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NOTE

Cole–Cole parameters for the dielectric properties of porcine tissues as a function of age at microwave frequencies

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Abstract

We have applied the Cole–Cole expression to the dielectric properties of tissues in the frequency range 0.4–10 GHz. The data underpinning the model relate to pig tissue as a function of age. Altogether, we provide the Cole–Cole parameters for 14 tissue types at three developmental stages.

Introduction

Modelling the dielectric properties of tissues facilitates their incorporation in numerical simulations of human exposure to electromagnetic fields. The latter is an active field of study that matured over the last two decades fuelled by the concurrent eruption of wireless telecommunication technology. In recent years, several research groups developed numerical models of children of various ages to obtain a realistic assessment of their exposure in view of their increasing exposure to wireless communication and connectivity devices (Anderson 2003, Christ *et al* 2005, Dimbylow and Bolch 2007, Lee *et al* 2009).

There have been numerous references in the literature to the variation of the dielectric properties of tissue with age (Thurai *et al* 1984, 1985, Peyman *et al* 2001, 2007, Peyman and Gabriel 2003, Schmid and Überbacher 2005). While scientific rigour requires that the effects of such variation be investigated when using models of children, the published data were not deemed sufficiently comprehensive to warrant their incorporation in most of the studies.

Recently, Peyman *et al* (2009) published the dielectric properties of 14 porcine tissue types, at microwave frequencies, as a function of age. They tabulated the permittivity and conductivity at four frequencies commonly used by telecommunications devices to enable their use in exposure assessment. More useful, however, is the parameterization of the spectra to allow their use at any frequency or multiple frequencies within the confines of the model. In this note, we apply the Cole–Cole model to these data.

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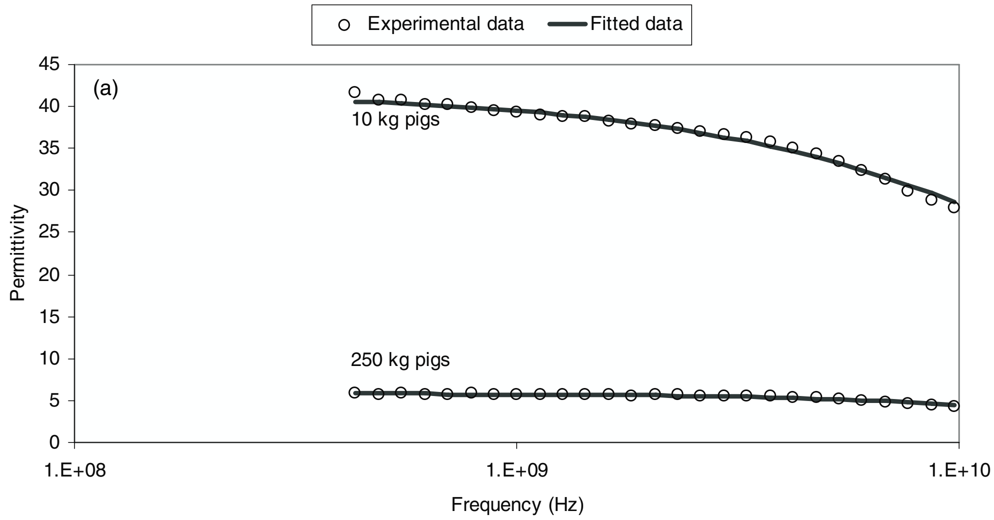

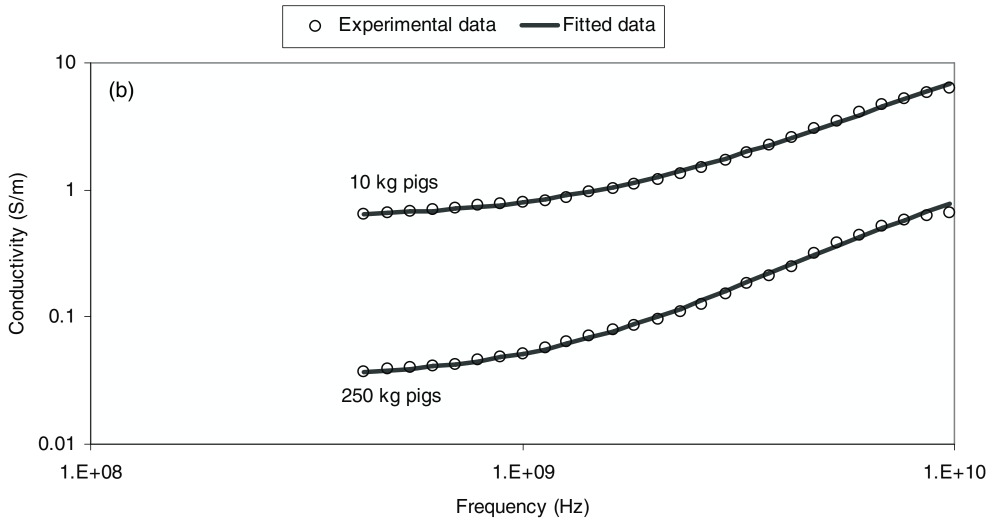

Figure 1. The experimental and fitted values of (a) permittivity and (b) conductivity for bone marrow (30%) of 10 kg and 250 kg pigs.

Materials and methods

The data considered for analysis are those of Peyman *et al* (2009). In brief, dielectric measurements were made on excised tissues of pigs falling into one of three groups: the average weight and age in each category were (i) 10.6 ± 1.3 kg and 37 days, (ii) 53.9 ± 4.6 kg and 90–105 days and (iii) 253.1 ± 30.7 kg and 626 days, covering the development stages from piglets to mature animals. Up to nine animals have been used at each age category and several measurements (at least six) were carried out on each tissue in order to construct a large data set and sound statistical representation. The extrapolation of animal data to human is a difficult and approximate step; in the case of dielectric properties it is more straightforward provided the corresponding animal and human tissues have similar structure

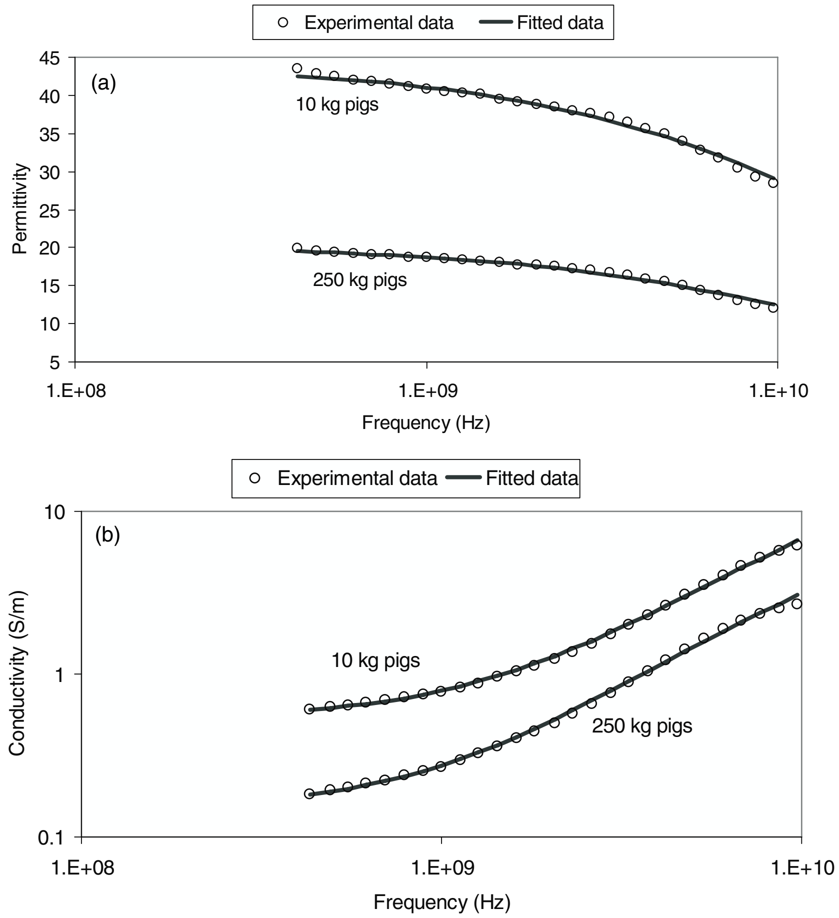

Figure 2. The experimental and fitted values of (a) permittivity and (b) conductivity for skull of 10 kg and 250 kg pigs.

and composition. At microwave frequencies, the most important parameter is the tissue water content. With respect to the variation with age, one can reasonably assume correspondence at the beginning and end points of the growth curve, that is, the correspondence of very young children with a 10 kg pig and an adult human with a 250 kg animal. More tentatively, a 50 kg pig is at par with a prepubescent human (12–13 years old) on the basis of incomplete sexual maturity.

The Cole–Cole model was applied to the permittivity and conductivity in the frequency range of 0.4–10 GHz. In this frequency range the polarization of tissue water is the main contributor to the observed dielectric properties; its relaxation can be modelled by the well-known Cole–Cole expression (Cole and Cole 1941)

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

where $\hat{\varepsilon}$ is the complex relative permittivity, ω the angular frequency and the Cole–Cole parameters have their usual significance.

Table 1. Dielectric parameters of water dispersion in porcine tissues as a function of age obtained by fitting the experimental data at 37 °C to equation (1). The ± term corresponds to the 95% confidence interval.

Tissue/age	ε_s	τ_{relax} (ps)	σ_i (Sm^{-1})	α	RMSE[a]
Bone marrow 30%					
10 kg	41.80 ± 0.42	8.42 ± 0.63	0.59 ± 0.01	0.28 ± 0.02	0.52
50 kg	14.69 ± 0.20	10.72 ± 1.12	0.18 ± 0.01	0.24 ± 0.03	0.27
250 kg	5.84 ± 0.05	12.51 ± 1.10	0.033 ± 0.002	0.11 ± 0.03	0.09
Bone marrow 50%					
10 kg	41.34 ± 0.40	8.34 ± 0.61	0.58 ± 0.01	0.27 ± 0.02	0.52
50 kg	20.20 ± 0.31	9.80 ± 1.13	0.22 ± 0.01	0.25 ± 0.04	0.41
250 kg	8.08 ± 0.07	10.99 ± 0.90	0.049 ± 0.002	0.13 ± 0.03	0.13
Cornea					
10 kg	57.64 ± 0.43	7.76 ± 0.49	0.89 ± 0.01	0.22 ± 0.02	0.64
50 kg	54.69 ± 0.44	7.91 ± 0.52	0.85 ± 0.01	0.24 ± 0.02	0.63
250 kg	52.90 ± 0.36	8.18 ± 0.48	0.89 ± 0.01	0.18 ± 0.02	0.60
Dura					
10 kg	57.64 ± 0.46	7.04 ± 0.50	0.94 ± 0.01	0.26 ± 0.02	0.64
50 kg	53.24 ± 0.51	7.75 ± 0.59	0.86 ± 0.01	0.26 ± 0.02	0.68
250 kg	46.86 ± 0.40	9.82 ± 0.58	0.66 ± 0.01	0.23 ± 0.02	0.57
Fat					
10 kg	14.68 ± 0.18	10.49 ± 1.07	0.19 ± 0.01	0.15 ± 0.03	0.31
50 kg	13.33 ± 0.20	10.02 ± 1.26	0.17 ± 0.01	0.19 ± 0.04	0.30
250 kg	5.83 ± 0.06	10.22 ± 1.10	0.048 ± 0.002	0.14 ± 0.04	0.11
Grey matter					
10 kg	55.07 ± 0.73	5.69 ± 0.68	0.77 ± 0.02	0.34 ± 0.03	0.80
50 kg	54.24 ± 0.73	5.68 ± 0.70	0.80 ± 0.02	0.34 ± 0.03	0.81
250 kg	52.61 ± 0.55	6.23 ± 0.60	0.81 ± 0.01	0.29 ± 0.03	0.69
Intervertebral disc					
10 kg	61.36 ± 0.61	7.81 ± 0.60	1.21 ± 0.02	0.28 ± 0.02	0.78
50 kg	53.15 ± 0.44	9.18 ± 0.53	0.83 ± 0.01	0.26 ± 0.02	0.57
250 kg	50.83 ± 0.66	10.78 ± 0.84	0.83 ± 0.01	0.32 ± 0.02	0.67
Intervertebral disc centre					
10 kg	66.60 ± 0.39	6.20 ± 0.40	1.60 ± 0.01	0.21 ± 0.02	0.63
50 kg	66.88 ± 0.34	6.62 ± 0.37	1.53 ± 0.01	0.16 ± 0.02	0.60
250 kg	60.35 ± 0.49	6.39 ± 0.47	1.58 ± 0.01	0.29 ± 0.02	0.62
Long bone					
10 kg	29.59 ± 0.52	12.59 ± 1.39	0.28 ± 0.01	0.38 ± 0.03	0.40
50 kg	21.15 ± 0.47	16.21 ± 2.37	0.15 ± 0.01	0.38 ± 0.03	0.33
250 kg	16.26 ± 0.32	16.36 ± 2.14	0.07 ± 0.01	0.36 ± 0.03	0.25
Mammary fat					
10 kg			N/A		
50 kg	18.58 ± 0.25	9.93 ± 1.04	0.23 ± 0.01	0.20 ± 0.03	0.38
250 kg	15.03 ± 0.19	10.10 ± 1.08	0.18 ± 0.01	0.18 ± 0.04	0.31

Table 1. (Continued.)

Tissue/age	ε_s	τ_{relax} (ps)	σ_i (Sm^{-1})	α	RMSE[a]
Mammary glands					
10 kg					
50 kg			N/A		
250 kg	47.84 ± 0.38	8.05 ± 0.52	0.77 ± 0.01	0.22 ± 0.02	0.56
Skin					
10 kg	49.03 ± 0.62	7.80 ± 0.69	0.58 ± 0.01	0.34 ± 0.03	0.64
50 kg	47.23 ± 0.59	8.84 ± 0.76	0.57 ± 0.01	0.30 ± 0.03	0.69
250 kg	39.08 ± 0.54	10.38 ± 0.95	0.42 ± 0.01	0.26 ± 0.03	0.69
Skull					
10 kg	44.42 ± 0.54	8.84 ± 0.71	0.54 ± 0.01	0.33 ± 0.02	0.55
50 kg	37.54 ± 0.51	9.37 ± 0.82	0.46 ± 0.01	0.35 ± 0.02	0.48
250 kg	20.27 ± 0.27	13.23 ± 1.10	0.15 ± 0.01	0.29 ± 0.02	0.29
Spinal cord					
10 kg	39.33 ± 0.73	6.21 ± 0.92	0.44 ± 0.02	0.37 ± 0.04	0.70
50 kg	34.90 ± 0.83	6.54 ± 1.18	0.39 ± 0.02	0.38 ± 0.05	0.77
250 kg	25.87 ± 0.46	7.87 ± 1.07	0.28 ± 0.01	0.32 ± 0.04	0.51
Tongue					
10 kg	57.00 ± 0.60	8.35 ± 0.67	0.82 ± 0.02	0.26 ± 0.02	0.81
50 kg	56.43 ± 0.60	8.22 ± 0.66	0.80 ± 0.02	0.26 ± 0.02	0.80
250 kg	57.64 ± 0.42	8.71 ± 0.48	0.82 ± 0.01	0.22 ± 0.02	0.62
White matter					
10 kg	42.77 ± 0.74	6.50 ± 0.89	0.50 ± 0.02	0.35 ± 0.04	0.75
50 kg	37.13 ± 0.81	7.01 ± 1.10	0.42 ± 0.02	0.38 ± 0.04	0.73
250 kg	30.67 ± 0.53	8.13 ± 1.04	0.35 ± 0.01	0.32 ± 0.04	0.59

[a] Root mean square error.

All the parameters were fitted except for the ε_∞ value which was fixed at 3 (for tissues with very low water content this value was fixed at 2). This assumption is based on the knowledge that the corresponding value for water is about 5 and also the fact that the water content of tissue is of the order of 60%. Moreover, a variation of about 25% in the value of ε_∞ has very little effect on the other fitted parameters.

Equation (1) is an empirical formulation, not intended for detailed mechanistic investigations but quite suitable for comparative studies where there is a known, dominant interaction mechanism such as the molecular rotation of tissue water (Gabriel *et al* 1996).

The analysis was carried out using a complex curve-fitting program using iteration and least-squares minimization of the root mean square error (RMSE) or the sum of squared residuals (residual being the difference between the observed value and the value provided by the model).

The data for each tissue at each age were fitted separately. The tissues considered in this study are bone marrow, cornea, dura, fat, intervertebral disc, intervertebral disc centre, grey matter, long bone, mammary fat, skin, skull, spinal cord, tongue and white matter. Data for mammary glands from the 250 kg pigs are also included in this analysis. The dielectric properties of bone marrow have been obtained at two positions (30% and 50%) from the distal end of the bone.

Results and discussion

Figures 1 and 2 show the measured and fitted dielectric data for bone marrow and skull tissues at different ages. For all the tissues the fitted parameters and 95% confidence intervals at different ages are shown in table 1. Included in this table are also the RMSE values of each fit.

The Cole–Cole parameters for water at 37 °C calculated from Liebe *et al* (1991) are as follows:

$$\varepsilon_\infty = 4.9, \qquad \varepsilon_s = 74.3 \qquad \text{and} \qquad \tau = 6.27\,\text{ps}.$$

By comparison, ε_s for tissue is lower and decreases with age which correlates with the tissue water content. The trend with age is not statistically significant for cornea, grey matter, mammary fat and tongue. There is also a decrease with age in σ_i and an increase in τ which also, indirectly, correlate with the water content and the state of water in tissue (Grant *et al* 1978, Gabriel *et al* 1983).

The predictions of the model for all tissues at all frequencies agree with the experimental values to well within the stated experimental errors if these are taken to be the standard error of mean multiplied by a factor of 3 (effectively 99% confidence interval). At the frequencies tabulated in Peyman *et al* (2009), the agreement is much closer.

The limits of the model are strictly those of the underpinning data, which are in the range of 0.4–10 GHz. It is important to note that the fitted Cole–Cole functions presented in table 1 are only valid for the frequency range of 0.4–10 GHz, and they should not be extrapolated to lower or higher frequencies.

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