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Electromagnetic Absorption in the Head of Adults and Children Due to Mobile Phone Operation Close to the Head

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The Specific Absorption Rate (SAR) produced by mobile phones in the head of adults and children is simulated using an algorithm based on the Finite Difference Time Domain (FDTD) method. Realistic models of the child and adult head are used. The electromagnetic parameters are fitted to these models. Comparison also are made with the SAR calculated in the children model when using adult human electromagnetic parameters values. Microstrip (or patch) antennas and quarter wavelength monopole antennas are used in the simulations. The frequencies used to feed the antennas are 1850 MHz and 850 MHz. The SAR results are compared with the available international recommendations. It is shown that under similar conditions, the 1g-SAR calculated for children is higher than that for the adults. When using the 10-year old child model, SAR values higher than 60% than those for adults are obtained.

Keywords Biological effects; Cell phones; Finite difference time domain–FDTD; Mobile phones; Specific absorption rate–SAR.

Introduction

There has been a significant expansion of cell phone systems all over the world and particularly in Brazil in the last few decades. There are now more than 1.8 billion cell phone users in the world, and more than 94 million cell phone users in Brazil, with indications that these rates of use will increase even faster in the next few years. In parallel with this, an increased concern from the scientific community, the authorities, and the population regarding the safety of these phones has arisen. A major problem is the distance between the antenna and the user's head, especially when conventional monopole (or whip) or helix antenna are used. These radiate

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nearly symmetrical around them. In this situation, the electromagnetic (EM) energy absorbed in the head tissues is significant and can result in serious risks for the users.

Several authors have used the Finite Difference Time-Domain (FDTD) method to simulate the Specific Absorption Rate (SAR) in the cell phone user's head (e.g., Fernández et al., 2004; Gandhi et al., 1996; Jensen and Rahmat-Samii, 1995). It is currently the most appropriate choice when highly nonhomogeneous structures are involved for which boundary techniques have fundamental limitations. The SAR results estimated and measured show exposure levels close (or even above) the limits of the available recommendations (ICNIRP, 1998; IEEE/ANSI, 1991). These consider only the thermal effects of the electromagnetic absorption.

Recently, the use of cell phones by young children has been strongly stimulated. Some authors have focused this, and different results were presented (Anderson, 2003; Gandhi et al., 1996; Martínez-Búrdalo et al., 2004; Schönborn et al., 1998; Wang and Fujiwara, 2003). In Gandhi et al. (1996), the model of the children head was based on a scaled adult model and a SAR increase (compared with the adult) of around 120 % has been obtained. In Schönborn et al. (1998), the head model was based on MRI using similar electromagnetic parameters as those for the adults, and no significant differences between adult and children SAR results were observed. In Anderson (2003), the head model was approximated by spheres considering some variation of the electromagnetic parameters, and an increase of around 20% in the calculated SAR was shown. In Martínez-Búrdalo et al. (2004), using also scaled model for the children's head with adult electromagnetic parameters, no significant variation for the average SAR in the whole head was observed, and an increase of around 35% in the SAR was calculated when considering the brain.

In this article, the FDTD method was used to simulate the SAR in the head of adult and a child, and to compare the results simulated for the child with those obtained for the adults. Adult and child head model were previously developed and presented by our research group (de Salles et al., 2002, 2003; Fernández et al., 2004, 2005). The electromagnetic parameters for the child were fitted to this age. Comparisons also were made with SAR calculated in the children model when using adult human electromagnetic parameters values. Simulations were performed using CRAY T 94 supercomputer from CESUP (www.cesup.ufrgs.br).

All the SAR results were calculated using planar microstrip (or patch) directional antennas and quarter wavelength monopole antennas. The monopole antennas are now widely used in mobile phones. Their radiation pattern on the horizontal plane is nearly symmetrical around them. Then, in the usual situation of operation, when these antennas are placed very close to the head, most of the radiated energy is absorbed in the user's head (e.g., in the brain tissues, in the eyes, etc.) and a smaller portion of energy is radiated to the nearest base station. This is an undesired situation, since there is degradation in the communication quality, the battery drain, and the user's health risk are increased.

The use of planar antennas with moderate directivity for mobile phones has been suggested previously (de Salles et al., 2003; Fernández et al., 2004; Jensen and Rahmat-Samii, 1995). These antennas radiate more in the direction opposed to the head, improving the quality of communication, reducing the battery drain and the user's health risk. They can have small dimensions and a compact form, integrated to the cell phone box. Also, they can be very inexpensive, resulting therefore in an interesting alternative to this application.

Table 1
Spatial discretization

Model cases	Adult A	10-year old B and C
Scale factor	1	1
Cranial perimeter (mm)	563.5	523.9
Δx (mm)	0.910	0.9460
Δy (mm)	1.887	2.269
Δz (mm)	1.968	1.601
Device distance (mm)	Δx	Δx

Antenna Models

The cell phones were modeled using microstrip (patch) planar antennas and quarter wavelength monopole antennas. The patch antennas were designed following the cavity models described by Taflove (1998) and Garg et al. (2001), and the monopole antennas were simulated using a quarter wavelength thin wire. The antenna dimensions were adjusted according to the cell grid shown in Table 1. Special care was taken to feed the antenna at the exact resonance frequency. S11 simulations using FDTD and FFT show the resonance frequency. This was the frequency used to feed the antenna. The antenna is feed with a harmonic signal; 1850 MHz and 850 MHz frequencies were used as the feed frequency. As the delivered power to the antenna may be different for each case, due to principally mismatch in the impedance input, these were normalized. The value of 600 mW was used for 850 MHz antennas and 125 mW was used for 1850 MHz antennas. Among others, a main objective of this work is to compare the child and adult exposures in three different situations (Cases A, B, and C, as described below), and for each antenna.

SAR Simulations in the Adult Head

SAR simulations for the adult human are performed using a model based on the visible man (available at www.vhd.org.br) as described in previous works (de Salles et al., 2002, 2003; Fernández et al., 2004). This is based on medical images. From this the numerical domain is developed, where the field is calculated. Each cell in this domain matrix is associated to a spatial place and to the corresponding tissue in each place. The derivation of the mesh which is used for the domain of calculations based in the discretization of the adult head has been described in a previous paper (de Salles et al., 2002). No interpolation or smoothing were implemented to prevent staircasing. A three-dimensional view of the adult head is shown in Figures 1(a) and (b). The head is rotated to put the ear-to-mouth line vertically. This facilitates the cell phones antennas positioning.

In this work, the physical and electrical parameters used for the different tissues in the adult head were analogous to those used by other authors (de Salles et al., 2002; Jensen and Rahmat-Samii, 1995; Watanabe et al., 1996). The permittivity, equivalent conductivity, and density are associated to each kind of tissue, in function of the frequency of operation.

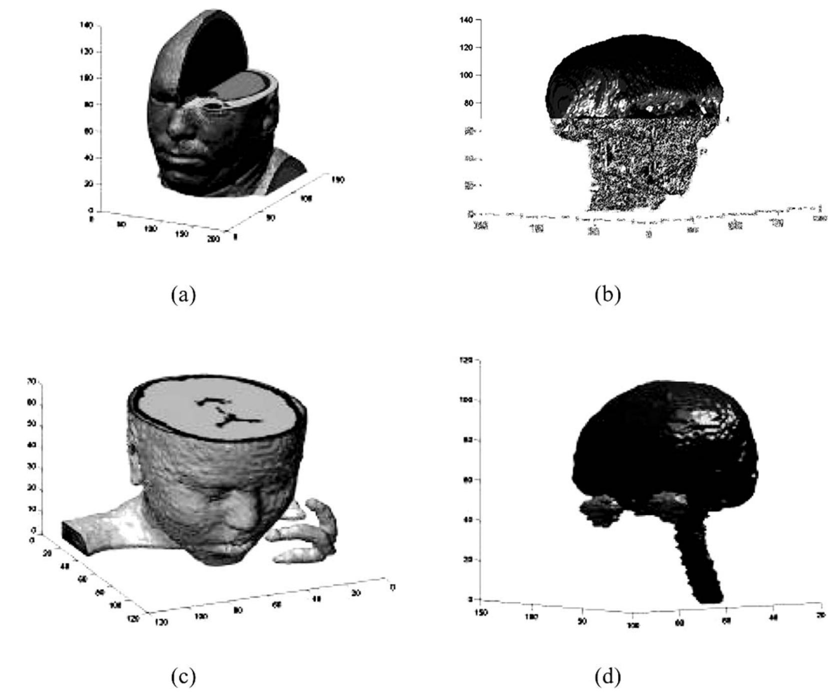


Figure 1. Three-dimensional images from both head models: (a) adult head without a quadrant; (b) adult skull; (c) child head without a quarter of the head top; (d) brain, eyes, spinal chord on the child model.

In Table 2, the parameters used at 1.85 GHz are indicated. These values are close to those recommended by the FCC (Federal Communications Commission): (available at www.fcc.gov/fcc-bin/dielec.sh).

If the hand were placed close to the antenna, it could substantially modify some radiation parameters, such as the antenna input impedance and radiation pattern, as well as the SAR values. The exact influence of this effect would be a function of the relative position between the antenna and the hand. In Watanabe et al. (1996), it has been shown that, if the hand is not placed directly over the antenna, SAR values are disturbed only a little.

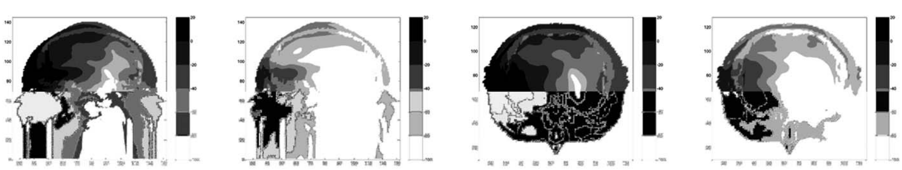
The electric field intensity ($20 \times \log|E|$) for the two antennas is shown in Figure 2, on the left for the $\lambda/4$ monopole, and on the right for the patch antenna, in frontal cut (xz plane) (at the $\lambda/4$ monopole antenna plane) and coronal cut (xz plane) (at the bottom of the $\lambda/4$ monopole antenna), above and below, respectively. It can be observed that the fields inside the head can be substantially reduced (by more than 10 to 13 dB) when the planar antenna is used. These results are in close agreement to those described in Jensen and Rahmat-Samii (1995). The distance between the head and the antenna is 5.4 mm.

The SAR distribution in dB ($10 \times \log$ [SAR]) for the same frontal and coronal cuts is shown in Figure 3. These SAR values are normalized to an average power of Pdel = 600 mW delivered to the antenna, then 0 dB corresponds to a SAR = 1 mW/g. Again, it can be observed that reduced SAR levels (at least 10 to 13 dB down) are obtained when the patch antenna is used, if compared to

Table 2
Physical properties for the adult man and fitted for the 10-year old child at 1850 MHz

Age		Adult		10-year old	
Properties	ρ (g/cm^3)	ε_r	$\sigma(\Omega^{-1}/\mathrm{m})$	ε_r	$\sigma(\Omega^{-1}/\mathrm{m})$
Air	0.00	1.00	0.00	1.00	0.00
Average skull	1.85	15.56	0.43	18.48	0.54
Skin (wet)	1.01	43.85	1.23	54.63	1.53
Average muscle	1.04	54.44	1.39	61.68	1.57
Average brain	1.03	43.54	1.15	52.52	1.44
Vitreous humour	1.01	68.57	2.03	81.81	2.47
Fat (mean)	0.92	11.02	0.19	13.15	0.23
Eye tissue (sclera)	1.17	53.57	1.60	63.91	1.95
Brain spinal fluid	1.01	67.27	2.92	80.11	3.55
Nerve (spinal chord)	1.04	30.87	0.84	36.83	1.02
Lens nucleus	1.10	34.65	0.79	41.34	0.96

the $\lambda/4$ monopole antenna. The maximum human exposure limit recommended by ICNIRP (1998), is a SAR $= 2\,\mathrm{mW/g}$. This is the same as recommended by the Brazilian agency (ANATEL, 2002). It is observed that under the conditions of these simulations, when the monopole antenna is used, the SAR in the head can be several times above the 2 mW/g limit. This is in very close agreement to the results



(a) (b) (c) (d)

Figure 2. Frontal (xy plane) and coronal (xz plane) images showing the electric field distribution ($20 \times \log|E|$) obtained at the end of the simulations: (a) monopole antenna (frontal); (b) microstrip antenna (frontal); (c) monopole antenna (coronal); (d) microstrip antenna (coronal).

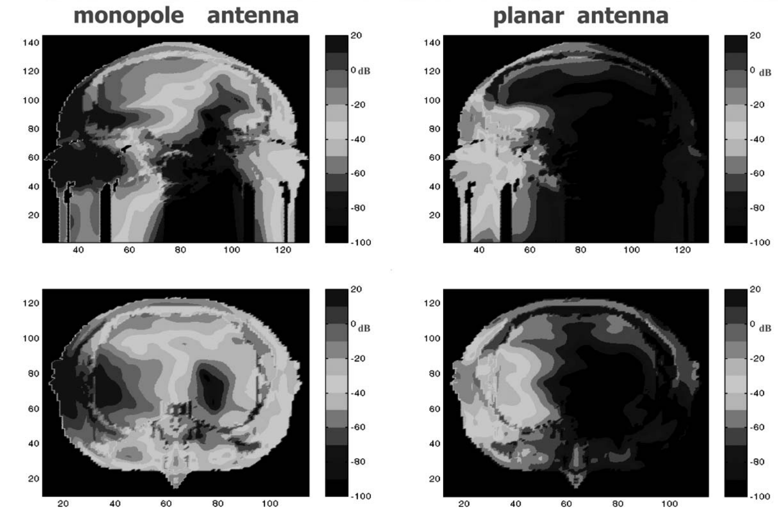


Figure 3. Frontal (xy plane) and coronal (xz plane) images showing the SAR distribution ($10 \times \log |E|$) obtained at the end of the simulations. Left: $\lambda/4$ monopole and right: microstrip patch antenna.

described elsewhere (Bernardi et al., 2001; Iskander et al., 2000; Jensen and Rahmat-Samii, 1995; Watanabe et al., 1996). However, as has been shown in a previous paper (de Salles et al., 2002), if the antenna were operated at a distance sufficiently apart from the user's head (e.g., $d \geq 2.5$ cm from the head), then the SAR in the head would be below the ICNIRP limit of 2 mW/g.

Among others, one of the purposes of this article is to compare the relative specific absorption rates when monopole and planar antennas are used, showing a reduction in the SAR when planar antennas are used. This is true even when spatial average or punctual SAR values are taken into account. The microstrip (or patch) antenna simulations show that the field intensity and the SAR in the head are reduced to levels below the ICNIRP limits (Fernández et al., 2004). Similar results obtained for other planar antennas were reported elsewhere (Bernardi et al., 2001; Iskander et al., 2000; Jensen and Rahmat-Samii, 1995; Watanabe et al., 1996).

In order to calculate the radiation efficiency, the power absorbed in the user's head is added to the antenna losses and this is named overall absorbed power Pabs. Since the power absorbed in the user's head is reduced when the planar antennas are used, then an increase on the radiation efficiency $\eta = (\text{Pdel} - \text{Pabs})/\text{Pdel}$ is obtained, as compared to the use of $\lambda/4$ monopole antennas. This was discussed earlier (Jensen and Rahmat-Samii, 1995).

SAR Simulations in a Child Compared with Adult

In order to compare the simulated SAR due to cell phones operated close to the head in adults and children, the model of the children previously developed (Fernández et al., 2005) was used. The geometric and the electromagnetic parameter differences between the adult and child were considered in the simulations.

Three-dimensional view of these models are shown in Figure 1. Both models were rotated to put the ear-to-mouth line vertically. This facilitates the cell phones antennas positioning.

Three different simulation cases were implemented. In Case A, the adult model with the adult parameters (Gabriel and Gabriel, 1996) was used. In Case B, the 10-year old child model with adult electromagnetic parameters was considered. In Case C, the 10-year old child model with the electromagnetic parameters fitted to this age was used. These were obtained from comparison with the results obtained for rats (Peyman et al., 2001). The electromagnetic parameters for adult human are well established, with accuracy better than 5% (Gabriel and Gabriel, 1996). However, data for children are still not available. A study with rats (Peyman et al., 2001) shows that conductivity and permittivity decrease with age. For 10-day old and younger rats, the values are around 20% higher than for sexually mature (adult) rats (e.g., 50 days). One reason for this could be the higher salt-water concentration in the tissues of the young. The measured results for adult individuals in different animal species show that there is a parameter variation lower than 5% from animal to animal when considering the same type of tissue. This was the rationale, and using similar correspondence between parameters values and age for humans as for rats, we obtained the fitted parameters for the children. These values are shown in Table 2.

The cranial perimeters in both models were approximated from ellipsis. The calculated values are in close agreement with those shown in Schönborn et al. (1998). To adjust for the corresponding dimensions and in order to save processor memory, FDTD simulation were performed having different cell dimensions for each of the three cases (Taflove, 1995, 1998). Then, the distance between the antenna and the head are slightly different. These are shown in Table 1.

The simulated peak SAR and average SAR (1 g and 10 g) are presented. The 1 g-SAR and the 10 g-SAR were calculated as spatial averages of boxes with $11\Delta x \times 6\Delta y \times 5\Delta z$ (1 g-SAR, Case A), $24\Delta x \times 11\Delta y \times 11\Delta z$ (10 g-SAR, Case A), $10\Delta x \times 6\Delta y \times 5\Delta z$ (1g-SAR, Cases B and C), $23\Delta x \times 12\Delta y \times 11\Delta z$ (10 g-SAR, Case B and C). Since there is not a great variation in the densities of the different tissues, this can be considered a reasonable approximation.

As mentioned before, the child and adult head models were rotated in order to a better positioning of the cell phone, and then the vertical cuts do not correspond exactly to coronal cuts. Figure 4 shows the SAR calculated in all cases.

In Tables 3–6, the maximum simulated SAR results in the brain for all the cases are shown. In accordance with the IEEE/ANSI and the ICNIRP recommendations (IEEE/ANSI, 1991; ICNIRP, 1998), one of the major parameters to be considered is the 1 g mean SAR. It is observed that an increase in the 1 g-SAR was obtained for the children model with the adult parameters (Case B) and for the children model with the fitted parameters (Case C). The 1 g-SAR in the child head for the antennas fed at 1850 MHz shows an increase relative to the adult of about 32% for Case B and 60% for Case C, independently of the type of antenna used. At 850 MHz this relative increase was even higher, but different for each antenna type. The patch antenna at 850 MHz shows an increase of 98% between the 1 g-SAR of the adult and the child in Case B and 131% between the adult and the child in Case C. Also, an increase in the mean SAR (whole head) simulated in the child (Cases B and C) is observed when compared to the adult (Case A). However, a significant difference between the mean SAR (whole head) for the child in Cases B and C was not observed.

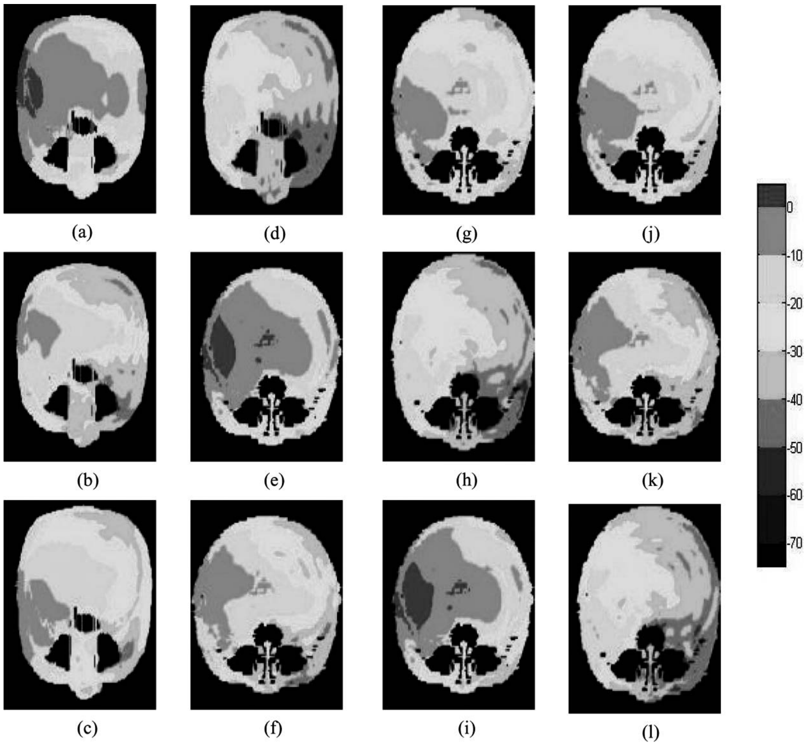


Figure 4. SAR distribution on adult and child head. A logarithmic scale was $10^* \log_{10}$ (SAR(mW/g)/1.6(mW/g))). (a) adult with quarter wavelength monopole at 850 MHz and 600 mW; (b) adult with quarter wavelength monopole at 1850 MHz and 125 mW; (c) adult with microstrip (or patch) antenna at 850 MHz and 600 mW; (d) adult with microstrip (or patch) antenna at 1850 MHz and 125 mW; (e) child with adult parameters with quarter wavelength monopole at 850 MHz and 600 mW; (f) child with adult parameters with quarter wavelength monopole at 1850 MHz and 125 mW; (g) child with adult parameters with microstrip (or patch) antenna at 850 MHz and 600 mW; (h) child with adult parameters with microstrip (or patch) antenna at 1850 MHz and 125 mW; (i) child with fitted parameters with quarter wavelength monopole at 850 MHz and 600 mW; (j) child with fitted parameters with quarter wavelength monopole at 1850 MHz and 125 mW; (k) child with fitted parameters with microstrip (or patch) antenna at 850 MHz and 600 mW; (l) child with adult parameters with microstrip (or patch) antenna at 1850 MHz and 125 mW.

Table 3
SAR—Quarter wavelength monopole (1850 MHz), power = 125 mW

Model	Adult	10-year old child	
Electromagnetic parameters	Adult parameters	Adult parameters	Children parameters
		SAR values (W/kg)	
Peak SAR (one voxel)	1.490	3.58	4.40
1 g-SAR	0.527	0.794	0.885
10 g-SAR	0.362	0.556	0.596
Mean SAR (whole head)	0.021	0.032	0.032

Table 4
SAR—Quarter wavelength monopole (850 MHz), power = 600 mW

Model	Adult	10-year old child	
Electromagnetic parameters	Adult parameters	Adult parameters	Children parameters
		SAR values (W/kg)	
Peak SAR (one voxel)	3.68	5.97	6.20
1 g-SAR	1.8	2.38	2.89
10 g-SAR	1.7	1.74	2.05
Mean SAR (whole head)	0.149	0.193	0.191

Discussions and Conclusions

The SAR in an adult and in a 10-year old child was calculated and comparison of the SAR results obtained for the adult and the child with planar microstrip (or patch) and $\lambda/4$ monopole antenna, at 1850 MHz and 850 MHz, were shown. It is observed that under the conditions of these simulations, when the $\lambda/4$ monopole antenna is used, the SAR in the head of an adult can be several times above the 2 mW/g ICNIRP thermal limit. When the directional antenna is used, a SAR reduction in the head between 20 to 30 times is estimated.

SAR results around 60% higher than those simulated for the adults were observed for the children with fitted parameters, independent of antenna type or frequency. The relation between the 1g-SAR calculated with the child model and the 1g-SAR calculated using the adult model was higher at 850 MHz than at 1850 MHz. This is probably due to the wavelength, since at 850 MHz it is of the same order of magnitude as the child head dimensions.

The increase in the mean SAR in the whole head, between the adult and the child, is expected due to the reduced dimensions in the child head, as well as the higher values of the permittivity and of the conductivity in the child brain tissues. Also, children's growing skulls are thinner than those of adults, and therefore less resistant to radiation. This is in accordance with the results obtained by other authors (Gandhi et al., 1996).

Table 5
SAR—Microstrip (or patch) antenna (1850 MHz), power = 125 mW

Model	Adult	10-year old child	
Electromagnetic parameters	Adult parameters	Adult parameters	Children parameters
		SAR values (W/kg)	
Peak SAR (one voxel)	0.091	0.190	0.207
1 g-SAR	0.055	0.109	0.131
10 g-SAR	0.036	0.086	0.086
Mean SAR (whole head)	0.0058	0.0085	0.0085

Table 6
SAR—Microstrip (or patch) antenna (850 MHz), power = 600 mW

Model	Adult	10-year old child	
Electromagnetic parameters	Adult parameters	Adult parameters	Children parameters
	SAR values (W/kg)		
Peak SAR (one voxel)	0.670	1.16	1.26
1 g-SAR	0.359	0.477	0.590
10 g-SAR	0.231	0.342	0.347
Mean SAR (whole head)	0.0451	0.0516	0.0524

It is important to remark that only the thermal limit has been considered so far. In principle, as the digital phone radiates lower mean power in comparison to the analog phones, their risk associated with the heating of tissues is then reduced. However, since most mobile communication systems are now pulse-like in nature, modulated at low frequencies, such as the GSM, UMTS, CDMA, TDMA systems, then they are able to induce currents in the brain tissues and this can result in some low level non thermal effects, e.g., blood brain barrier (BBB) alterations, single and double strand DNA breaks, chromosomal aberrations, etc., at RF energy levels substantially below the thermal threshold. Several papers and reports have already shown adverse health effects at exposure levels well below the thermal limits (e.g., Lai, 2005; Lai and Singh, 1996; Reflex, 2005; Salford et al., 1994). Further to that, a recent epidemiological study has shown 1.7 to 5.9 fold increase in risk for malignant brain tumors, with >10 years latency period for long-term mobile phone and cordless phone users (Hardell et al., 2006). As a substantial percentage of the population now uses mobile phones for a long time during each day and for several years, operating the antenna very close to their head, then this exposure can effectively represent a serious risk for their health.

Finally, due to the increased use of mobile phones by adults and children, and since compliance tests use head phantoms based exclusively on adult data, the results shown in this article may suggest that further theoretical and experimental research must be immediately done in order to evaluate these issues aiming to reduce risks, specially for the children. This is in accordance to the World Health Organization's (WHO) effort, included in the WHO Children's EMF Research Agenda, recommending research studies relevant to the risk of adverse health effects in children from exposure to electromagnetic fields – EMFs (WHO, 2004).

Meanwhile, since the present guidelines are questionable in protecting the cell phone user's, the Precautionary Approach should be promptly adopted, and the cell phone exposure should be kept to a minimum, following the ALARA principle (As Low as Reasonably Achievable). For example, the responsible health public authorities should disseminate some basic recommendations for the cell phone user's, such as to make only short and essential calls, always use hands-free kits, and maintain the antenna far away from their body during the calls. In order to reduce irreparable public health damage, it is clear that the adoption of the Precautionary Approach, until more detailed and scientifically robust information on any health effects becomes available, should not be further delayed.

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