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INTERACTIONS OF ELECTROMAGNETIC FIELDS WITH BIOLOGICAL MATERIAL

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1. Introduction

The effects of electromagnetic fields on biological materials have been observed and utilised for well over a century. Like with all physical agents, depending on the biological end points, the outcome of the interaction of such fields with people can be beneficial or detrimental; the same interaction mechanism can lead either way. The main differences are intentional application and control of the event in the case of biomedical applications as opposed to incidental or accidental exposure to such fields which, in excess, can lead to undesirable effects. Progress in the fields of exploitation of and protection from electromagnetic fields hinges on understanding the basic interaction mechanisms and the resulting biological response, questions that are not helped by the presence of endogenous bioelectric fields.

The acute effects which, depending on frequency, include cellular stimulation and tissue heating are well understood and, consequently, form the basis of numerous applications. The challenge facing scientists today is identifying and understanding other more subtle interactions that may occur at field intensity levels below the threshold for the known effects.

The study of such interactions requires that matter be modelled in quantum mechanical terms as discrete charges that react to the electric field. In practice, the classical theories, in which matter is considered as a continuum, are more commonly applied. The macroscopic theory of dielectric phenomena fall within the latter category.

Dielectric spectroscopy is an important tool in the study of interactions at the molecular level. The linear dielectric properties (relative permittivity ε' and total conductivity σ) describe the macroscopic behaviour of matter under the action of a low or moderate intensity electric field. The interpretation of dielectric properties in terms of molecular parameters entails the difficult extrapolation from phenomenological or macroscopic description of matter to a microscopic one. Models for such studies have, depending on their derivation, limited ranges of applicability and can coexist [1].

This paper will report on some aspects of dielectric studies of biological materials with reference to the underlying cellular and molecular responses. It will draw on recent studies to illustrate the dependence of the dielectric properties on the structure and composition of material and hence, in the case of biological materials, on the physiological state.

2. The Dielectric Properties of Biological materials

The dielectric properties of biological materials are highly frequency dependant in the range from hertz to gigahertz. The spectrum is characterised by three main dispersion regions referred to as α, β and γ regions at low, medium and high frequencies. Each of these relaxation region is, in its simplest form, the manifestation of a main polarisation mechanism. These are, in order of increasing frequency, counterion polarisation, interfacial polarisation and dipolar orientation.

The main mechanism responsible for the α dispersion in tissue is one of ionic diffusion in the electrical double layers adjacent to charged cellular membranes. Theoretical studies of such phenomena predict large values for the permittivity at low frequencies and these have been observed. Any change in the constitution of the ionic medium of the cells is expected to affect the nature and extent of this counterion polarisation. In biological material, such changes may occur in response to alterations in the metabolic activity or other physiological events including death. For this reason, one would expect significant differences between the *in vivo* and *in vitro* α dispersion of tissues. Such differences have been observed experimentally within hours of death [2-3]. A recent review of the literature pointed to the scarcity of data in the frequency range below 10 kHz [4]. This state of affairs was due to inherent experimental difficulties and not lack of interest in this frequency range. A recent study [5] identified the two main sources of systematic errors in the frequency range 10 Hz to 10 MHz and provided corrections procedures for their alleviation (Fig. 1). An example of such data is presented in Fig. 2 together with results at higher frequencies to illustrate the dielectric spectrum for tissues over ten frequency decades. Data from [5] fall well within the corresponding values in the literature as illustrated in Fig. 3 in the case of the dielectric properties of liver tissue.

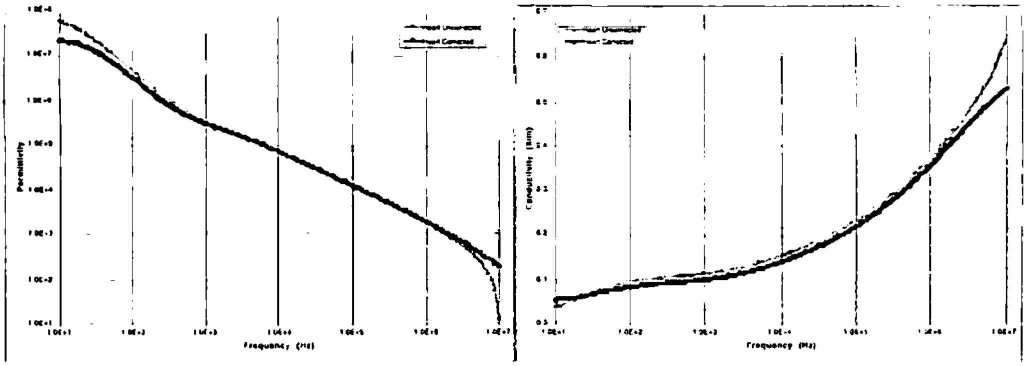

Fig. 1. The dielectric properties of heart tissue obtained from impedance measurements before and after correction for stray inductance at the high frequency end and electrode polarisation at low frequencies.

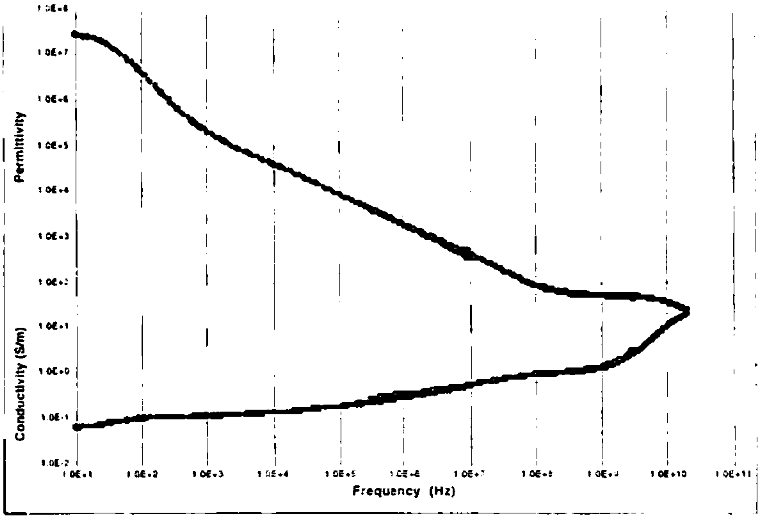

Fig. 2 The dielectric spectrum of kidney cortex tissue obtained from three sets of measurements.

Interfacial polarisation occur in heterogeneous materials where interfaces act as barriers to charge drift leading to polarisation and subsequent relaxation effect. The theory underpinning this effect is commonly known as the Maxwell-Wagner effect and, in biological tissues, occurs at the level of the cellular membrane and is described by the β dispersion in the 100's of kHz region. The destruction of cellular membrane is signalled by significant changes in this dispersion. An example of such an effect is given in Fig. 4 which shows the permittivity and conductivity spectrum of muscle before and after the destruction of the cellular membrane through freeze-thaw injury. Similar differences have been observed in measurements with the electric field along and across the muscle fibres [5 - 6]. Significant differences in the β dispersion were also reported between healthy and cancerous tissue [7].

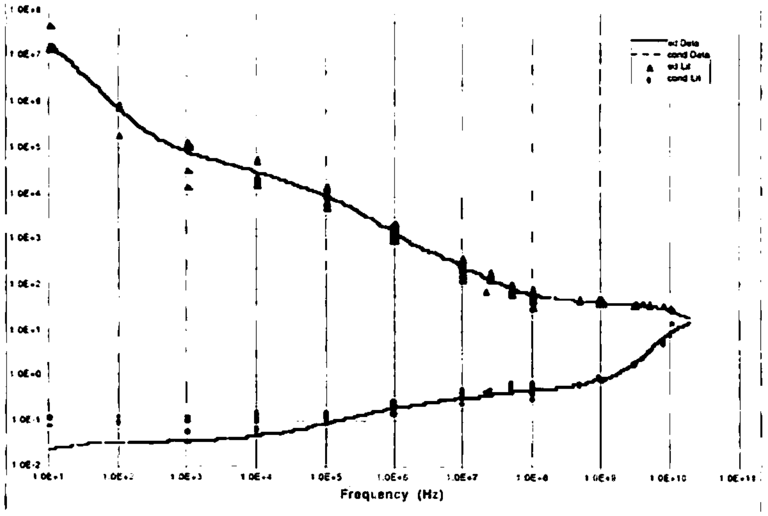

Fig. 3 Comparison between experimental data from [5] and corresponding literature data.

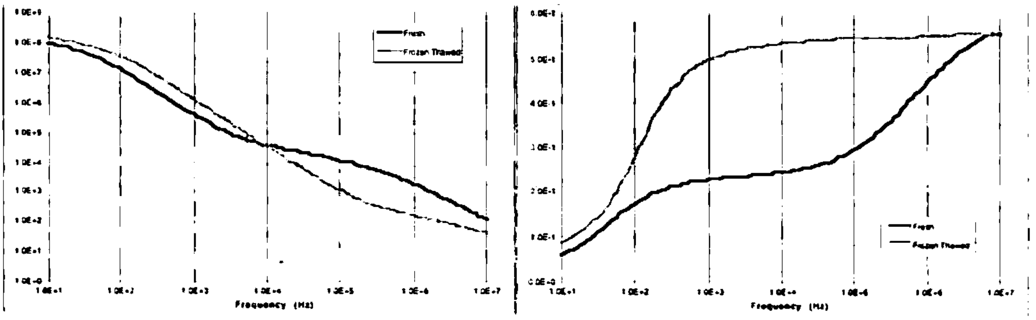

Fig. 4 Effect of freeze-thaw injury on the permittivity and conductivity of muscle tissue. The conductivity on the right side graph is in S/m . The data has not been corrected for electrode polarisation and is presented to show the differential due to damage to the cell membrane.

Another important interaction mechanism in tissue and other biological materials is the orientation of dipolar structures. These are mostly polar organic and inorganic molecules the most important of which being the water molecule. The theory of dipolar polarisation was developed by Debye, Onsager, Kirkwood, and later Fröhlich and others who obtained expressions for the dielectric dispersion in terms of molecular parameters [1]. The relaxation of tissue water is described in the γ dispersion. Conditions giving rise to a change in the water content of tissue are reflected in the parameters of this dispersion [8]. Studies of the γ dispersion and in particular the apparent lengthening of the relaxation time as a function of the water content of tissues [9] raises important questions about the microwave heating of tissue and the distribution of energy absorption at the molecular level. Such studies are relevant to the determination of whether or not electromagnetically induced heating is different in its end result from any other form of heating.

3. Related studies

One aspect of the study of the interaction of electromagnetic fields with people is the measurements of internal fields in specially formulated physical models or phantoms that mimic the response of the body. The relevant parameters are the shape and dielectric properties of the various tissues. These are the properties to match when formulating phantoms.

Phantoms are developed for specific exposure situations, as needed. An interim stage in the development of a head phantom is given in Fig. 5 to illustrate the anatomical details that are carried through in a model used for the assessment of exposure to electromagnetic radiation from mobile communication equipment [10].

Fig. 5 Interim stage in the development of a head phantom [10].

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