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The dielectric properties of human pineal gland tissue and RF absorption due to wireless communication devices in the frequency range 400–1850 MHz

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Abstract

In order to enable a detailed analysis of radio frequency (RF) absorption in the human pineal gland, the dielectric properties of a sample of 20 freshly removed pineal glands were measured less than 20 h after death. Furthermore, a corresponding high resolution numerical model of the brain region surrounding the pineal gland was developed, based on a real human tissue sample. After inserting this model into a commercially available numerical head model, FDTD-based computations for exposure scenarios with generic models of handheld devices operated close to the head in the frequency range 400–1850 MHz were carried out. For typical output power values of real handheld mobile communication devices, the obtained results showed only very small amounts of absorbed RF power in the pineal gland when compared to SAR limits according to international safety standards. The highest absorption was found for the 400 MHz irradiation. In this case the RF power absorbed inside the pineal gland (organ mass 96 mg) was as low as 11 μW, when considering a device of 500 mW output power operated close to the ear. For typical mobile phone frequencies (900 MHz and 1850 MHz) and output power values (250 mW and 125 mW) the corresponding values of absorbed RF power in the pineal gland were found to be lower by a factor of 4.2 and 36, respectively. These results indicate that temperature-related biologically relevant effects on the pineal gland induced by the RF emissions of typical handheld mobile communication devices are unlikely.

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

1. Introduction

For years, the question of whether exposure to radio frequency (RF) electromagnetic fields (EMF) can cause cancer has been heavily discussed in science. This discussion is especially enhanced by the fact of the steadily increasing number of RF applications, e.g. modern wireless communication devices, in daily life. However, despite a considerable amount of scientific publications already available, reviews of published epidemiological studies (e.g. Elwood 2003) and *in vivo* as well as *in vitro* investigations (e.g. Heynick *et al* 2003) can give no clear picture of the issue so far. Especially the fact that no plausible 'non-thermal' interaction mechanism between RF energy and biological tissue could be established so far has caused a controversial scientific discussion. Because melatonin is known as a powerful antioxidant, playing an important role of free radical scavenging (Wakatsuki *et al* 2001), a possible suppressive effect of EMF on melatonin synthesis and/or melatonin secretion could serve as a possible explanation of the positive findings in some of the above-mentioned cancer studies. Therefore, several experimental studies have been carried out in recent years, investigating the effect of RF exposure on the pineal gland (corpus pineale) and melatonin production and secretion, respectively. The types of published studies include *in vitro* investigations on isolated pineal glands of hamsters (Sukhotia *et al* 2006), animal studies on rats (Vollrath *et al* 1997, Bakos *et al* 2003, Hata *et al* 2005, Koyu *et al* 2005), as well as human studies with respect to RF exposure from mobile phones (Radon *et al* 2001, Burch *et al* 2002, Wood *et al* 2006). Despite the fact that these studies did not provide evidence for the hypothesized effect of RF exposure on the pineal gland and melatonin production and secretion, it is interesting to note that so far no data are available concerning a quantitative analysis of RF exposure of the pineal gland in situations relevant in practice, e.g., during mobile phone usage. This is most probably due to the fact that currently available numerical head models used in RF dosimetry mostly do not provide sufficient anatomical details and do not accurately represent the small-sized pineal gland. Furthermore, the dielectric properties of pineal gland tissue have not yet been published, to our knowledge.

In order to enable detailed and realistic RF dosimetry in the pineal gland we have developed a numerical model of the respective brain region at a spatial resolution of 0.1 mm × 0.1 mm × 0.1 mm and assessed the dielectric properties on a sample of 20 freshly removed human pineal glands. Based on this we present computational results regarding tissue specific RF power absorption in the pineal gland during exposure to generic models of RF emitting handheld devices in the frequency range 400–1850 MHz, representing devices of modern wireless communication technologies such as, for example, (TETRA) radio sets and GSM as well as UMTS mobile phones.

2. Materials and methods

2.1. Dielectric property measurements on pineal gland tissue

The dielectric properties of tissues are essential parameters in RF dosimetry because they are directly related to the distribution as well as the extent of RF energy absorption. In general, the currently most comprehensive and widely used data base of RF dielectric properties of body tissues is based on the work of Gabriel *et al* (1996), which provides dispersive parameter models for many important body tissues. However, values for the pineal gland are not available so far. Therefore, the dielectric properties in the frequency range 400 MHz–6 GHz of freshly removed human pineal gland tissue were measured immediately after excision, less than 20 h after death. In total the pineal glands of 20 different patients were investigated. The tissue

Table 1. Evaluation of measurement uncertainty. Measurements on reference liquids (methanol and 0.9% saline solution) were carried out immediately before and immediately after the measurements on the pineal gland tissue and the results were compared to established data from the literature.

		Reference values (Stogryn 1978, Jordan *et al* 1978)		Prior to the measurements		After the measurements		Maximum deviation	
Liquid	f (GHz)	ε_r (1)	σ (S m^{-1})	ε_r (1)	σ (S m^{-1})	ε_r (1)	σ (S m^{-1})	$\Delta\varepsilon$ (%)	$\Delta\sigma$ (%)
0.9% NaCl solution at 20°C	0.4	80.1	1.43	79.5	1.55	80.0	1.56	−0.7	9.1
	0.9	79.9	1.58	79.3	1.69	79.9	1.70	−0.8	7.6
	1.8	79.3	2.17	77.8	2.26	78.0	2.27	−1.9	4.1
	2.45	78.6	2.82	76.3	2.88	76.0	2.90	−3.3	3.1
	5.5	73.0	8.17	70.3	7.84	70.5	7.90	−3.7	−4.0
Methanol at 20°C	0.4	33.8	0.10	34.7	0.09	34.5	0.09	2.7	−9.5
	0.9	31.3	0.44	32.7	0.43	32.5	0.43	4.5	−2.2
	1.8	25.5	1.30	27.5	1.35	27.6	1.35	8.2	3.8
	2.45	21.6	1.91	23.2	2.0	23.5	2.01	8.8	5.3
	5.5	11.6	3.63	12.3	3.96	12.4	3.93	6.9	9.1

samples were balanced with respect to gender (ten male, ten female) and the patients' age at death ranged between 26 and 91 years (mean 63 years). All pineal glands were resected during a routine autopsy procedure and were measured within 15 min after excision. The tissue temperature during the measurements was 18 °C ± 1 °C, because no re-heating of the tissue was applied in order to avoid structural changes and/or dehydration of the tissue samples.

The whole procedure related to tissue excision and handling was approved by the Ethics Committee of the Medical University of Vienna. As the measurement system an open-ended coaxial probe, made of a commercially available 50 Ohm semi rigid coaxial cable (UT-047-M, Micro-Coax, Pottstown, PA, USA) with an outer diameter of 1.3 mm, was used in combination with a computer controlled vector network analyzer (HP8722C, Agilent, Santa Rosa, CA, USA). An air/short/water calibration procedure was performed prior to each measurement session. After the calibration, measurements of reference liquids (methanol and 0.9% NaCl solution) were performed in order to check the calibration and to get an estimate of the measurement uncertainty. Because it is known that simple open-ended coaxial probes (without hermetic sealing at the probe tip) might be problematic if liquid is leaking into the aperture of the probe (Popovic *et al* 2005), reference measurements have been carried out not only prior to the measurements (after calibration), but also immediately after the measurements in order to make sure that no such problems have occurred during the measurements. Deviations of less than 1% between the reference measurements immediately prior and after the measurement were considered as acceptable. Reference data for methanol and 0.9% NaCl solution were taken from Jordan *et al* (1978) and Stogryn *et al* (1978), respectively. The results of the reference measurements showed that the uncertainty in the considered frequency range is below ±10% for both permittivity and conductivity (table 1).

Furthermore, the minimum required sample thickness was determined by measuring the dielectric properties of a 0.9% NaCl solution at decreasing distance between the dielectric probe and the bottom of a flat cup containing the solution. Two different cups (one of solid brass and one of styrofoam) were used in order to simulate both a perfectly conducting as well as an (almost) perfectly insulating secondary boundary of the sample liquid. From these

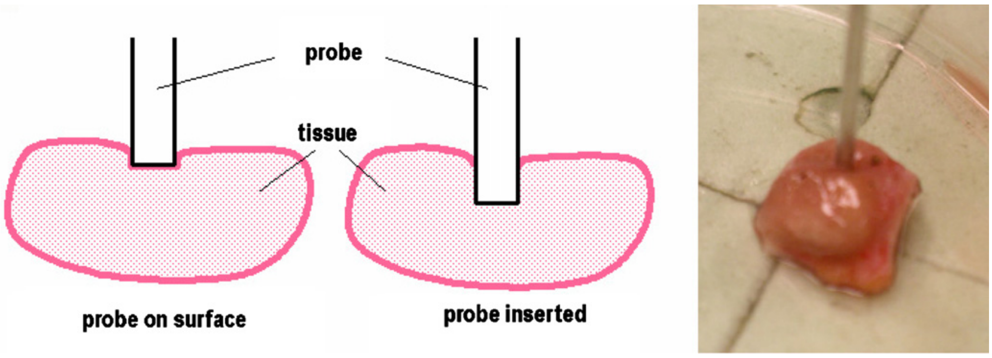

Figure 1. Two different types of dielectric property measurements (at two different locations each) were carried out on each of the pineal glands. Left: measurements on the surface; center: measurements with the probe inserted into the gland; right: photograph of a typical measurement on the surface.

experiments it could be derived that the additional measurement uncertainty over the entire considered frequency range was kept below 3% for a sample thickness of more than 1.5 mm, which could be achieved for all pineal gland tissue samples. The determined sensing depth of not more than 1.5 mm for an open-ended coaxial probe having an outer diameter as small as 1.3 mm is well in line with the results of more detailed investigations published by Hagl *et al* (2003). On each pineal gland the dielectric properties were assessed twice at different locations on the intact surface of the gland and twice with the probe inserted into the gland, i.e., in total four different measurements were carried out on every investigated pineal gland (figure 1).

2.2. Development of the numerical model

In humans the pineal gland is a piriform redish–gray organ, approximately the size of a pea, situated in a shallow depression between the superior colliculi of the tectal plate inferior to the splenium of the corpus callosum. It is connected with the diencephalons by the two habenular commissures and the posterior commissure at the dorsal wall of the third ventricle. For developing the numerical model of the pineal gland, vertical slices at a separation distance of 0.1 mm of a central human brain section (provided by the Center for Anatomy and Cell Biology, Medical University of Vienna) were obtained by a frozen section technique (figure 2). Each slice was scanned at a resolution of 1200 dpi using a commercially available and properly adapted document scanner. Based on these digital images the segmentation (0.1 mm $\times$ 0.1 mm) of the pineal gland and the surrounding brain structures were carried out at the IT'IS Foundation, Zurich, Switzerland.

Afterwards, the segmented images were converted into a three-dimensional model in the Standard ACIS® Text (SAT) file format. The developed high-resolution model was then inserted into a commercially available male head model based on the visible human data set (0.5 mm $\times$ 0.5 mm horizontal, 2 mm vertical resolution, 47 different tissue regions). This was done by using the graphical user interface (GUI) of the FDTD-based simulation platform SEMCAD X (Schmid & Partner Engineering AG, Zurich Switzerland), which provides powerful tools for manually modeling 3D objects (based on the ACIS® 3D modeling technology) and capabilities for importing SAT-files and several other commonly used data formats of 3D objects.

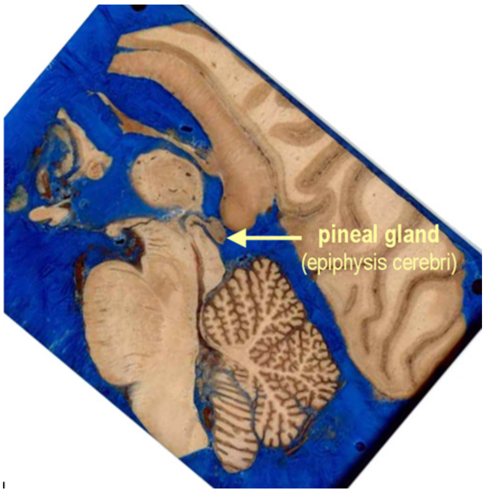

Figure 2. Example of a digital image obtained by frozen section technique (saggital cross section through the pineal gland) serving as the basis for image segmentation and model generation.

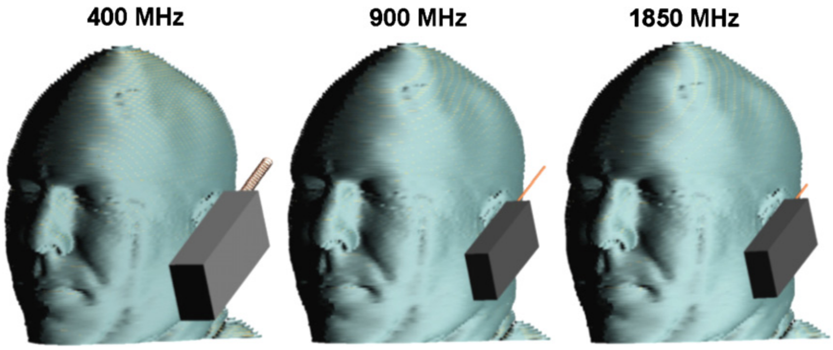

Figure 3. Considered source models and exposure conditions for the irradiation at 400 MHz, 900 MHz and 1850 MHz, respectively.

2.3. Computational methods

The FDTD-based simulation platform SEMCAD X (Schmid & Partner Engineering AG, Zurich, Switzerland) was used for computing the RF power absorption in the head during exposure to different generic mobile phone models operating at 400 MHz, 900 MHz and 1850 MHz, respectively. The generic phones were manually modeled using the 3D modeling capabilities of SEMCAD X. Each of the phone models was positioned at the left side of the head in the position of typical usage, similar to the 'tilt' position according to IEEE Std. 1528-2003 (figure 3). At 400 MHz a resonant helix antenna (axial length 61 mm, helix diameter 8.6 mm, wire diameter 1 mm, 14 turns) on top of a metallic box (130 mm $\times$ 50 mm $\times$ 30 mm) was considered as a representative model for a handheld radio set such as that used, for example, in a TETRA system. At 900 MHz and 1850 MHz quarter wave monopoles (diameter 2 mm) on top of a metallic box (100 mm $\times$ 40 mm $\times$ 20 mm) were chosen as representatives for mobile phones of the GSM900 and the DCS1800 and UMTS systems, respectively. The whole computational domain was discretized using a non-uniform mesh with mesh size between 0.25 mm and 3 mm (5 mm in case of 400 MHz irradiation) using the built-in voxeling tool of

SEMCAD X. This tool allows a high degree of customization of the grid to be generated, at the same time, however, keeping track of the basic requirements with respect to the stability of the FDTD solver. The grading ratio, i.e., the ratio of the edge lengths of two neighboring FDTD cells was kept below 1.1 in the entire grid, which ensures a smooth transition of the voxel size between regions of different spatial resolutions and therefore minimizes numerical errors introduced by using a non-uniform grid. The grid step in the region of the pineal gland was kept constant at 0.25 mm and below 1.5 mm in the irradiated hemisphere of the head model. This resulted in a total of approximately 20–25 million FDTD cells, depending on the considered source model. Perfectly matched layer (PML) boundary conditions were chosen to truncate the computational domain.

3. Results

3.1. Dielectric properties of pineal gland tissue

As shown in figure 4, permittivity as well as conductivity shows considerable variations among the investigated tissue samples. Taking the total of all 20 tissue samples the standard deviations in permittivity and conductivity with respect to their mean value were larger than approximately 8% and 12%, respectively. This can be explained by that fact that in 9 out of the 20 investigated pineal glands, brain sand (pineal acervuli) was detectable even on a macroscopic scale, i.e., by visual inspection. Brain sand is well known in medicine as mineral concretions which can be located both inside the pineal parenchyma as well as in the pineal capsula (Antic *et al* 2004). Based on its morphology and its chemical compositions two kinds of brain sand are distinguished. The first kind usually appears to be relatively large (up to a few millimeters) mulberry-like carbonate-hydroxyapatite concretions analyzed in detail by Bocchi and Valdre (1993). The second type of brain sand, appearing as calcite microcrystals less than 20 μm in size, was physically and chemically analyzed by Baconnier *et al* (2002). Due to this composition and especially its low water content the presence of brain sand is likely to reduce the overall permittivity as well as the conductivity of the pineal gland tissue. Moreover, due to the fact that the grain size of brain sand can reach the millimeter range, its presence will also induce a high degree of heterogeneity with respect to the dielectric properties of the measured pineal gland tissue, and therefore large variations in the obtained measurement results had to be expected. Both assumptions are confirmed by our measurement results as shown in figure 4. Subdividing the total tissue sample into one group ($n = 9$) consisting of pineal glands containing brain sand and another group without macroscopically detectable brain sand ($n = 11$), it can be seen that the mean values of the dielectric properties in the group containing brain sand are smaller than in the total sample and that the standard deviations in the group with brain sand are larger (standard deviation in permittivity data approximately 11%, standard deviation in conductivity data up to approximately 18%) compared to the total sample. On the other hand the group without brain sand shows higher mean values of permittivity as well as conductivity and at the same time lower variations (standard deviations of permittivity and conductivity approximately 5% and 9%, respectively) compared to the total sample. Furthermore, it has to be noted that the occurrence of brain sand could not be related to the patients' age which is in line with Galliani *et al* (1989). Even the pineal glands of the two youngest patients included in this study (24 and 34 years) show remarkably high degrees of brain sand presence (figure 5).

For the dosimetric computations in this study the total mean values of the measured dielectric properties, i.e. taking into account all 20 tissue samples, were assigned to pineal gland tissue (table 2).

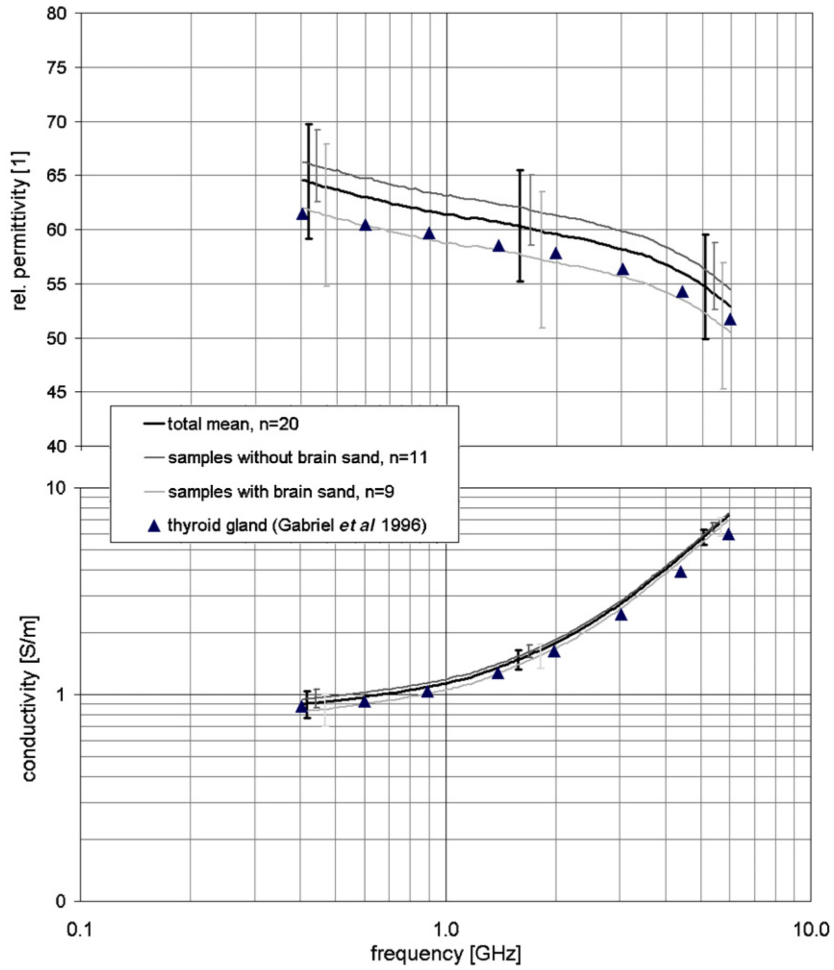

Figure 4. Mean values of the measured dielectric properties of pineal gland tissue in the frequency range 400 MHz–6 GHz. Error bars indicate standard deviation. For comparison the dielectric properties of thyroid gland tissue according to Gabriel *et al* (1996) is shown, which are commonly used for 'gland tissue' in RF dosimetry.

Table 2. Mean permittivity and mean conductivity values of pineal gland tissue used for the dosimetric computations.

Frequency (MHz)	Permittivity (1)	Conductivity (S m^{-1})
400	64.6	0.9
900	61.7	1.09
1850	59.8	1.64

3.2. RF absorption in the pineal gland during exposure to typical handsets

Figure 6 depicts the distribution of SAR (not averaged, normalized to 1 W source power) in cross sections of the head through the pineal gland for all three frequencies considered. The figure clearly shows that there is almost no contrast in the RF absorption in the pineal gland, when compared to the surrounding brain tissue.

Figure 5. The pineal gland of a 34 year old male patient (top) and a compact grain of brain sand extracted from it (bottom).

Table 3. Computational results in terms of the maximum mass averaged RF-absorption in the pineal gland, normalized to 1 W of RF source power. In the last column the 1 g averaged SAR of a cubical region with the pineal gland in the center is indicated for comparison too. Additionally, for each frequency the source power required to meet the IEEE C95.1-2005 basic restriction of 2 W kg^{-1} (10 g average over all tissues in the head) is given in the second column.

Frequency (MHz)	Source power for IEEE basic restriction (mW)	Total power absorbed (pineal gland) (μW W^{-1})	Mean SAR (range) (pineal gland) (mW g^{-1} W^{-1})	SAR 1 g (including pineal gland) (mW g^{-1} W^{-1})
400	501	22.5	0.234 (0.177–0.423)	0.201
900	210	11.0	0.114 (0.066–0.218)	0.101
1850	102	2.5	0.026 (0.016–0.048)	0.024

Table 3 summarizes the tissue specific absorption in the pineal gland in terms of the total absorbed power as well as the total mass-averaged SAR (total absorbed power in the tissue divided by total mass of the tissue). Furthermore, the SAR averaged over a cubical tissue region of 1 g, containing the pineal gland (at the center) is given for comparison in table 3. All SAR values given in table 3 are normalized to a source power of 1 W. Additionally, for each frequency the source power which produces a SAR value equal to the basic restriction according to IEEE C95.1-2005, i.e., 2 W kg^{-1} averaged over 10 g of tissue (all tissues in the head) is given in the second column of table 3.

4. Discussion

Regarding the dielectric properties of pineal gland tissue the obtained measurement results indicated values similar to those published by Gabriel *et al* (1996) for the thyroid gland. In the case of permittivity the deviations between the total mean value of our measurement results and the corresponding data for the thyroid gland was 5% less over the entire considered frequency range 400 MHz–6 GHz, and therefore clearly within the range of the measurement uncertainty (figure 4). The obtained conductivity data also show good agreement (deviations less than 10%) with the published thyroid data for frequencies up to approximately 2 GHz. For higher frequencies the deviation between our measured data for the pineal gland and the

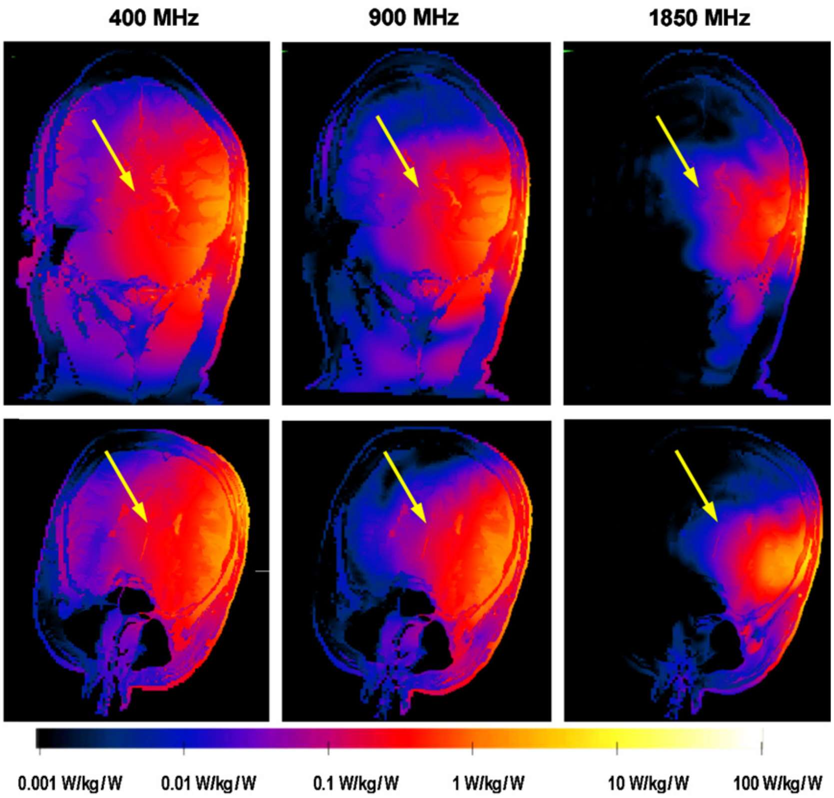

Figure 6. SAR distribution (not averaged, normalized to 1 W source power) in vertical (top row) and horizontal (bottom row) cross sections through the pineal gland (indicated by the arrows).

published thyroid data increases steadily up to approximately 23% at 6 GHz. Concerning the measured dielectric data, two remarks must be made. First, the measurements were obtained at a tissue temperature of approximately 18 °C which is significantly lower than body temperature. However, a translation of the measured values to body temperature is difficult because a corresponding temperature coefficient of pineal gland tissue is not known so far. In general, the temperature coefficients of body tissues are only rarely known but were reported to depend on the tissue type and on frequency (Gabriel *et al* 1996). In the frequency range considered here, the tissue temperature coefficients were reported to be in the order of approximately 1% $^{\circ}C^{-1}$ (Gabriel *et al* 1996, Schmid *et al* 2003). Consequently, the presented measured dielectric data of pineal gland tissue must be seen as affected by a corresponding uncertainty of approximately ±20% due to the difference of tissue sample temperature during the measurements and body core temperature. The second aspect to be mentioned here belongs to the question of possible post-mortal changes of the tissue's dielectric properties, i.e., if data obtained on excised tissue does still reflect the dielectric properties of living tissue. While some earlier work reported a slight change (of up to 15%) of the dielectric properties of porcine brain tissue in the transition from life to death (e.g. Schmid *et al* 2003), a recently published study with the scope of porcine cerebrospinal tissues (Peyman *et al* 2007) found no significant differences of the dielectric properties measured *in vivo* and *in vitro* (gray matter, white matter, dura and spinal cord). Specific information on this issue for pineal gland tissue is not yet available. Hence, if there is any *in vivo*/*in vitro* difference it seems to be comparably small.

Concerning RF absorption the obtained computational results showed that, when normalized to constant source power, the SAR in the pineal gland is highest for the irradiation with the lowest considered frequency (400 MHz) and lowest for the highest considered frequency (1850 MHz). In general, this could be expected due to an inverse relation between the penetration depth of the radiation and the frequency.

Furthermore, the RF absorption pattern shows only very little contrast between the pineal gland and the surrounding brain tissue, even though a slightly higher SAR was detectable in the pineal gland due to its slightly higher conductivity (figure 6). This similarity in RF absorption is underlined by the fact that the total mass averaged SAR in the pineal gland is only less than 15% higher than the average SAR in the 1 g cubical tissue region containing the pineal gland in the center (compare the last two columns in table 3).

Generally, the values of absorbed RF power in the pineal gland are very low, especially in the frequency range of modern mobile phones, i.e., at approximately 900 MHz and 1850 MHz, respectively. Considering typical transmit power values of such devices, i.e. 250 mW for 900 MHz and 125 mW for 1850 MHz, it can be derived from table 3 that the amount of RF power absorbed in the pineal gland is in the order of approximately 2.75 μW and 0.31 μW, respectively.

Higher, but still relatively low RF absorption in the pineal was found in the case of the 400 MHz radiation source, considered representative for walkie talkie usage close to the ear. In this case the absorbed power in the pineal gland can be computed to be 11.3 μW when considering a device with 500 mW source power.

The computed data of RF absorption in the pineal gland can only be seen as an estimate for the general case. Variations of these data must be expected due to the biological variability with respect to head size, tissue composition and the above-mentioned uncertainties regarding the dielectric properties. Especially for a smaller head size (as in the case of children), a somewhat higher RF absorption in the pineal gland might be possible compared to the presented data. This is expected because in a smaller head the pineal gland is surrounded by a smaller amount (a thinner layer) of lossy tissue and therefore more RF energy reaches deep brain regions. Quantitative figures about the variation of RF absorption in the pineal gland due to different head size, tissue composition and dielectric properties of tissue cannot be easily given based on the current knowledge because available studies dealing with this kind of uncertainty analysis focused on maximum 1 g and 10 g averaged spatial peak SAR in the head and not on tissue specific absorption. Therefore, this issue has to be seen as the subject of future research.

Based on our computed data and on the considerations above it appears unlikely that the RF emitted by typical handheld mobile communication devices can cause biologically relevant temperature effects in the pineal gland, even under worst case considerations.

Concerning possible non-thermal effects based on piezoelectric phenomena due to the presence of brain sand of the calcite microcrystal type as suggested by Baconnier *et al* 2002, the maximum peak electric field strength occurring in the pineal gland might be of interest, which correspond to 20.2 V m^{-1}, 10.2 V m^{-1} and 2.8 V m^{-1} for typical RF sources of 400 MHz/500 mW, 900 MHz/250 mW and 1850 MHz/125 mW, respectively. However, from our side no statement regarding the mentioned piezoelectric phenomena can be given at present.

5. Conclusion

In this paper an analysis of RF absorption in the pineal gland of an adult head model, caused by mobile communication devices operated close to the head in the frequency range 400–1850 MHz, was carried out for the first time. FDTD-based computations showed only very low amounts of absorbed RF power in these organs, when considering source power values of typical handheld devices. Therefore, a temperature related biologically relevant RF induced effect of such devices on the pineal gland and its function seems to be unlikely.

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