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Variation of the dielectric properties of tissues with age: the effect on the values of SAR in children when exposed to walkie–talkie devices

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Abstract
In vitro dielectric properties of ageing porcine tissues were measured in the frequency range of 50 MHz–20 GHz, and the total combined uncertainties of the measurements were assessed. The results show statistically significant reduction with age in both permittivity and conductivity of 10 out of 15 measured tissues. At microwave frequencies, the observed variations are mainly due to the reduction in the water content of tissues as an animal ages. The results obtained were then used to calculate the SAR values in children of age 3 and 7 years when they are exposed to RF induced by walkie–talkie devices. No significant differences between the SAR values for the children of either age or for adults were observed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Accurate knowledge of the dielectric properties of tissues is required in order to calculate the energy deposition when they are exposed to microwaves. Until recently, the literature data consisted mostly of dielectric properties of tissues from mature animals with a few older studies reporting systematic changes in the dielectric properties of ageing brain tissues (Thurai *et al* 1984, 1985). More recent studies looked at the variation of dielectric properties of several rat tissues including brain as a function of animal age and found similar trends (Peyman *et al* 2001, Peyman and Gabriel 2003). These studies have triggered a question on the extent to which the variation of dielectric data as a function of age would affect the result of dosimetry in animal exposure studies, and consequently, the possible implications for the exposure of the children. The impact of variation of dielectric data on dosimetry is not simple (Hurt *et al* 2000, Mason *et al* 2000, Gajšek *et al* 2001a, 2001b); it depends on many factors including the exposure parameters and dosimetric unit (specific absorption rate, SAR, in watts per kilogram) under consideration. A recent review by Gabriel (2005) used published rat dielectric data and assessed the impact of their variation as a function of age on the exposure of rodents to plane wave fields. The results showed that the increase in permittivity and conductivity had a balancing effect on the energy deposition in the case of plane wave irradiation, but this may not necessarily be the case when the exposure is in the near field of a source.

Several other studies have attempted to investigate the possible differences between the exposure of children and adults to EM fields. While some reported deeper penetration and higher absorption in smaller heads (Gandhi *et al* 1996, Gandhi and Kang 2002), subsequent studies did not confirm these findings (Anderson 2003, Martinez-Burdalo *et al* 2004, Bit-Babik *et al* 2005, Keshvari and Lang 2005, Wiart *et al* 2005, Christ and Kuster 2005, Wang *et al* 2006).

In an attempt to contribute to the ongoing discussion, this study has provided new dielectric data for tissues as a function of animal age. The systematic variation of dielectric properties with age has been investigated for several porcine tissues, which are regarded as a good substitute for human tissues as regards dielectric properties.

In order to demonstrate the possible variation with age, tissue samples from 10, 50 and 250 kg pigs were considered to cover different developmental stages from piglets to mature animals. To relate our findings to human tissue, we have made the following assumptions. The 10 kg pigs, which are less than 30 days old, are very young animals and far from puberty age; we have assumed that the dielectric properties of tissues from these piglets correspond to those of human children of age 1–4 years. The 50 kg pigs, which are about 100 days old, are still not fully matured in terms of sexual activity, and therefore are assumed to be equivalent to 11–13 years old human. Finally, at 250 kg, pigs are fully matured animals and are therefore considered equivalent to human adults. In making the above correspondences between the pigs and human age, the authors held discussions with a number of vets and studied the pig and human growth curves with markers of growth along the curves e.g. the sexual activity of animals, the calcification of the bones and bone marrow distribution and the decrease in total body water from 75% for new born to 60% for adults (Reference Man 1992). It is difficult to find a reliable correlation between human and pig growth curves, but it is possible to establish certain ages if one is careful as to the interpretation of the data. It is more straightforward to correlate the end point, i.e. the piglets to be equivalent of very small children and mature pigs equivalent to adults (>25 years old), whereas the ages in-between are more difficult to correlate.

The frequency range of measurements was 50 MHz–20 GHz which falls mostly within the γ dispersion region of the dielectric spectrum of tissues. The spectral parameters of γ dispersion are known to be strongly correlated with the water content of the tissue (Grant *et al* 1978, Schwan and Foster 1980, Pethig and Kell 1987, Gabriel 2007). Similar to the outcome of the Peyman *et al* (2001) study, we expect to see variations as a function of age if the water content of tissues varies throughout the developmental stages of the animal.

The newly obtained data can be used to investigate the difference in the calculated SAR in children and adult heads. One scenario that of the RF exposure in children induced from a walkie–talkie device is discussed in this paper.

2. Materials and methods

2.1. Dielectric measurement

The relative permittivity ε' and conductivity σ (S m^{-1}) of porcine tissues were measured in the frequency region of 50 MHz–20 GHz, using open-ended coaxial probes and a computercontrolled network analyser (Agilent 8720D). This procedure, developed by Gabriel *et al* (1994), has been shown to be suitable for the dielectric measurement of biological tissues. The internal diameter of the probes used for measurements were 1.67 and 2.98 mm, respectively. The data obtained by both probes agree well within the stated measurement uncertainty; the smaller probe was used to sample thin tissues.

The network analyser was calibrated at two hourly intervals during a measurement session. It was checked regularly by measurements on reference liquids with well-characterized dielectric properties.

2.2. Materials

Tissues were obtained from pigs weighing 10, 50 and 250 kg; the approximate ages of the animals in the three categories are 30, 100 and 600 days. The pigs in the 250 kg category were all sows.

Due to practical difficulties of handling 250 kg animals it was not possible to carry out an *in vivo* study; instead, the measurements were made on excised tissue, *in vitro*. The authors do not consider this a limitation as it does not affect the comparative aspect of the study.

In total, 22 animals were used (ten 10 kg, six 50 kg and six 250 kg pigs). In all, 15 tissues have been characterized from each age category, and each tissue was measured at least six times.

The tissues were dissected immediately after the death of the animals following the administration of a terminal overdose of pentobarbital (a barbiturate). All the procedures were carried out under the Animals (Scientific Procedures) Act 1986, the UK legislation covering the use of animals in scientific research.

The tissues were kept in tight containers in a Grant water bath with a Haake 001-2873-stirrer/heater unit to maintain a temperature of 37 °C. Strict temperature control was applied during the measurement sessions; the lab was climate controlled for temperature and humidity. No additive or preservative was required to maintain the integrity of the tissues. Efforts were made to avoid contamination of tissues with body fluids; cotton swabs were used to remove blood and CSF from the tissues.

The brain was completely removed and then dissected to differentiate grey matter, white matter and dura. Bone marrow was measured at two distances from the end of the bone: 30% and 50%. These percentages were selected in order to allow comparison of marrow dielectric properties with age where the distribution of the different marrow types changes with animal age.

Dielectric measurements carried out on different areas of the skull: mandible, zygomatic arch and top of the skull. The periosteum was measured on three bones: long bone, rib bone and skull. Finally, back musculature was dissected away from spine processes of lumbar vertebra and also part of the transverse process of the lumbar vertebra to access the intervertebral disc (annulus fibrosus) and its centre (nucleus pulposus).

2.3. Uncertainty of dielectric measurements

The uncertainty associated with dielectric measurements of biological tissues has been analysed in a recent publication by Gabriel and Peyman (2006) using numerical and experimental methods. Experimentally, the total combined uncertainty comprising both random and systematic errors was assessed by repeated measurements on well-characterized reference liquids.

Table 1. List of tissues with and without systematic variation as a function of age.

Dielectric properties vary with age	No significant variation
Bone (cortical)	Cornea
Bone marrow (at two distal positions)	Grey matter
Dura	Mammary fat
Intervertebral disc (two regions)	Tongue
Periosteum	
Skin	
Skull	
Spinal cord	
White matter	

Statistical analysis of the experimental data showed that the random errors (repeatability) follow a normal distribution. Therefore, the mean and standard deviation of the mean (SDM) could be taken to be the best estimates of the measured data and their random errors.

In the case of reference liquids (pure, stable, temperature regulated, properties known), random and systematic errors were found to be similar to each other in magnitude. In the case of tissues, the natural inhomogeneity in composition and practical difficulties of sampling such as imperfect contact and possible contamination with bodily fluids add to the variability of the measurement and significantly increase the observed random errors. For most tissues, the random errors were found to be up to an order of magnitude larger than the sum of all systematic errors.

The technique used in this study measures the dielectric properties of reference liquids such as 0.1 M NaCl, to within 1–2% uncertainty across the frequency spectrum (Gabriel and Peyman (2006). For the tissues, measured in this study, the total combined uncertainty is calculated at each sampling frequency across the spectrum. This is equivalent to one standard deviation and is multiplied by a coverage factor (k) of 2 or 3 to provide 95 and 99% confidence levels respectively.

3. Results and discussion

From the 15 tissues measured, 10 showed systematic variation in the dielectric properties as a function of animal age (table 1). The numerical values of the measured permittivity and conductivity of tissues from animals in the three categories are presented in table 2. Corresponding graphical data for grey matter, white matter, skull and bone marrow are also presented in figures 1–4. The dielectric properties of 50 kg pigs are not included in the graphs for clarity as in all cases they were between those of the 10 and 250 kg. The error bars represent three times total the combined uncertainty.

In the case of the cornea, grey matter, mammary fat and tongue, average data from the three age groups agreed to well within the measurement total combined uncertainty and no significant differences were observed. However, systematic decrease was observed in both measured permittivity and conductivity values of other considered tissues when the animal aged from 10 kg to 250 kg. The differences between the measured permittivity and conductivity of the 10 and 250 kg pigs are well above three times the total combined uncertainty ($k = 3$).

The results also showed a significant decline in both permittivity and conductivity of the long bone, skull and bone marrow (measured at distances of 30% and 50% of the length of the bone measured from the end) when animals aged from 10 kg to 250 kg. To a lesser extent, similar trends were observed for the dielectric properties of intervertebral disc and its centre.

Table 2. The measured permittivity and conductivity of ageing porcine tissues at selected frequencies.

Tissue	Frequency (MHz)	10 kg		50 kg		250 kg	
		ε'	σ (S m^{-1})	ε'	σ (S m^{-1})	ε'	σ (S m^{-1})
Bone (cortical)	450	28.1 ± 2.0	0.34 ± 0.04	19.7 ± 2.2	0.20 ± 0.04	15.4 ± 0.7	0.11 ± 0.01
	900	26.3 ± 1.9	0.45 ± 0.05	18.6 ± 2.0	0.28 ± 0.04	14.5 ± 0.6	0.17 ± 0.02
	1800	24.4 ± 1.9	0.71 ± 0.06	17.3 ± 2.0	0.48 ± 0.06	13.6 ± 0.6	0.32 ± 0.02
	2400	23.8 ± 1.9	0.93 ± 0.07	16.7 ± 1.9	0.64 ± 0.08	13.2 ± 0.6	0.44 ± 0.03
Bone marrow (30%)	450	41.3 ± 1.0	0.65 ± 0.02	14.6 ± 2.1	0.20 ± 0.04	5.8 ± 0.6	0.04 ± 0.01
	900	39.5 ± 1.0	0.77 ± 0.03	14.0 ± 2.0	0.23 ± 0.04	5.7 ± 0.5	0.05 ± 0.01
	1800	37.9 ± 1.0	1.09 ± 0.04	13.5 ± 1.9	0.34 ± 0.06	5.6 ± 0.5	0.08 ± 0.01
	2400	37.2 ± 1.0	1.41 ± 0.04	13.3 ± 1.9	0.44 ± 0.08	5.6 ± 0.5	0.12 ± 0.02
Bone marrow (50%)	450	41.0 ± 1.6	0.64 ± 0.03	20.0 ± 1.7	0.25 ± 0.02	8.0 ± 1.2	0.06 ± 0.02
	900	39.2 ± 1.6	0.75 ± 0.03	19.2 ± 1.6	0.31 ± 0.03	7.9 ± 1.1	0.07 ± 0.02
	1800	37.6 ± 1.5	1.07 ± 0.05	18.6 ± 1.5	0.45 ± 0.04	7.7 ± 1.1	0.12 ± 0.03
	2400	36.9 ± 1.5	1.37 ± 0.05	18.3 ± 1.4	0.60 ± 0.06	7.7 ± 1.1	0.18 ± 0.05
Cartilage	450	N/A	N/A	51.3 ± 0.9	0.90 ± 0.06	N/A	N/A
	900	N/A	N/A	48.3 ± 1.0	1.07 ± 0.06	N/A	N/A
	1800	N/A	N/A	46.3 ± 0.9	1.51 ± 0.07	N/A	N/A
	2400	N/A	N/A	45.2 ± 0.8	1.91 ± 0.07	N/A	N/A
Dura	450	57.6 ± 0.8	1.01 ± 0.03	53.0 ± 1.0	0.93 ± 0.02	47.0 ± 2.3	0.72 ± 0.04
	900	55.1 ± 0.8	1.16 ± 0.03	50.3 ± 1.0	1.07 ± 0.02	44.6 ± 2.2	0.86 ± 0.04
	1800	53.1 ± 0.8	1.55 ± 0.03	48.9 ± 1.0	1.48 ± 0.03	42.8 ± 2.1	1.25 ± 0.06
	2400	52.4 ± 0.8	1.97 ± 0.03	47.9 ± 1.0	1.85 ± 0.04	42.0 ± 2.1	1.66 ± 0.08
Fat	450	14.6 ± 0.4	0.20 ± 0.01	7.7 ± 0.4	0.07 ± 0.00	5.8 ± 0.3	0.05 ± 0.01
	900	14.3 ± 0.4	0.23 ± 0.01	7.5 ± 0.3	0.08 ± 0.00	5.7 ± 0.3	0.06 ± 0.01
	1800	14.0 ± 0.4	0.34 ± 0.01	7.4 ± 0.4	0.13 ± 0.01	5.6 ± 0.3	0.10 ± 0.01
	2400	13.9 ± 0.4	0.45 ± 0.02	12.5 ± 2.4	0.38 ± 0.09	5.6 ± 0.3	0.13 ± 0.01
Grey matter	450	54.9 ± 0.9	0.85 ± 0.02	54.0 ± 1.0	0.87 ± 0.03	52.9 ± 0.7	0.87 ± 0.02
	900	51.7 ± 0.9	0.98 ± 0.02	50.9 ± 1.0	1.00 ± 0.03	49.9 ± 0.7	1.00 ± 0.02
	1800	49.7 ± 0.9	1.30 ± 0.03	49.2 ± 1.0	1.33 ± 0.04	48.1 ± 0.7	1.34 ± 0.03
	2400	49.1 ± 0.9	1.66 ± 0.04	48.5 ± 1.0	1.65 ± 0.04	47.5 ± 0.6	1.69 ± 0.04
Intervertebral disc *(annulus fibrosus)*	450	61.2 ± 0.6	1.29 ± 0.03	52.7 ± 0.9	0.91 ± 0.05	49.9 ± 0.9	0.92 ± 0.04
	900	58.1 ± 0.6	1.48 ± 0.03	50.1 ± 1.0	1.08 ± 0.05	46.6 ± 0.8	1.10 ± 0.04
	1800	55.6 ± 0.6	1.92 ± 0.03	48.1 ± 0.9	1.53 ± 0.05	43.9 ± 0.8	1.54 ± 0.04
	2450	54.6 ± 0.6	2.38 ± 0.04	47.1 ± 0.9	1.94 ± 0.05	42.9 ± 0.8	1.97 ± 0.05
Intervertebral disc centre *(nucleus pulposus)*	450	66.9 ± 1.3	1.66 ± 0.04	67.1 ± 0.5	1.58 ± 0.10	59.9 ± 1.7	1.65 ± 0.10
	900	64.7 ± 1.3	1.82 ± 0.03	65.3 ± 0.4	1.74 ± 0.10	57.4 ± 1.7	1.82 ± 0.10
	1800	62.7 ± 1.3	2.23 ± 0.04	63.9 ± 0.5	2.16 ± 0.11	55.3 ± 1.8	2.22 ± 0.11
	2400	62.2 ± 1.3	2.66 ± 0.05	63.2 ± 0.5	2.59 ± 0.11	54.5 ± 1.8	2.63 ± 0.11
Mammary fat	450	N/A	N/A	27.8 ± 2.1	0.20 ± 0.02	15.0 ± 2.3	0.20 ± 0.04
	900	N/A	N/A	27.8 ± 2.1	0.20 ± 0.02	14.6 ± 2.2	0.24 ± 0.04
	1800	N/A	N/A	27.8 ± 2.1	0.20 ± 0.02	14.2 ± 2.1	0.34 ± 0.06
	2400	N/A	N/A	27.8 ± 2.1	0.20 ± 0.02	14.1 ± 2.1	0.44 ± 0.08
Periosteum	450	37.0 ± 0.9	0.44 ± 0.03	31.7 ± 1.5	0.39 ± 0.03	29.1 ± 2.5	0.33 ± 0.04
	900	35.0 ± 0.9	0.58 ± 0.04	29.7 ± 1.4	0.51 ± 0.03	28.0 ± 2.5	0.42 ± 0.04
	1800	32.8 ± 0.8	0.92 ± 0.04	27.8 ± 1.4	0.81 ± 0.05	26.7 ± 2.4	0.68 ± 0.05
	2400	31.9 ± 0.8	1.22 ± 0.05	26.9 ± 1.4	1.06 ± 0.06	26.2 ± 2.3	0.92 ± 0.07

Table 2. (Continued.)

Tissue	Frequency (MHz)	10 kg		50 kg		250 kg	
		ε'	σ (S m^{-1})	ε'	σ (S m^{-1})	ε'	σ (S m^{-1})
Skin	450	48.4 ± 0.7	0.66 ± 0.01	46.9 ± 0.8	0.64 ± 0.02	39.4 ± 3.2	0.48 ± 0.06
	900	45.5 ± 0.7	0.80 ± 0.01	44.2 ± 0.8	0.78 ± 0.02	36.8 ± 3.0	0.62 ± 0.07
	1800	43.2 ± 0.7	1.17 ± 0.02	42.1 ± 0.8	1.16 ± 0.02	34.9 ± 2.9	0.93 ± 0.10
	2400	42.4 ± 0.7	1.52 ± 0.03	41.2 ± 0.8	1.5 ± 0.03	34.2 ± 2.8	1.24 ± 0.13
Skull	450	43.3 ± 1.2	0.62 ± 0.03	36.4 ± 2.5	0.52 ± 0.05	19.7 ± 2.1	0.19 ± 0.03
	900	41.1 ± 1.1	0.75 ± 0.03	34.3 ± 2.4	0.65 ± 0.06	18.8 ± 2.0	0.26 ± 0.04
	1800	39.2 ± 1.1	1.11 ± 0.04	32.6 ± 2.3	0.95 ± 0.07	17.8 ± 1.9	0.44 ± 0.05
	2450	38.3 ± 1.1	1.45 ± 0.04	31.8 ± 2.3	1.22 ± 0.08	17.4 ± 1.9	0.61 ± 0.07
Spinal Cord	450	38.5 ± 1.5	0.50 ± 0.03	34.0 ± 0.8	0.45 ± 0.02	25.8 ± 1.9	0.32 ± 0.03
	900	36.6 ± 1.4	0.59 ± 0.03	32.3 ± 0.8	0.53 ± 0.02	24.2 ± 1.9	0.39 ± 0.04
	1800	35.2 ± 1.4	0.84 ± 0.04	31.1 ± 0.8	0.74 ± 0.02	23.2 ± 1.8	0.56 ± 0.05
	2400	34.7 ± 1.4	1.09 ± 0.05	30.7 ± 0.8	0.95 ± 0.03	22.9 ± 1.8	0.72 ± 0.06
Tongue	450	56.9 ± 0.7	0.90 ± 0.02	56.0 ± 0.3	0.87 ± 0.01	57.4 ± 0.4	0.89 ± 0.01
	900	54.2 ± 0.7	1.06 ± 0.02	53.4 ± 0.4	1.03 ± 0.01	55.4 ± 0.4	1.05 ± 0.01
	1800	52.0 ± 0.7	1.48 ± 0.02	51.7 ± 0.3	1.47 ± 0.02	53.4 ± 0.4	1.50 ± 0.02
	2400	51.2 ± 0.7	1.92 ± 0.02	50.7 ± 0.3	1.88 ± 0.02	52.5 ± 0.3	1.97 ± 0.03
White matter	450	42.3 ± 1.9	0.57 ± 0.04	36.4 ± 1.0	0.49 ± 0.01	30.6 ± 0.8	0.40 ± 0.02
	900	39.8 ± 1.8	0.67 ± 0.04	34.0 ± 0.9	0.59 ± 0.02	28.6 ± 0.7	0.48 ± 0.02
	1800	38.2 ± 1.8	0.94 ± 0.05	32.7 ± 0.9	0.82 ± 0.03	27.4 ± 0.7	0.68 ± 0.03
	2400	37.7 ± 1.7	1.21 ± 0.06	32.2 ± 0.9	1.05 ± 0.03	27.1 ± 0.7	0.90 ± 0.04

The term $\pm$ represents the total combined uncertainty. For 95% and 99% confidence intervals, the coverage factors of $k = 2$ and $k = 3$ can be used, respectively.

Generally, bone marrow exhibits the largest decrease in both permittivity and conductivity with age (80–90%) while the long bone and skull showed up to 70% decline in their dielectric properties.

A discussion on the variation of dielectric properties of brain tissues has recently been reported (Peyman *et al* 2007). Increased myelination and decreased water content as a function of age is said to be the reason for the drop in permittivity and conductivity values of white matter and spinal cord as animals age. Similar trends have been observed by Schmid and Überbacher (2005) where they studied the age dependence of dielectric properties of bovine brain and ocular tissues. They observed a significant age dependence of the dielectric properties of white matter and lens tissue, but not for grey matter, cornea and the vitreous body of the eye.

In the case of the water content of bone, Timmins and Wall 1977 report that the fractional water content is similar across species for the same type of bone, but within a single species it varies with age, sex and disease state. Variations in the amount of water are related to changes in the degree of mineralization of the calcified bone matrix. During mineralization of the osteoid, water is gradually replaced by calcium apatatite, which fills the volume previously occupied by water, because the osteoid volume does not change during calcification (Robinson and Elliot 1957 and Neuman and Neuman 1981). This reduction in water content and the increase in the calcification of the bone is the reason for the significant decrease in both permittivity and conductivity of bone tissues as a function of animal age.

The largest variation in the dielectric properties as a function of age is observed in bone marrow tissues. Bone marrow is made up of red marrow, which produces red and white

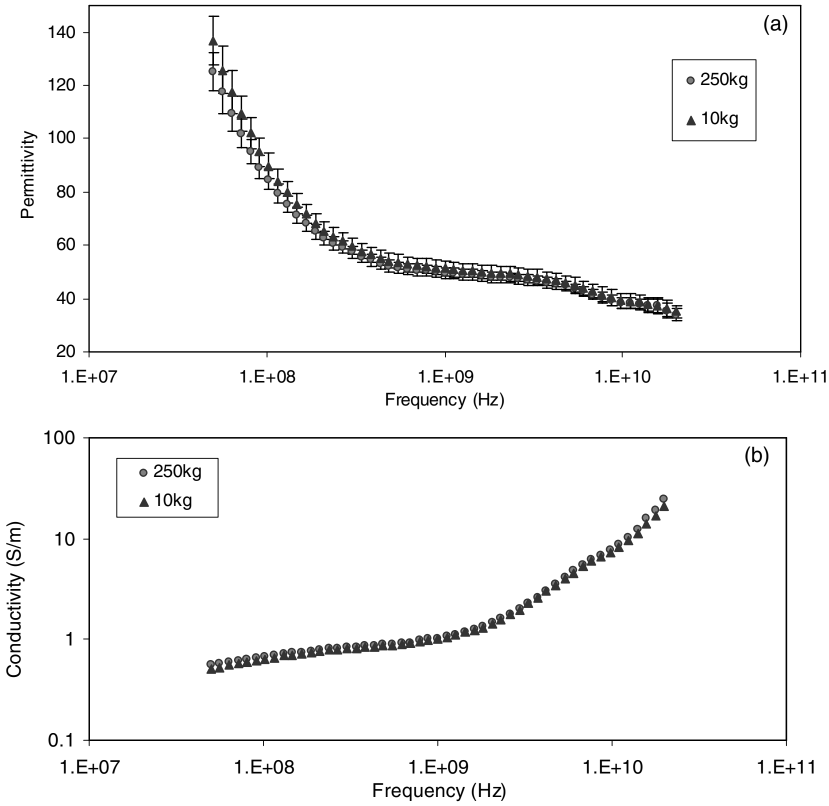

Figure 1. The measured (a) permittivity and (b) conductivity of grey matter for 10 and 250 kg pigs The error bars are the total combined uncertainty with $k = 3$ which represent the 99% confidence interval.

blood cells, and yellow marrow, which contains fat and connective tissue and produces some white blood cells. In the young animals the marrow is mostly red and as the animal grows older, the marrow acquires a higher fat content and hence a yellow colour. In the adults most bones contain yellow marrow and red marrow is limited to the spongy bone in the skull, ribs, sternum, clavicles, vertebrae and pelvis. Normal adult bone marrow contains an age-related proportion of fat cells. This can be up to 60% fat in rib and vertebra and over 80% in femur (Allen *et al* 1995). The red bone marrow has higher water content compared to yellow bone marrow, which accounts for higher dielectric properties in younger animals.

Finally, the measured dielectric data of intervertebral disc (annulus fibrosus) and its centre (nucleus pulposus) also follow a similar trend of decreasing as a function of animal age but to a lesser extent. The nucleus pulposus is the soft, fibrocartilaginous central portion of the intervertebral disc and consists of a network of delicate collagenous fibres in a mucoprotein gel rich in polysaccharide. It consists of a gelatinous mass, particularly in the young person. The outer region of the disc (annulus fibrosus) is firm and banded. With increasing age the nucleus loses water, becomes firmer and the distinction between the two regions becomes less clear. Sether *et al* (1990) found a significant correlation between the decrease in signal intensity of MR images and age due to the decrease in water and glycosaminglycans and increase in collagen in the disk. The drop in water content could be the main reason for the observed decrease in the measured dielectric properties.

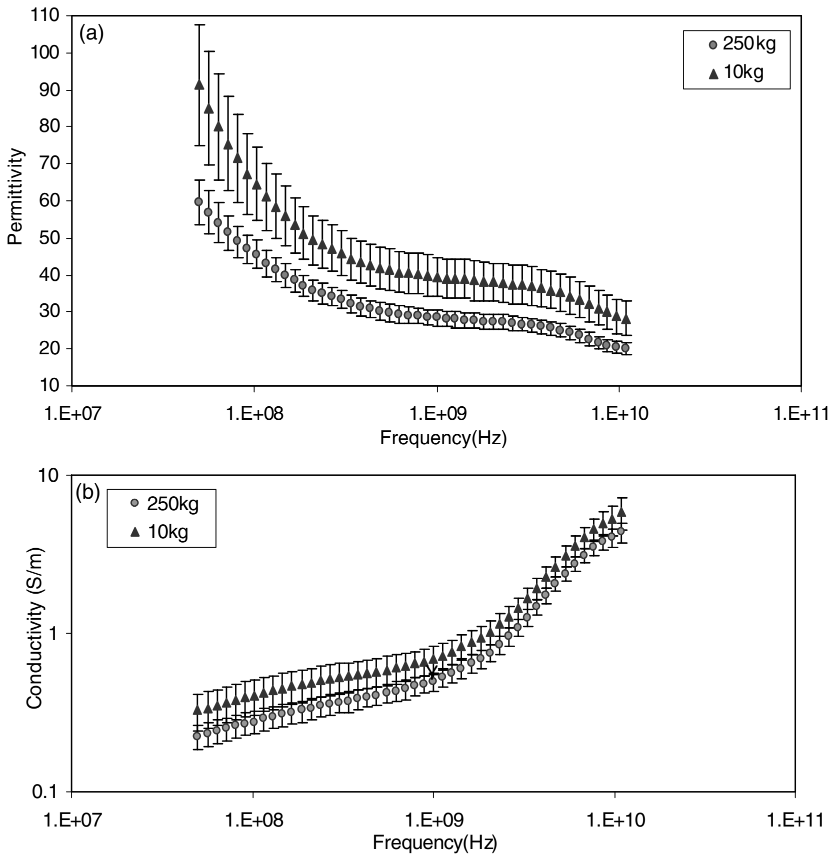

Figure 2. The measured (a) permittivity and (b) conductivity of white matter for 10 and 250 kg pigs The error bars are the total combined uncertainty with $k = 3$ which represent the 99% confidence interval.

It is important to note that the variations if the dielectric data are not uniform across the spectrum. As seen above, in the frequency range of γ dispersion the main effect is the variation in water content. However, at lower frequencies the variations will be due to cellular structural differences and this will have different frequency dependence.

4. Effect of the dielectric results on the SAR values in children when exposed to walkie–talkie equipment

We have investigated the influence of the ageing of the dielectric properties on the exposure of the head of children to emissions from walkie–talkie devices. The metric used for the assessment is the spatial peak SAR averaged over 10 g in two child head models. SAR expressed in watts per kilogram 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 through the following relationship:

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

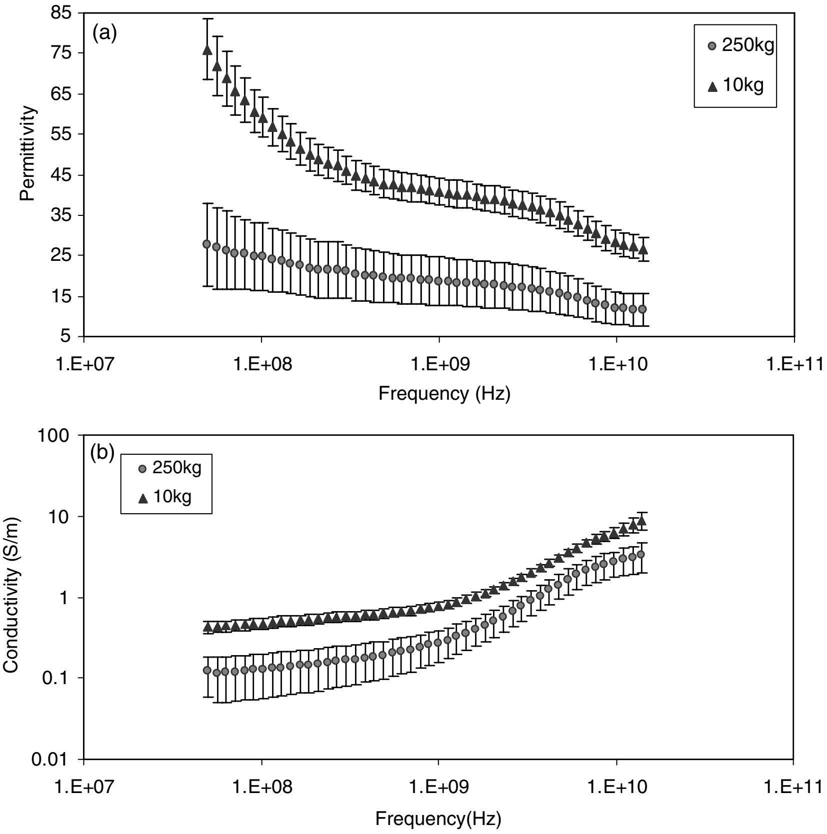

Figure 3. The measured (a) permittivity and (b) conductivity of skull for 10 and 250 kg pigs. The error bars are the total combined uncertainty with $k = 3$ which represent the 99% confidence interval.

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}).

The walkie–talkie operates at a frequency of 446 MHz with a time-averaged effective radiated power (ERP) of 250 mW; further details can be found in Martens and Vermeeren (2006). In figure 5(a) the walkie–talkie is held in a vertical position in front of the face, whereas figure 5(b) shows the eye position of the walkie–talkie.

Two child head models and two typical positions of a walkie–talkie relative to the head have been investigated with respect to electromagnetic exposure. The head models correspond to child heads 3 (C3Y) and 7 years (C7Y) old (figure 6).

The dielectric properties of the tissues of the child head phantoms have been assigned the values of the tissues in table 2 whereby the 1–4 years old were assigned the 10 kg pig data, the 11–13 years old the 50 kg pig data and adults the 250 kg data. The numerical assessment of the exposure was carried out using SEMCAD-X which is a commercial finite-difference time-domain tool (SPEAG, Switzerland). The grid step size in the head phantoms did not exceed 2.5 mm in all the three dimensions. The exposures to each head in both positions were carried out using the three sets of dielectric properties.

The spatial peak SAR has been determined for maximum constant input power as well as for maximum constant input current, corresponding to the two types of sources that can be

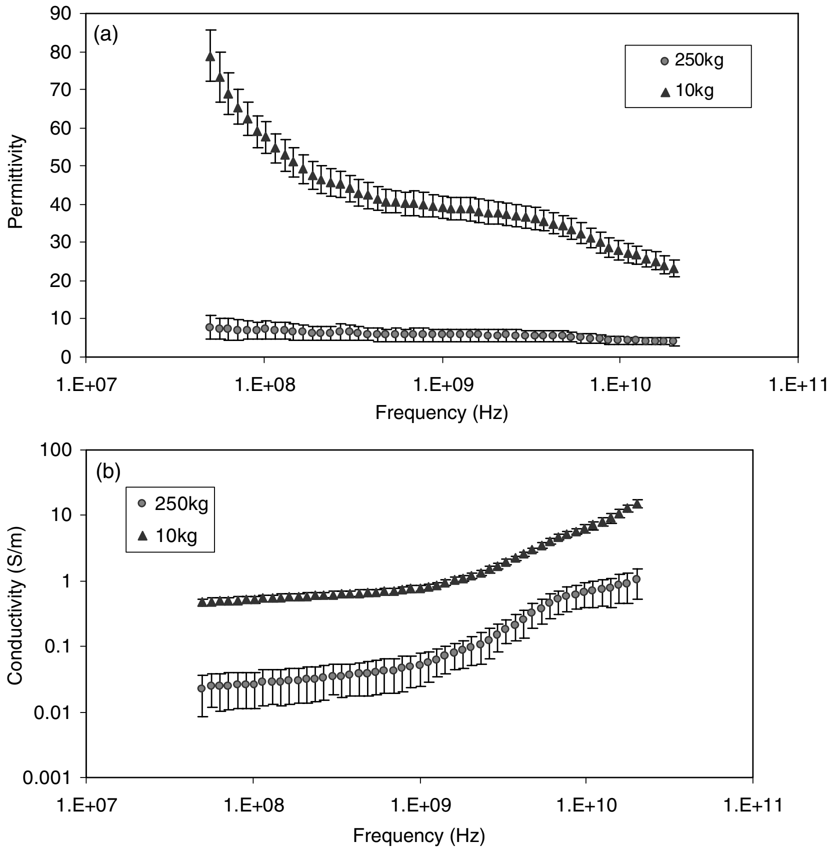

Figure 4. The measured (a) permittivity and (b) conductivity of bone marrow 30% for 10 and 250 kg pigs. The error bars are the total combined uncertainty with $k = 3$ which represent the 99% confidence interval.

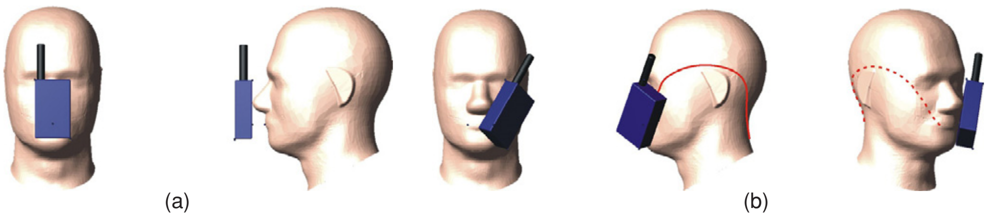

Figure 5. The (a) vertical and the (b) eye position of the walkie–talkie in front of the face of a user.

used in real walkie–talkies. The maximum input power P_{in} is calculated from the maximum ERP of 250 mW in free space (equals to 263 mW). The maximum rms input current equals the value of the input current necessary to achieve an ERP of 250 mW for the walkie–talkie in free space and is 153 mA. In order to estimate the spatial peak SAR for a real walkie–talkie from the above results, the ERP of several commercially available walkie–talkies have been measured.

The results of the assessment of the peak 10 g averaged SAR are shown in figure 7. For all the investigated cases, the local averaged SAR in 10 g does not exceed the 2 W kg^{-1} limit and

(a) (b)

Figure 6. The (a) 3 year old and (b) 7 year old head phantoms.

Table 3. Relation between dielectric data obtained experimentally and the tissues in the 10 g volume of maximum peak SAR_{10g}.

Tissue in child head models	Tissue measured experimentally
Connective tissue	Cartilage[a]
Nasal cavity (air and mucosa)	Air
Skin	Skin

[a] Only measured for 50 kg pigs.

the influence of the ageing of the tissues on the SAR_{10g} in the child head phantoms is limited, i.e. deviations on SAR_{10g} are less than 10% for the investigated configurations. The deviation on SAR_{10g} varies with the position of the peak 10 g SAR, whether constant input power or constant input current is considered, and the human head model. The peak SAR_{10g} is located at the left side of the nose for the eye position of the walkie–talkie and just above the nose and between the eyes for the vertical position of the walkie–talkie. As an example figure 8 shows SAR_{10g} in the C3Y for the two investigated walkie–talkie positions (vertical and eye position). The location of the peak SAR_{10g} is designated by a square. At the location at the side of the nose, the tissue within the averaging volume mainly consists of skin, connective tissue and the nasal cavity. At the position between the eyes, the tissues from the outside to the inside of the head are skin, connective tissue, nasal cavity and frontal sinus. Table 3 lists a mapping between these tissues where their dielectric properties have been obtained experimentally and those tissues in the head phantoms. Using this mapping, figure 9 shows the variation of the dielectric properties with age of these tissues. The variation of the tissue properties are not really reflected in a variation of the SAR_{10g} as shown in figure 7. Several arguments explain this observation. First, the averaging of the SAR dilutes the effect of the change in the SAR_{10g} as observed by De Salles *et al* (2006). Secondly, head tissues do not contribute equally in the averaging volume. Thirdly, not all the tissues in the averaging volume have the same variation of the dielectric properties with age, in this case, only skin contributed to the variation of the dielectric properties within the 10 g cube.

The marginal effect of the variation of dielectric properties on the 10 g averaged SAR has also been observed by Christ *et al* (2008). They defined C3Y and C7Y head models using the dielectric data in table 2 as in this paper and modelled the exposure of the children heads to 900 and 1800 MHz from generic wireless phones held to the ear. They observed up to 30% variation in 10 g average SAR due to age-dependent tissue properties. However, the variation was neither clearly systematic nor sufficiently large to establish variation in the dielectric properties as an important factor in the assessment of the exposure of children to wireless devices.

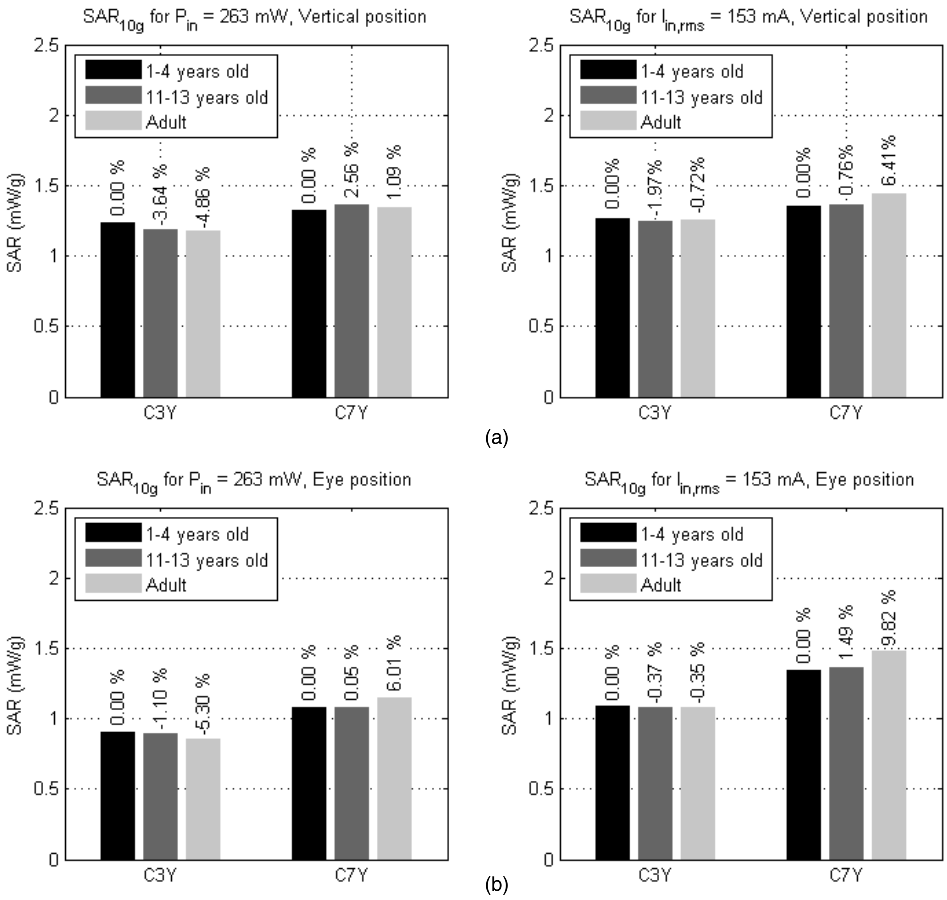

Figure 7. Assessment of the 10 g averaged SAR in a 3 and a 7 year old child head phantom for the walkie–talkie model in (a) the vertical position and (b) the 'eye position', and for the constant input power P_{in} and the constant rms current $I_{in,rms}$.

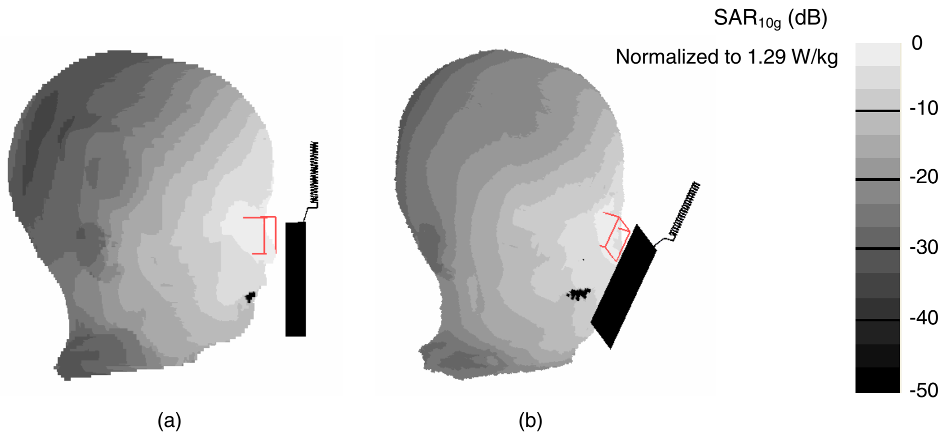

Figure 8. The SAR_{10g} on the surface of the face for C3Y with the walkie–talkie in (a) vertical position and (b) eye position. The tissues were assigned the dielectric properties for the age of 1–4 years. The square designates the position of the peak SAR_{10g}.

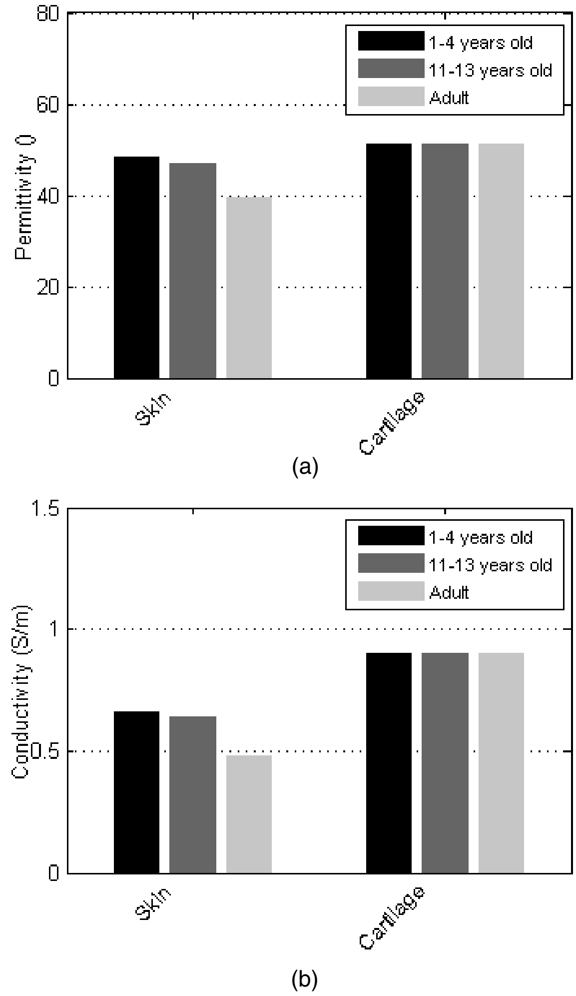

Figure 9. The dielectric properties as a function of age of the tissues in the 10 g volume where the peak SAR_{10g} occurs: (a) permittivity and (b) conductivity.

Note: the research above has been performed using an in-house designed model of a walkie–talkie and applying appropriate input power to obtain a maximum ERP of 250 mW. The ERP of several commercially available walkie–talkies have been measured according to the ETSI standards and found to range from 50 mW to 140 mW, which is more than 45% lower than the maximum allowed ERP of 250 mW. The results in figure 7 are therefore likely to be over-estimates of the exposure of children from real walkie–talkie devices.

5. Conclusion

Systematic variation of dielectric properties as a function of age has been observed for most of the measured tissues. These variations are mainly due to the decrease in the water content of the tissues.

The extent to which the dielectric properties could affect dosimetry results was investigated numerically for child head exposure to emissions from walkie–talkies. The effect on 10 g averaged SAR was marginal. Finally, the peak 10 g averaged SAR in the child head phantoms caused by a walkie–talkie is calculated to be within the safety limits.

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