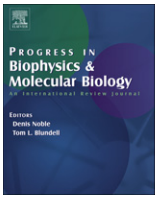
Progress in Biophysics and Molecular Biology 107 (2011) 434–438

Contents lists available at SciVerse ScienceDirect

Progress in Biophysics and Molecular Biology

journal homepage: www.elsevier.com/locate/pbiomolbio



Review

Dielectric properties of tissues; variation with age and their relevance in exposure of children to electromagnetic fields; state of knowledge

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A R T I C L E I N F O

Article history:
Available online 3 September 2011

Keywords:
Dielectric properties
Biological tissues
Dosimetry
Children

A B S T R A C T

This paper reviews and summarises the state of knowledge on dielectric properties of tissues; in particular those obtained as a function of age. It also examines the impact of variation in dielectric data on the outcome of recent dosimetric studies assessing the exposure of children to electromagnetic fields.

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1. Introduction

One of the main inputs required in the dosimetry studies assessing the exposure of people to electromagnetic fields (EMF) are dielectric properties of different body tissues which determine the interaction of the fields with the human body. Accurate knowledge of the dielectric properties of tissues is required in order to calculate the energy deposition when they are exposed to EMF.

Dielectric properties of tissues are frequency dependent and exhibit systematic changes due to the physiological state of the tissue; for instance the intactness of cellular membrane and the water content of the tissue. The dielectric spectra of tissues consist of three main dispersions predicted by known interaction mechanisms (Fig. 1). The α-dispersion is characterised by the very large permittivity values that are produced by ionic diffusion processes at the site of the cellular membrane at very low frequencies (below a few kHz). At intermediate frequencies (kHz region), the β dispersion occurs due to the polarisation of the cellular membrane. Finally, the γ dispersion at microwave frequencies is mainly due to the polarisation of water molecules inside the tissue. The dielectric spectrum of biological tissues can be mathematically modelled by one or more terms of the well-known Cole–Cole expression (Cole and Cole, 1941):

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

Where $\hat{\varepsilon}$ is the complex relative permittivity, ω the angular frequency and the Cole–Cole parameters have their usual significance. Modelling the dielectric properties of tissues using Equation (1) facilitates their incorporation in numerical simulations of human exposure to electromagnetic fields.

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doi:10.1016/j.pbiomolbio.2011.08.007

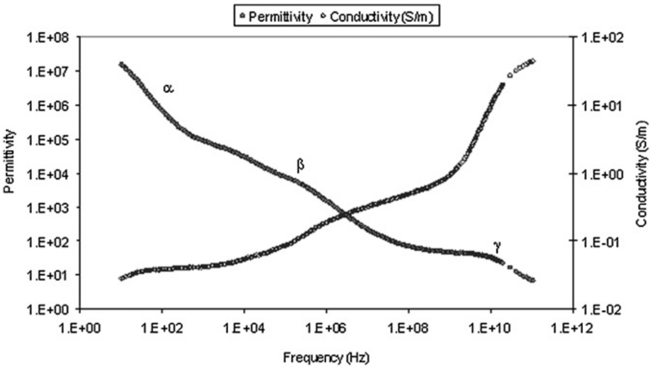

Fig. 1. Dielectric spectrum of ovine liver (Gabriel et al. 1996b).

At radiofrequencies, the metric used for assessing people's exposure is the Specific Energy Absorption Rate (SAR) expressed in watts per kilogram (W kg^{-1}). SAR is a function of the electric field induced in the body at any one point and the conductivity of the body tissue at that point:

$$\mathrm{SAR} = \sigma\frac{|E^2|}{\rho} \tag{2}$$

where σ is the conductivity of the tissue in S m^{-1}, ρ is mass density of the tissue in kg m^{-3} and E the root mean square (rms) electric field strength (V m^{-1}).

Dielectric properties of tissues and their variation with frequency is well studied, reported and reviewed (Schwan and Foster, 1980; Pethig, 1984; Pethig and Kell, 1987; Gabriel et al., 1996a,b,c). While, the earlier studies focused on the interaction mechanisms, later ones aimed to provide a reliable and accurate database of dielectric properties of different body tissues across the frequency spectrum. These data are a necessary input in the electromagnetic dosimetry studies where the exposure of people to external fields are assessed.

Until recently, the literature data consisted mostly of dielectric properties of tissues from mature animals (Gabriel et al., 1996 a–c), usually used to simulate adult models of the human head/body. Two earlier studies had reported on systematic changes in the dielectric properties of ageing brain tissues (Thurai et al., 1984, 1985). In the last few years, and due to substantial concern about the possible differences between the exposure of children and adults to electromagnetic fields, the focus of many studies has been shifted towards the development of childrens' head/body models. To provide relevant dielectric data for children's models, several studies have been carried out on dielectric properties of animal tissues from a range of ages (Peyman et al., 2001, 2007; Schmid and Überbacher, 2005; Peyman and Gabriel, 2010). These studies have triggered discussions on the extent to which the variation of dielectric data as a function of age would affect the results of dosimetry studies, and consequently the possible implications for the exposure of children.

This paper summerises the current knowledge of dielectric properties of tissues over a wide frequency range and their variation as a function of age. It also reports the effect of these changes on dosimteric studies at radiofrequencies.

2. Dielectric properties of tissues, state of knowledge

2.1. 1996 database

In 1996, Gabriel et al. carried out a systematic review of almost half a century's literature available at the time in terms of the dielectric properties of tissues over ten frequency decades. They then carried out an extensive experimental study on a large number of biological tissues at body temperature using three different measurement techniques spanning the frequency range of 10 Hz–20 GHz (Gabriel et al., 1996b). Their experimental results showed good agreement between data obtained from three experimental setups in the overlapping frequency ranges. The data were also largely in good agreement with the corresponding values in the literature. Finally, Gabriel et al. (1996c) used their experimental data, complemented by the data surveyed from the literature, to develop a parametric model (consisting of four Cole–Cole terms plus one ionic conductivity term) to describe the variation of dielectric properties of tissues as a function of frequency. The Cole–Cole model parameters later became available on the internet (Gabriel and Gabriel, 1997) and have been used extensively since to reconstruct the dielectric spectrum of each tissue in dosimetry studies.

2.2. MTHR study

Although the 1996 database has been used extensively in dosimetric studies, there were still some gaps and limitation associated with it. In particular, since most measurements were carried out on excised tissues, critics argued that data pertaining to live tissue would be more relevant in bioelectromagetic studies. In addition, low frequency dielectric data are associated with larger uncertainties due to practical difficulties such as electrode polarisation and only few values are available for them in the literature. Therefore, the authors of the 1996 database have cautioned the use of the Cole–Cole model for lower frequency parts of the spectrum as the best estimate based on the literature data before 1996, until more reliable and accurate data becomes available. Also, a better understanding of the uncertainty associated with dielectric measurements was needed.

To fill the above gaps and update the state of knowledge on the subject, a systematic study was carried out as part of the UK's Mobile Telecommunication Health Research (MTHR) program. The main objective of the study was to review the literature data post 1996 and obtain and analyse extensive and novel experimental data acquired from measurements on “live” animals at microwave frequencies. The study was also aimed to identify different random and systematic sources of errors associated with the dielectric measurements and develop a procedure to assess the total combined uncertainty for the dielectric data.

Dielectric data (permittivity ε' and conductivity σ) were collected from live porcine tissues, which are thought to be a good animal substitute to human tissue and would make a good basis for comparison with the data from the 1996 database that were mostly derived from measurements on excised ovine tissue (Peyman et al., 2005, 2007).

For most of the tissues (brain and abdominal tissues) the new data were in good agreement with the 1996 database. However, in the case of skeletal tissues, the large numbers of independent dielectric measurements on both skull and long bone of different pigs show generally higher values than those reported in the Gabriel et al. (1996c) database (Fig. 2). These high values could possibly be due to the differences in the species and the age of the animals used in MTHR study and other studies. As it is apparent from Fig. 2, there is a big difference between data collected from young pigs (50 kg) and those of the older pigs (250 kg mature sows). The 1996 database values are closer to data gathered from older animals.

Another important outcome of the MTHR study was that it did not report any systematic difference between dielectric data collected under *in-vivo* and *in-vitro* conditions at microwave frequencies