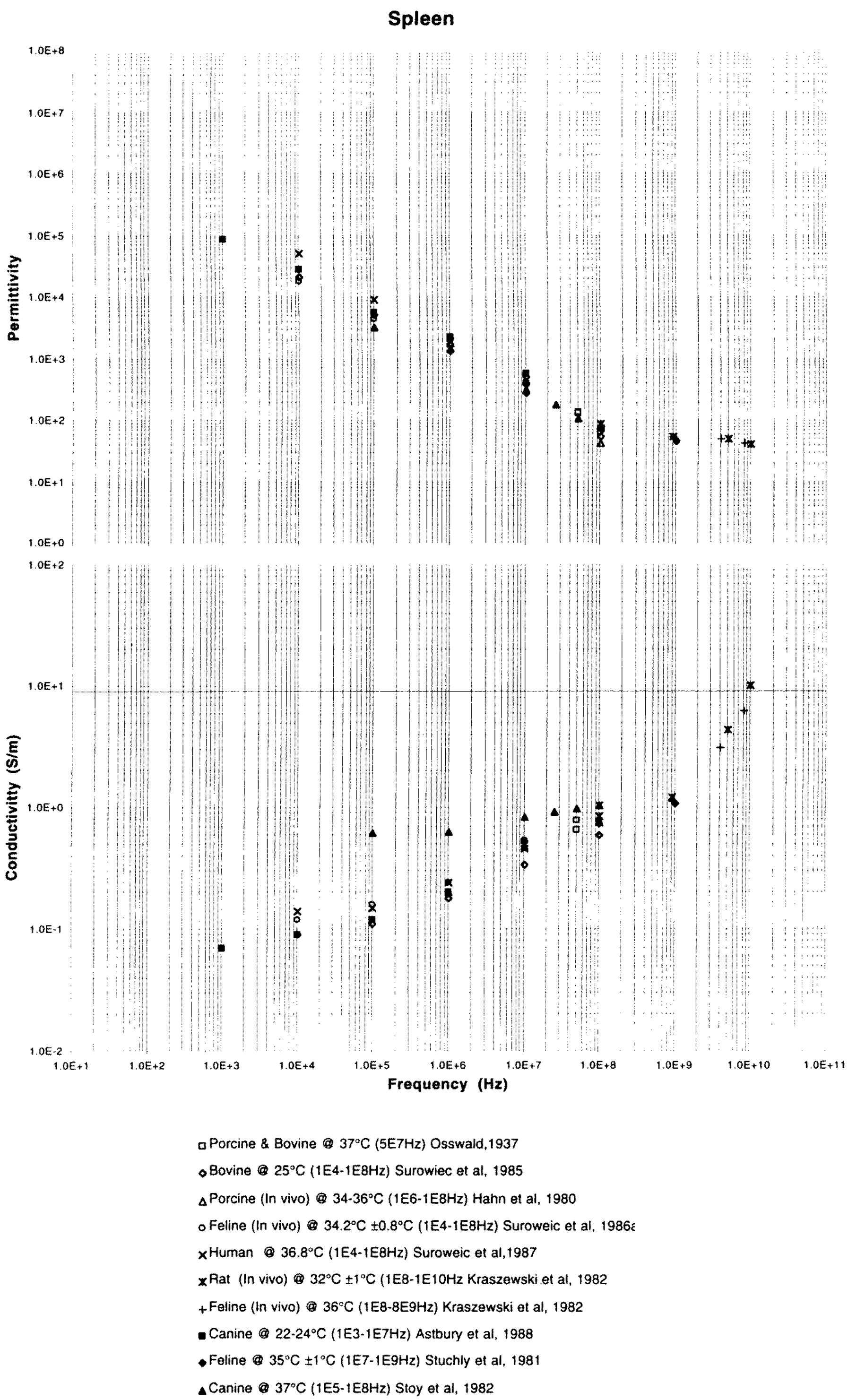


Figure 1. (*h*) Spleen.

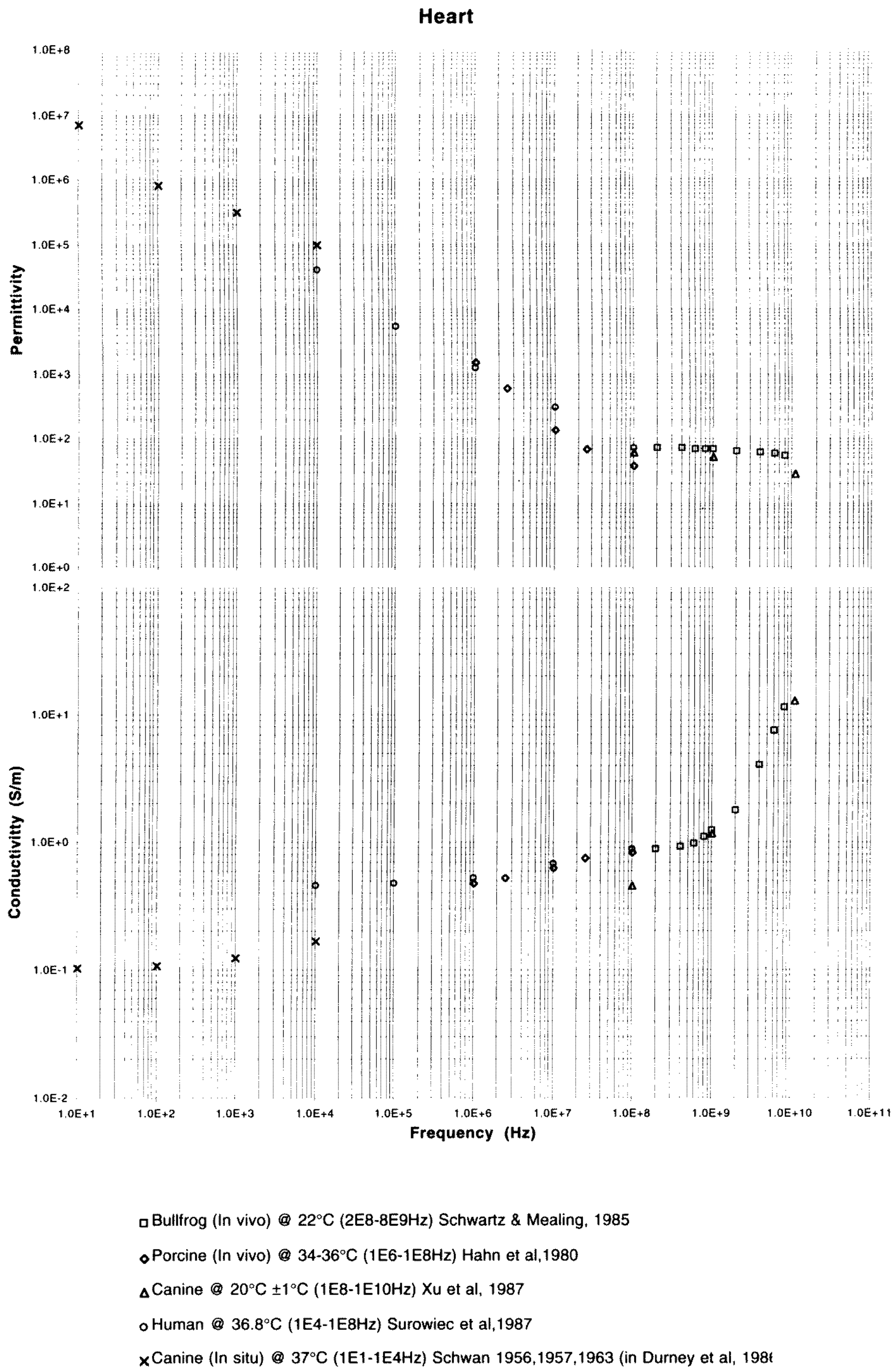


Figure 1. (*i*) Heart.

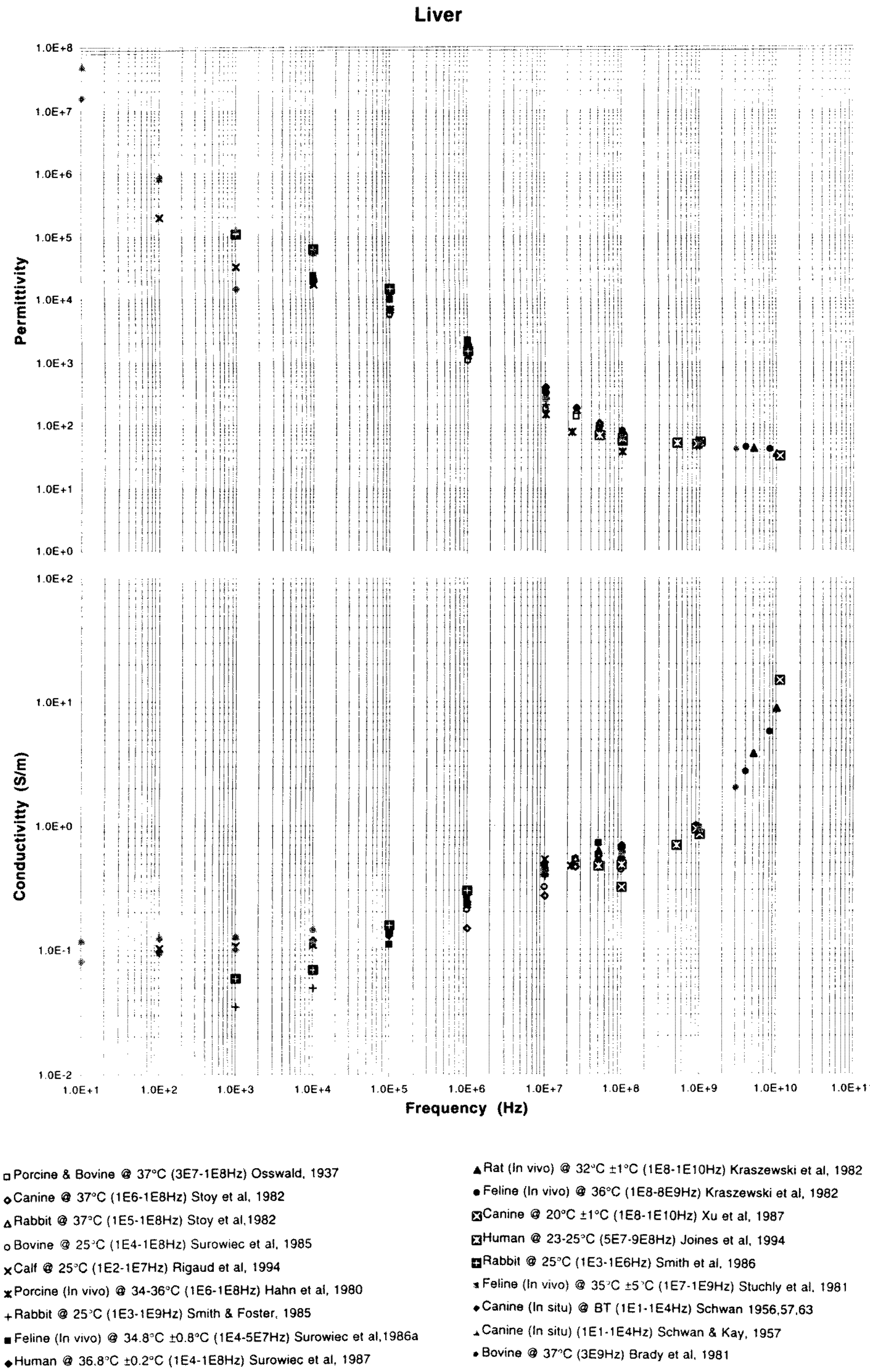
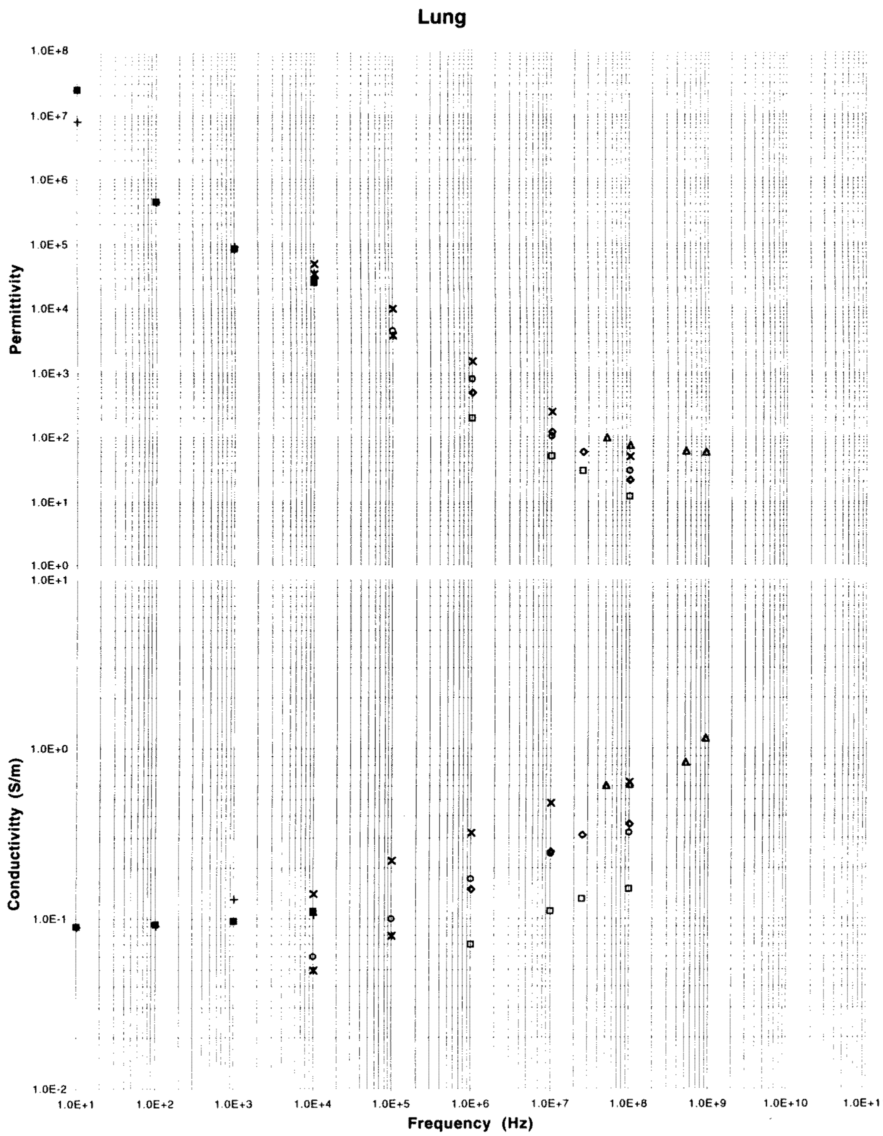


Figure 1. (*j*) Liver.



□ Porcine (In vivo-inflated) @ 34-36°C (1E6-1E8Hz) Hahn et al, 1980

◇ Porcine (In vivo-deflated) @ 34-36°C (1E6-1E8Hz) Hahn et al, 1980

△ Human @ 23-25°C (5E7-9E8Hz) Joines et al,1994

○ Feline (In vivo-inflated) @ 34°C (1E4-1E8Hz) Surowiec et al,1987

× Feline (In vivo-deflated) @ 34 °C (1E4-1E8Hz) Surowiec et al, 1987

⁎ Bovine @ 20°C (1E4-1E5Hz) Nopp et al, 1993

+ Canine (In situ) (1E1-1E4Hz) Schwan 1956b,57,63a (in Durney et al, 1986)

■ Canine (In situ-inflated) (1E1-1E4Hz) Schwan & Kay, 1957 (in Foster & Schwan, 1989

Figure 1. (*k*) Lung.

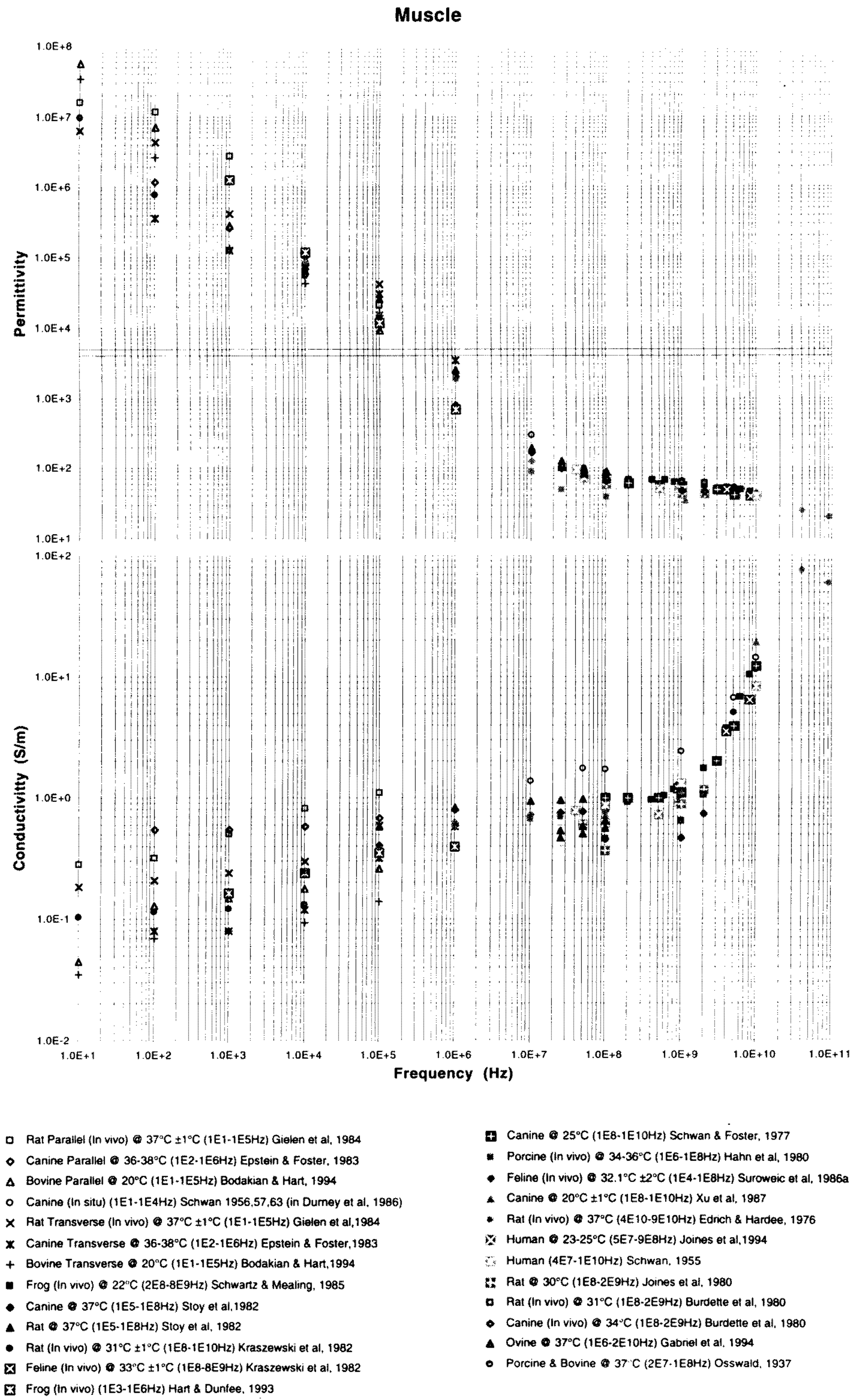


Figure 1. (*l*) Muscle.

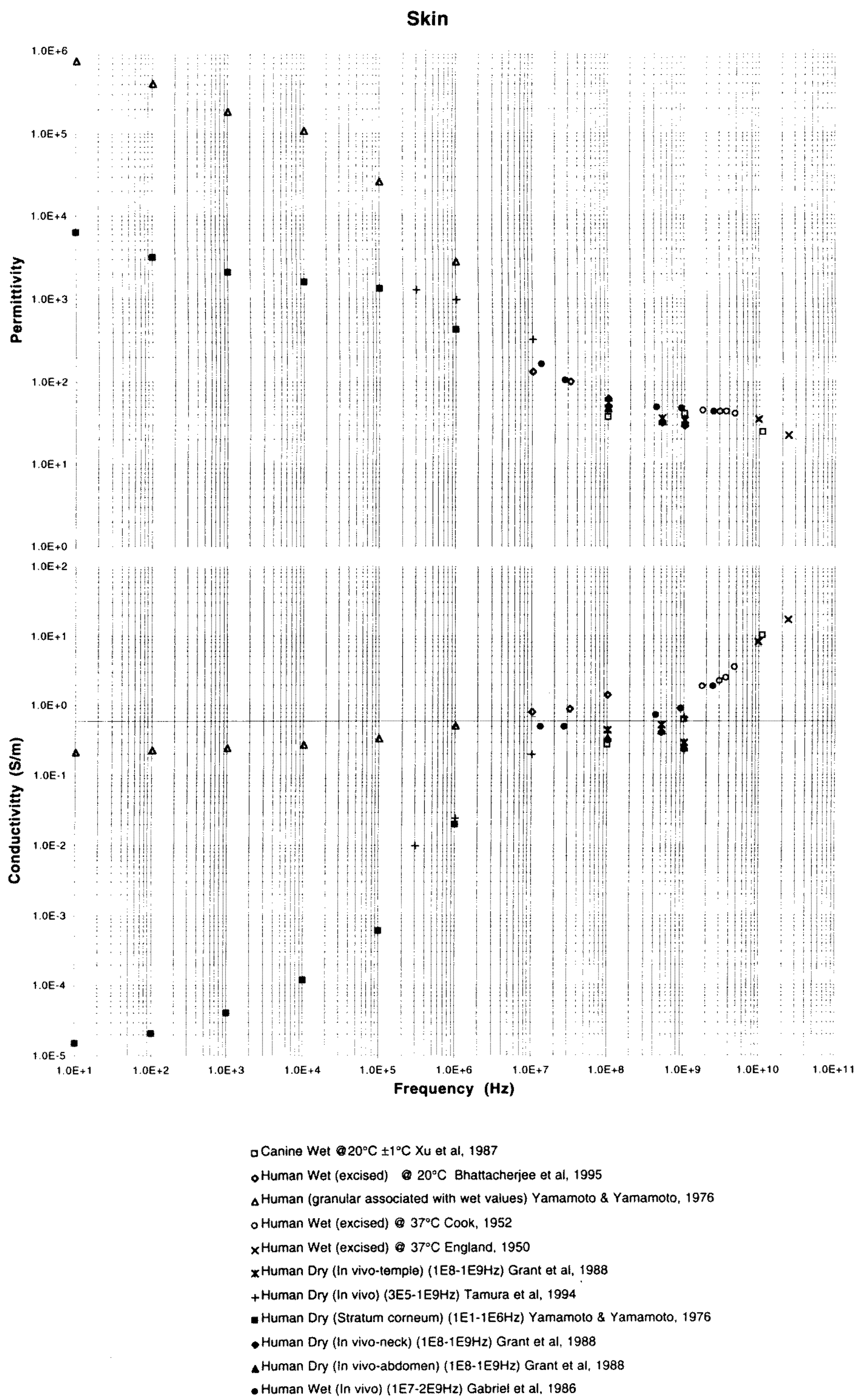


Figure 1. (*m*) Skin.

of the head, brain is well characterized above 100 kHz, but data for dura, cerebrospinal fluid and cartilage are not reported at all. For most tissues the data below 100 kHz are either very limited or non-existent. This omission is not a reflection of the interest in such data but a limitation imposed by measurement techniques not designed to cope with well known sources of systematic errors at low frequencies. Data for tissues such as muscle are well characterized in terms of number of reports, but illustrate the spread in values from studies that extend over limited frequency ranges. Averaging the values available at each frequency will distort the frequency dependence, which is best determined by measuring a sample across the whole range. These issues are addressed in the following two papers (Gabriel *et al* 1996a, b).

Acknowledgments

The authors wish to acknowledge Professor E H Grant for his help and encouragement. This project was supported by the US Air Force under contract F49620-93-1-0561.

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