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Review

Dielectric Properties of Biological Tissue: Variation With Age

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The dielectric properties of whole brain, skin, and skull were determined experimentally in the frequency range 300 KHz–300 MHz. Tissue samples were excised from 10, 30, and 70 day old Wistar strain rats. The data are presented in graphical format and compared to previously published data in the frequency range 0.1–20 GHz. Good agreement is observed between the two data sets. At frequencies in excess of about 100 MHz, where the γ dispersion is dominant, the permittivity and conductivity increase monotonically with decreasing age. At lower frequencies, the site of the β dispersion, a change in the frequency dependence of the dielectric parameters is observed and is most evident in the spectra for brain and skin. This is attributed to changes in the tissue structure. Age-related dielectric data, available for 9 of the 34 tissues, were incorporated in a numerical plane wave exposure dosimetry study on anatomically heterogeneous rat models with body sizes corresponding to the ages of 10, 30, and 70 days at a number of spot frequencies from 27 to 2000 MHz. The results reveal that the variation in the dielectric properties affect the whole body SAR by less than 5% with the most conservative value (highest SAR) obtained when 70 day properties are used. Bioelectromagnetics Supplement 7:S12–S18, 2005. © 2005 Wiley-Liss, Inc.

Key words: brain; skin; skull; bone; Wistar rat and dosimetry

INTRODUCTION

There is a great deal of information in the literature on the dielectric properties of tissues. Most of the data originate from measurements on samples from fully-grown animals. A few studies reported systematic changes in the dielectric properties of brain tissue as a function of the age of the animal [Thurai et al., 1984, 1985]. More recently, Peyman et al. [2001] reported dielectric data for several tissue types, including brain tissue, obtained from newborn to fully-grown rats in the frequency range 130–10 GHz. Their data on brain tissue agreed reasonably well with Thurai et al. and indicated similar trends for other tissues. Inevitably, questions arose about the significance of such findings for dosimetry in animal exposure experiments and about any possible implications for the exposure of children. On the face of it, variations in dielectric properties must impact on dosimetry; however, as many authors found out, the extent of the effect is dependent on numerous factors including exposure parameters and on the metric used for dosimetry [Hurt et al., 2000; Mason et al., 2000; Gajsek et al., 2001a,b].

This study will deal with some of these issues, first by reporting further dielectric data at intermediate frequencies (300 KHz–300 MHz) and second, by making a preliminary assessment of their impact on the exposure of rodents to plane wave fields.

Biological material is a mixture of water, ions, and organic molecules organized in cells, sub-cellular structures, and membranes, and its dielectric properties are highly frequency dependent in the range from Hz to GHz. The spectrum is characterized by three main dispersion regions referred to as α, β, and γ regions at low, intermediate, and high frequencies. Each of these regions is, in its simplest form, the manifestation of a dominant polarization mechanism.

The data reported in Peyman et al. [2001] fall mainly in the γ dispersion region that is dominated by the dielectric response of the aqueous component. The 300 kHz–300 MHz range is the site of the β dispersion. It originates from a polarization mechanism commonly known as the Maxwell–Wagner effect, whereby interfaces act as barriers to ionic charge drift leading to

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polarization and subsequent relaxation effects. In biological tissues, the β dispersion occurs at the level of the cellular membrane. Changes in cellular structure and their ionic environment affect this dispersion region.

The intermediate frequency (IF) data will be briefly reported here; a full account will be the subject of a separate publication. In particular, a comparison will be made with Peyman et al. [2001] data, which will be referred to as high frequency (HF) data for identification purposes.

The IF and HF data pertain to rat tissue and are therefore particularly relevant in the assessment of exposure of this animal type. Consequently, age-related dielectric data were incorporated in a numerical plane-wave exposure dosimetry study on anatomically heterogeneous rat models with body sizes corresponding to the ages of 10, 30, and 70 days at a number of spot frequencies from 27 to 2000 MHz. Moreover, we varied the dielectric properties in isolation to view their contribution without interference from the large, frequency-dependent effect of animal size. These results will be reported briefly here and fully in a separate publication [Alfadhl et al., 2005].

DIELECTRIC PROPERTIES—VARIATION WITH AGE

The dielectric properties of animal tissue (relative permittivity ε and conductivity σ) were determined experimentally using a previously reported procedure [Gabriel et al., 1994]. A full account of the study, including data on brain, skin, skull, thigh muscle, liver, kidney, spleen, and heart tissues is given in Peyman and Gabriel [2003]. This syudy will report the data for brain, skin, and bone excised from 10 to 70 day old Wistar strain rats, measured at 37 °C. Rats were obtained from the animal house of Guy's Hospital (London, UK). A trained technician sacrificed them using CO_2 and performed the dissections. All national animal welfare regulations were adhered to.

Measurement Procedure

All measurements were performed within 3–5 h of the sacrifice of the animal. Care was taken to avoid loss of moisture from the tissue and to reduce to a minimum, the handling of the samples. No preservative material has been used. Tissues were kept in small containers and placed in a water bath to maintain a 37 °C temperature. In case of tissues that are too thin to provide sufficient sample volume, several tissue layers were used. The skin was shaved prior to measurement. In view of the small size of the rat brain, the whole brain was sampled and no attempt was made at separating Gray and white matter. Five tissue samples from each of ten animals per category were used to provide the final database.

The measurement were made in the frequency range of 300 kHz–1 GHz using a 10 mm (inner diameter of the outer conductor) open-ended coaxial probe and a computer controlled network analyzer, following a previously reported procedure [Gabriel et al., 1994]. Care was taken to minimize all known sources of systematic errors. The network analyzer was calibrated, and the calibration validated and maintained throughout the measurement period. The sample size was kept within the optimum range (sample at least twice the probe diameter) to ensure a semi-infinite lossy sampling volume [Gabriel et al., 1994]. Uncertainties due to variation in the temperature of the sample were minimized by maintaining probe and sample at the same temperature, and keeping the samples in the water bath between measurements.

Measurement Uncertainty

Biological tissues are inhomogeneous and show considerable variability in structure and composition, and therefore in dielectric properties. Such variations are natural and constitute the main source of uncertainty for tissue data, exceeding by far the sum of all contributions from the measurement procedure and instrumentation. For all tissues except skin and skull bone, the observed variability, expressed as standard deviation percent, ranged from ±1% to 10% for permittivity and conductivity in the frequency range in excess of 10 MHz; at lower frequencies the variability ranged from ±3% to 15%. A wider range of values was observed for skull and skin tissues—up to ±15% to ±25% above and below 10 MHz, respectively. However, in view of the large number of measurements per tissue (in most cases about 50, 5 tissue samples from each of 10 animals per age group), the standard error of the mean and the total standard uncertainty are small single figures, significantly lower than these percentages.

Results

Figures 1–3 show IF and HF data for brain, skin, and skull tissue obtained from 10 and 70 day old rats. The good agreement throughout the common frequency region confirms the previously reported HF data [Peyman et al., 2001] and validates the IF data.

At HF, the differences between the data at 10 and 70 days can be explained in terms of change in water content. In the case of brain tissue, the change in water content may, at least partially, be due to a change in the ratio of gray to white matter as is known to occur with

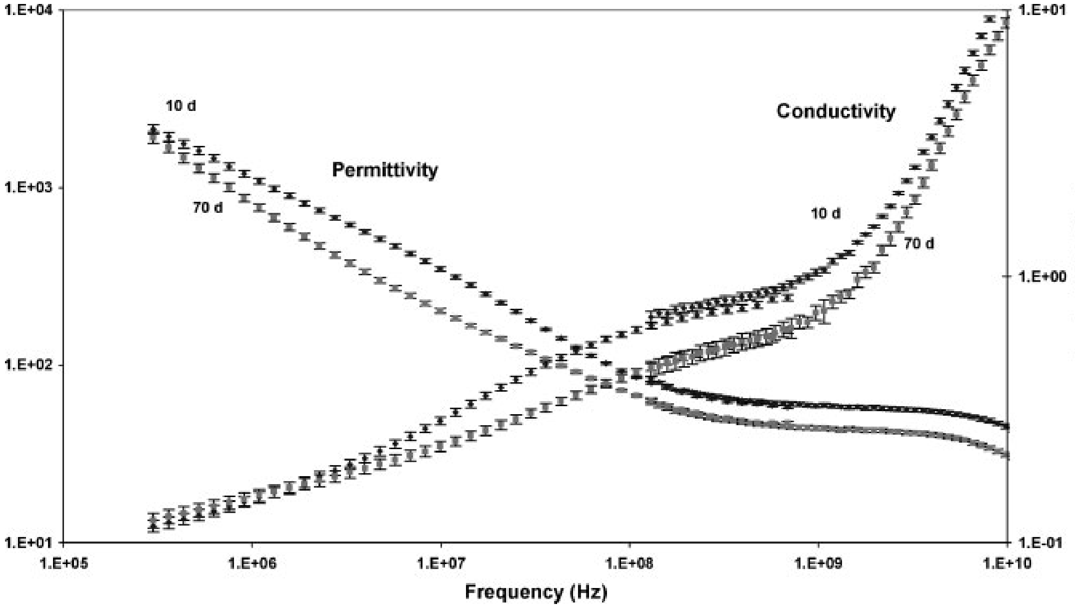

Fig. 1. Dielectric data for brain tissue at 37 °C. Error bars are 3 times the standard error of the mean. Good agreement is observed in the overlap frequency range between IF and HF data for both permittivity and conductivity.

age. Also evident in Figures 1–3 is a change in the frequency dependence of the IF data with age.

Data for ages between 10 and 70 days are not shown in Figures 1–3 for the purpose of clarity. However, one can gain a quantitative measure of the differences involved from Table 1 where percentage differences in the permittivity and the conductivity of tissues from 10 to 70 and also from 30 to 70 days are given at a certain frequencies encompassing the IF and HF ranges.

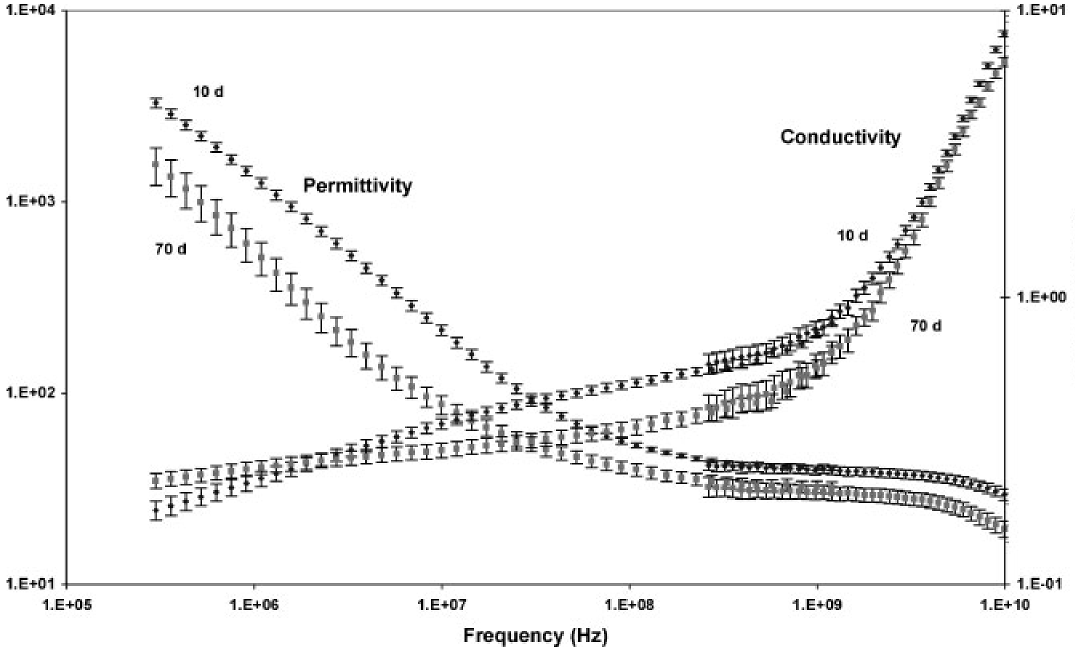

Fig. 2. Dielectric data for skin at 37 °C. Error bars are 3 times the standard error of the mean. Comment as for Figure 1.

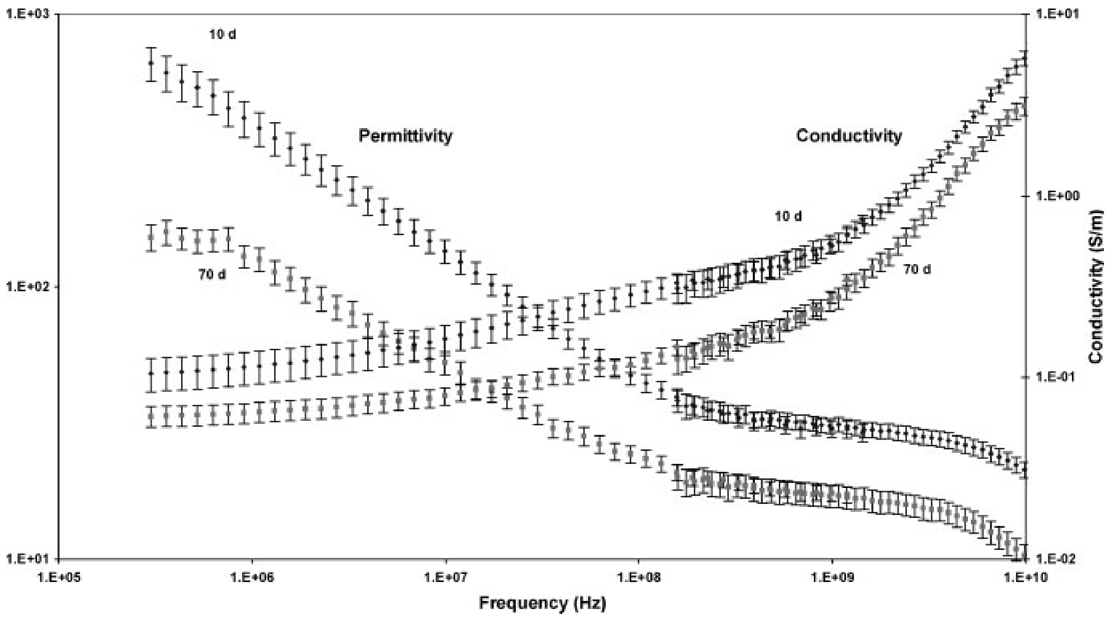

Fig. 3. Dielectric data for skull tissue at 37 °C. Error bars are 3 times the standard error of the mean. Comment as for Figure 1.

TABLE 1. Percentage Differences in the Permittivity and Conductivity

	Percentage difference between data for 10 and 70 days old[a]		Percentage difference between data for 30 and 70 days old	
Frequency/MHz	Permittivity	Conductivity	Permittivity	Conductivity
		Brain		
0.52	20.1	−4.5	−9.2	10.1
1.1	28.9	−1.8	−0.86	8.4
13	41.3	23.0	11.9	9.1
27	35.4	29.6	10.8	10.4
160	20.4	28.7	5.8	11.8
400	20.6	25.1	2.8	12.4
900	25.5	32.0	9.8	15.7
1800	25.7	28.0	8.6	10.1
2000	25.9	29.1	8.7	12.2
		Skull		
0.52	72.6	42.9	44.8	7.4
1.1	66.9	44.0	38.9	8.5
13	61.5	52.1	42.2	16.4
27	56.9	54.8	39.8	22.4
160	46.9	56.0	36.7	25.6
400	41.9	54.4	32.0	31.7
900	44.4	53.1	32.5	41.5
1800	44.9	47.2	31.9	33.1
2000	44.9	47.6	31.8	34.6
		Skin		
0.52	54.8	−19.2	47.5	5.4
1.1	59.2	−9.4	51.4	9.9
13	56.3	21.5	43.0	24.1
27	44.1	26.5	32.4	26.2
160	24.3	29.7	20.9	27.1
400	21.6	28.4	18.4	26.3
900	23.6	27.8	13.0	18.0
1800	24.2	21.1	12.4	9.2
2000	24.3	21.9	12.4	11.4

[a] Corresponds to Figures 1–3.

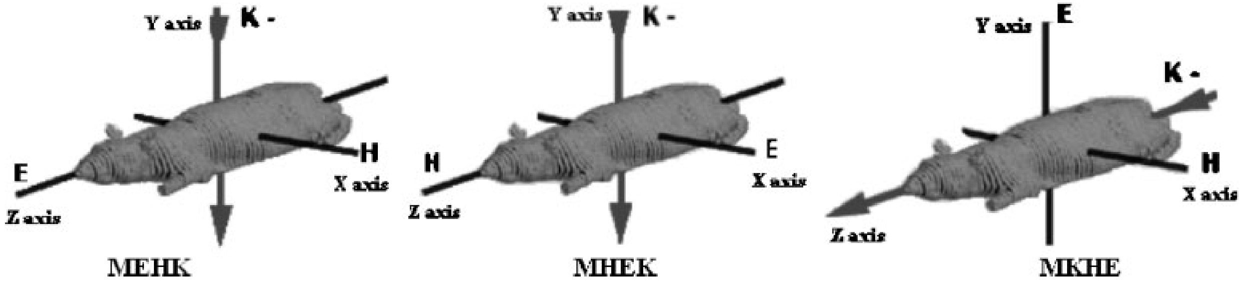

Fig. 4. Exposure orientations: M indicates a negative direction, E, and H represent the electric and magnetic field components respectively, and K represents the direction of propagation.

NUMERICAL STUDY–IMPACT OF VARIATION IN DIELECTRIC PROPERTIES ON SAR

Age-related dielectric data were input in a numerical study of exposure of rat models to plane waves at 27, 160, 400, 900, and 2000 MHz in three different polarizations, each corresponding to the electric, magnetic, or propagation vectors oriented along the length of the body (Fig. 4). The outcome was quantified in terms of whole body and tissue specific SAR, using a finite difference time domain procedure and a rat model scaled to the size of 10, 30, and 70 day old Sprague–Dawley animals with body lengths of 90–250 mm. The model is made of 34 tissue types; age-related dielectric data were available for only 9 of them: muscle, heart, liver, spleen, bone, skin, brain, lung, and kidney. In essence, we are looking at the effect of varying the properties of those 9 of 34 tissues.

The strongest coupling occurs in the MEHK polarization, resonant coupling is observed when the when the length of the body is about half the wavelength of the external field (Fig. 5). It is of course difficult to study the effect of dielectric properties in the presence of resonance absorption; if the change in dielectric properties produces a small shift in the resonance window it would appear to have a much larger effect than under non-resonant conditions. The spot frequencies 27 and 160 MHz are outside the resonance window and may be useful in providing information on the effect of changes in dielectric properties without too much interference. At 27 MHz, the field coupling is rather poor for all models irrespective of the tissue properties; it is therefore not very informative, leaving 160 MHz for further investigation. At this frequency, a normalized, whole body SAR of 21, 17, and 14 mW/kg per W/m^2 was obtained for the 10, 30, and 70 day models, respectively. These are rather large differences, suggesting the possible influence of factors other than tissue properties.

To eliminate all but the influence of tissue properties, the calculations at 160 MHz were repeated,

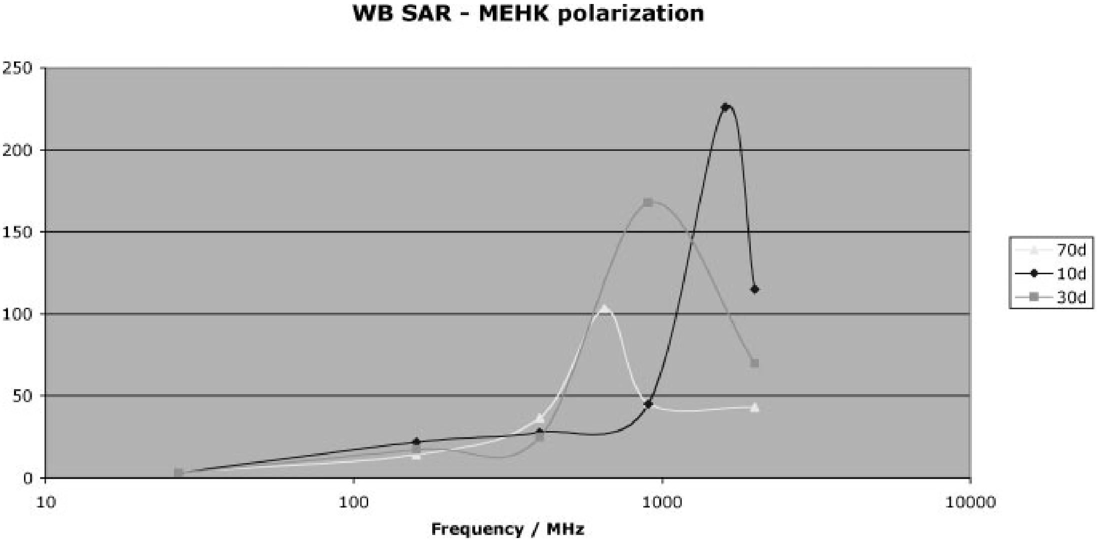

Fig. 5. Normalized whole-body SAR (mW/kg per W/m^2) for different size rat models exposed to a plane wave.

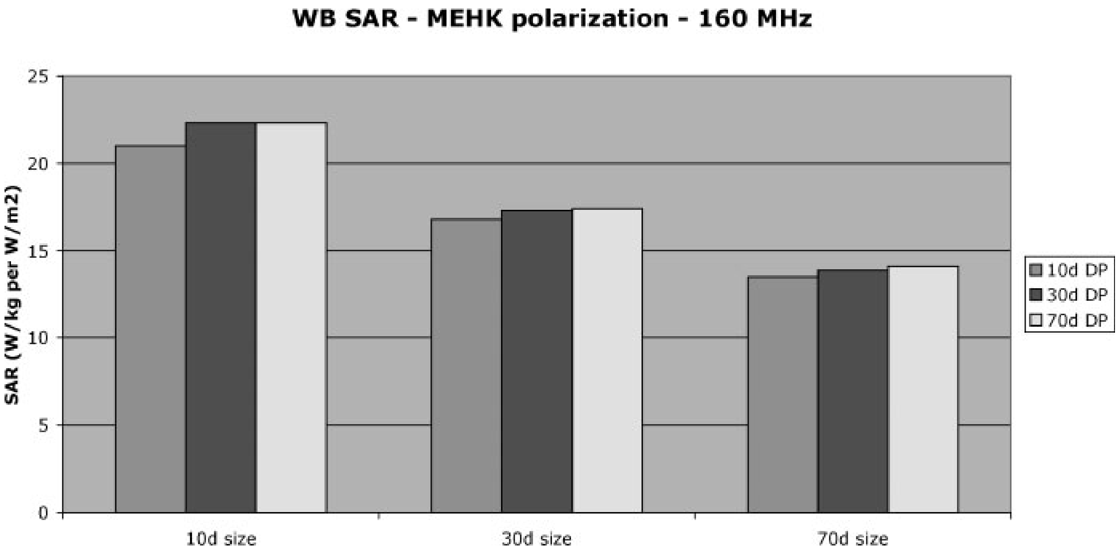

Fig. 6. Normalized whole-body SAR (mW/kg per W/m^2) 10, 30, and 70 day models; data obtained using dielectric properties (DP) corresponding to 10, 30, and 70 days for each model size.

allocating to each of the three model size tissue properties corresponding to 10, 30, and 70 day animals. The results are summarized in Figure 6; size is still an important determinant of the whole-body SAR at this frequency. The dielectric properties contribute less than 5%, with the most conservative value, i.e., the highest SAR, obtained when 70 day properties are used. Although small, this result is worth mentioning and is due to the lower permittivity of the 70 day skin, which improves the coupling under plane wave exposure conditions.

Perhaps not surprisingly, the effect on whole body SAR of varying the dielectric properties of 9 of 34 tissues is at best very small. Effects on SAR distribution and on the magnitude of the peak SAR have been observed [Alfadh et al., 2003; Alfadhl et al., 2005] but are not reported here. It is important to isolate the effect of changing tissue properties from all size and exposure parameters effects as was done for whole body exposure at 160 MHz.

Near Field Exposures

Near field exposures, where reactive coupling occurs, may well yield different results and conclusions from plane wave exposure and whole body SAR. To demonstrate this, a small number of simulations were

TABLE 2. Normalized SAR in a Lossy Half Space Illuminated at 900 MHz Under Near and Far Field Conditions. The SAR Induced by the Dipoles was Calculated in Each Case for the Same Feed-point Power, the Impedance of the Half Wave Dipole Varied With Distance to the Half Space and its Dielectric Properties

		SAR ratio			Dielectric parameters	
Source	Variation in dielectric properties	1 g	10 g	Peak	ε'	$\sigma (S/m)$
900 MHz half-wave dipole 2.8 mm distance from an infinite half space	Standard	1.00	1.00	1.00	41.50	0.97
	ε'+15%	0.94	0.97	0.86	47.73	0.97
	σ+15%	1.11	1.09	1.12	41.50	1.12
	ε' and σ +15%	1.04	1.06	0.97	47.73	1.12
900 MHz half-wave dipole 10 mm distance from an infinite half space	Standard	1.00	1.00	1.00	41.50	0.97
	ε'+15%	0.98	0.99	0.97	47.73	0.97
	σ +15%	1.11	1.08	1.14	41.50	1.12
	ε' and σ +15%	1.09	1.07	1.10	47.73	1.12
900 MHz plane wave incident on an infinite half space	Standard	1.00	1.00	1.00	41.50	0.97
	ε'+15%	0.92	0.93	0.90	47.73	0.97
	σ +15%	1.09	1.05	1.12	41.50	1.12
	ε' and σ +15%	1.00	0.98	1.02	47.73	1.12

made where the peak, 1 and 10 g SAR were calculated when a 900 MHz half wave dipole or plane wave illuminates a lossy half space. The permittivity and conductivity were then varied separately and together to give a better understanding of the effect on SAR of variation in the dielectric properties. The results show that an increase in both permittivity and conductivity has a fairly neutral effect in the case of plane wave irradiation, but not in the near field of the dipole (Table 2). This is in basic agreement with the simulations of Gandhi and Kang [2002]; they compared the peak 1 and 10 g SARs induced in the head from a generic hand-held transceiver placed at an angle of 30° relative to a head model. For this near field exposure, a higher surface current was induced in the skin due to the higher conductivity thus generally resulting in a higher SAR.

CONCLUDING REMARKS

Modeling of exposures in the near- and far-fields has affirmed the dielectric properties of skin to be one an important determinants in the coupling efficiency and hence in the intensity of the exposure. Skin, on the other hand, is an animal-specific organ; researchers must exercise caution when using animal skin dielectric data in human exposure studies. Elaboration of the question of the exposure of children versus adults must await more appropriate dielectric data and also MRI-based numerical models of children. The scientific community is aware of this need, which I am sure will be addressed in the near future.

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