Comparative SAR assessment in adults and children exposed to electromagnetic fields of radio frequency devices

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Abstract: Exposure to radio frequency electromagnetic fields has raised scientific and public concern regarding possible adverse effects to people exposed to such radiation. At cellular mobile communication frequencies, the most important parameter used to assess human exposure to electromagnetic fields is SAR (Specific Absorption Rate).

This paper will firstly address two exposure scenarios related to adult exposure to GSM electromagnetic fields :

Human exposure to 900 MHz GSM base station electromagnetic fields, whereby with EMR-300 is measured field strength on different points located meters away from base station antenna. Using SAR prediction formula we have calculated induced SAR values for people located near base station antenna. The obtained results are compared with maximum permissible levels and basic restrictions of international safety standards.

Human exposure to mobile phone GSM electromagnetic fields, whereby with a software (FDTD code) have simulated human head exposure to mobile phone radiation and have calculated Spatial Peak SAR over 1 g and 10 g of human body biological tissues.

Secondly, in order to investigate comparison of radio frequency energy absorption by head of children and adults, the Spatial Peak SAR over 1g and 10g is calculated for: uniformly down-scaled adult head with increased dielectrical parameters compared to adult ones and uniformly down-scaled adult head with adult dielectrial parameters.

SAR results are presented graphically and tabulary while comparative assessment is given in order to emphasize influence of head size and change of dielectrical parameters on radio frequency energy absorption by human tissues, and give possible answer whether children should be treated as special group regarding radio frequency exposure.

Even not an all inclusive approach is considered, obtained results indicate that SAM may be considered conservative for assessment of children exposure compliance to radio frequency electromagnetic fields.

Key-Words: Radio frequency, GSM, SAR, SAM, base station antenna, field strength, mobile phone, child, dielectrical properties.

1 Introduction

Tremendous growth of radio frequency mobile communications in general and of GSM (Global System of Mobile Communication) in particular has been followed by public concern about potential effects appearing at living organisms due to exposure to such radiation.

Even though mobile communications are considered by many as fundamentals of their lifestyle, concerns for potential health impacts caused by operation of mobile communications are becoming an issue for individuals, researchers, governments and other relevant institutions.

Many studies have been done and are ongoing regarding potential biological, thermal, non-thermal and behavioral effects to humans exposed to electromagnetic fields.
Not only negative impacts are being studied but also positive sides of exposure as application of electromagnetic in medicine as described on [5] are being addresses as well.
Interaction of radio frequency electromagnetic fields with a human is a multidimensional issue that depends from many parameters as indicated on [6] and [13].
When talking about human exposure, one always thinks of an adult of middle age, with no age or gender distinction.
On the other hand, based on last year's surveys about mobile phone usage among different age groups, an increase of mobile phone usage by children is being reported.
As per [18] in Germany about 90% of children between the age of 12 and 13 owned a mobile phone in 2008; in Hungary nearly 76% of fourth grade school children owned a mobile phone in 2006; in Sweden about 79 % of the children aged 7-14 reported mobile phone access in 2006.
In addition to other child related parameters, this increased usage development has added concerns regarding possible effects to children exposed to mobile phone radiation.
Different exposure standards and guidelines based on different research studies have been set up to ensure safety of electromagnetic devices and provide guidance on the safe exposure to electromagnetic fields.
In general, the safety standards are defined in terms of basic restrictions that represent limits on internal (induced) parameters such as SAR and induced currents; and maximum permissible exposure values such as electrical field strength and magnetic field which are derived from basic restrictions and represent limits on external fields.
Dosimetric studies are performed to quantify the interactions of electromagnetic fields with biological tissues.
At radio frequencies the most important dosimetric parameter used to assess human exposure to electromagnetic fields is SAR.
For this reason almost all national and international safety guidelines as ICNIRP [9] and IEEE [14] and recommended limits on human exposure to radio frequency electromagnetic fields are given in terms of SAR.

SAR (W/kg) is expressed either as a localized partial body SAR value or averaged over the whole body. It describes the amount of energy W absorbed by biological tissue in time (dt) and mass unit (dm) :

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) \quad (1)$$

SAR is related to the induced electrical field at a point by:

$$SAR = \frac{\sigma |E|^{2}}{\rho} = (\sigma + w\varepsilon_0\varepsilon^{"})\frac{|E|^2}{\rho} \quad (2)$$

where:
σ -Conductivity of body tissue
E -root mean square of intensity of electrical field at considered point,
ε_0 -permittivity of the free space,
$\varepsilon^{"}$ -loss factor
ρ -mass density of tissue at that point
w - angular frequency

Since SAR-time rate of radio frequency energy absorbed per unit mass, is very difficult and complex to be measured directly in human biological tissues, alternatives as measurement of incident field strength, power density, estimation by computational methods, and software simulations are being used to assess human exposure to electromagnetic fields.
According to equation (2) radio frequency energy deposition in a biological tissue at certain frequency depends directly from dielectrical properties of tissue, e.g. from σ and $\varepsilon^{"}$.
Dielectrical properties of biological tissues are function of frequency [23].
Theoretically, biological tissues with higher σ and $\varepsilon^{"}$ for same induced electrical field will give higher SAR.
Lately there have been few studies showing that dielectrical properties of biological tissues are age dependent [1]- [3].
According to these studies, dielectrical properties are function of water content while total body water content decreases with age.
This has triggered scientific discussion on whether child tissues should absorb more radio frequency

energy than adult tissue and therefore comparative SAR, emphasizing the effect of changes on dielectrical properties as function of age, should be considered.
On the other hand, absorbed energy as function of frequency also depends on geometry (shape and size) of exposed body. Resonance effect in the human body has to be taken into account because resonance typically scales with the size of the object relative to frequency (wavelength). Smaller objects such as child head compared to adult head typically have resonances at higher frequencies.
Taking into consideration increased usage of mobile phones by children, age dependence of dielectrical properties of biological tissues, and radio frequency energy deposition as function of size and shape, it is evident that child exposure to radio frequency should be assessed and compared to adult exposure. Moreover, all international guidelines and exposure limits are developed for adults and do not take into consideration child parameters.
The scope of paper is to investigate exposure to radio frequency sources focused on cellular communication system GSM.
Analyzing architecture of GSM [12], it is obvious that radiation coming from base station antenna and mobile phones should be addressed separately.
Since these are two different situations of human exposure, one far-field radiation and whole body exposed while second near-field exposure with most of radiation covering human head, they have been studied independently and are presented separately on next paragraphs.

2 Assessment of SAR in humans exposed to GSM base station antenna

Widespread use of mobile communication led to sitting of GSM base station antennas in densely populated areas. This raised concern particularly to people living in the vicinity of base station antennas which are being exposed to such radiation for a long time and cumulative effect of exposure may become an issue.
In some countries, base station antennas can be seen even in close proximity of educational institutions. If we consider child sensitive factors, and add a fact that today's children have longer life time exposure comparing to adults, the risk factor for children might be increased.

To evaluate exposure we have assessed human exposure to 900 MHz GSM base station antenna located on suburb of Kosovo's capital, Prishtina.
As all parts of human body are exposed to such radiation, the attention is focused on whole-body averaged SAR.
Since measurement of induced field in human body exposed to base station is impossible, in order to asses such exposure we have measured incident field strength in few locations (measurement points), meters away from base station antenna.
Results are to be compared with maximum permissible exposure levels and if they are satisfied we assume that basic restrictions given in terms of SAR will be satisfied too, even though for this exposure we have calculated SAR as well.
Measurements are done according to standards for this frequency range [4] and based on methodology described in details in our previous work [15]- [17].
Measurements are performed using radiation meter EMR-300, sensor type 8 E- field probe, 200 KHz -3 GHz, three axial sensors; so measurements are done independently of direction or polarization of radiating source.
Obtained measurement results are used in SAR prediction formula to calculate SAR for people exposed to BTS radiation.

At 900 MHz, average dielectric parameters of human body are:

$$\varepsilon_r = 55 \ and \ \sigma = 1.4$$

In dependence of incident electric field, SAR can be calculated as follows [12]:

$$SAR = \frac{\sigma}{\rho} \frac{\mu \omega}{\sqrt{\sigma^2 + \varepsilon^2 \omega^2}} (1 + \gamma_r)^2 \frac{|E_{inc}|^2}{Z_0^2} \quad (3)$$

$$\gamma_r = \frac{2\left|\sqrt{\varepsilon'}\right|}{\left|\sqrt{\varepsilon'} + \sqrt{\varepsilon_0}\right|} - 1 \quad (4)$$

$$\varepsilon' = \varepsilon + j\frac{\sigma}{\omega} \quad (5)$$

where:

γ_r - Corresponding reflection coefficient

ε' - Complex permittivity of the medium

E_{inc} - rms of the incident electrical field

Z_0 -free space impedance

μ -magnetic permeability

Results for electrical field strength and predicted SAR for people living near base station antenna are given in Tables 1 and 2.

Even though measurements are done on few points meters away from base of antenna, ground level, in paper are presented results of measurments on five points. Authors should be contacted for a complete list of measurements.

Measu. point	Distan (m)	E (V/m)		
		Inst.	Avg.	Max. of avg.
1	11	0.34	0.44	0.51
2	15	0.25	0.54	0.54
3	31	0.64	0.56	0.72
4	27	0.25	0.27	0.28
5	55	0.16	0.59	0.76

Table 1

Measu. point	Distan. (m)	SAR($\mu W / kg$)
1	11	0.20
2	15	0.23
3	31	0.41
4	27	0.06
5	55	0.46

Table 2

Comparing younger (10kg) to older (250 kg) animals, both permittivity and conductivity of almost all tissues were systematically higher for the younger animals [2].

If we assume that child biological tissues are more loosy, more conductive with higher values of dielectrical properties, the reflection of this on SAR based on equation (2) is self-evident.

3 Assessment of SAR in adults exposed to mobile phone electromagnetic fields

Radiation from mobile phone mostly covers human head. Moreover the transmitted power is not that high so we cannot expect high values of induced SAR in other parts of the body.

In order to assess human exposure to mobile phone GSM electromagnetic field simulations have been run for model: human head+mobile phone.

Simulations are performed based on Finite Difference Time-Domain (FDTD) method.

This method has proved its accuracy and its ability to estimate SAR in a heterogeneous media [7]. Based on this method, the Maxwell's equations are discretized in both space and time using central difference formulas of second-order accuracy on a staggered Yee-grid and electrical and magnetic fields are calculated. Due to memory limitations, the computational domain is being limited with perfectly-matched layers resulting on absorbing boundary conditions.

As a model for human head is used SAM (Specific Anthropomorphic Mannequin).

SAM has been defined in a way that ensures that SAR assessed in SAM should be above the SAR induced in heterogeneous, many-layered real adult head. So with its geometry and below mentioned tissue compositions, SAM provides a conservative approach regarding adult head exposure assessment.

SAM is based on the 90th percentile of American soldiers aged more than 20 of different ethnities and is composed from two tissues:

SAM shell with permittivity 3.9 and SAM liquid with permittivity 41.5 and conductivity 0.9.

Mobile phone is modeled as a perfectly conducting box with cylindrical monopole antenna [8].

Simulation model is shown on Figure 1.

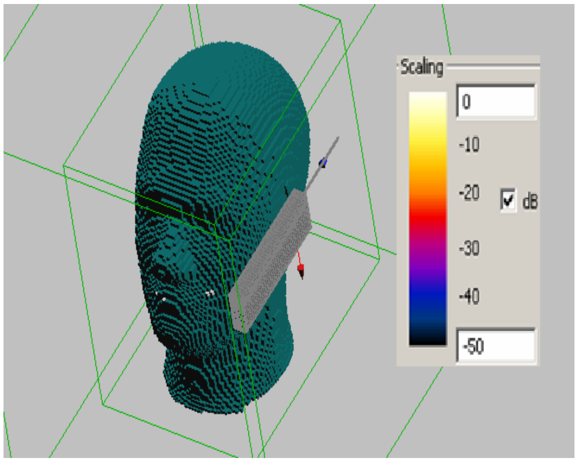

Fig. 1

Spatial Peak SAR as per IEEE 1529 recommendation has been calculated, same as [24] and [25].
Obtained results of Spatial Peak SAR for 900 MHz averaged over 1g of body tissues is 1.7 mW/g for typical transmitting power of mobile phone 250 mW.
Visually and graphically SAR distribution at different positions in a human head, different cuts with respective slices, are shown in Figures 2, 3 and 4.
As European safety standards give Spatial Peak SAR averaged over 10g of body tissues, simulations were run for the same model with unchanged parameters.
Obtained value for Spatial Peak SAR averaged over 10g of biological body tissue for same exposure conditions is 1.34 mW/g.

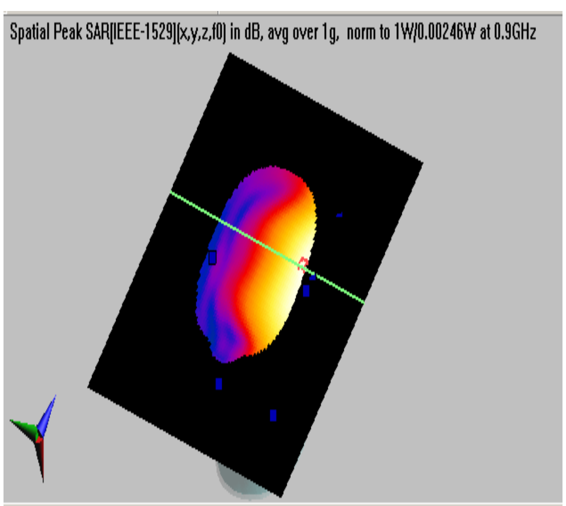

Fig. 2

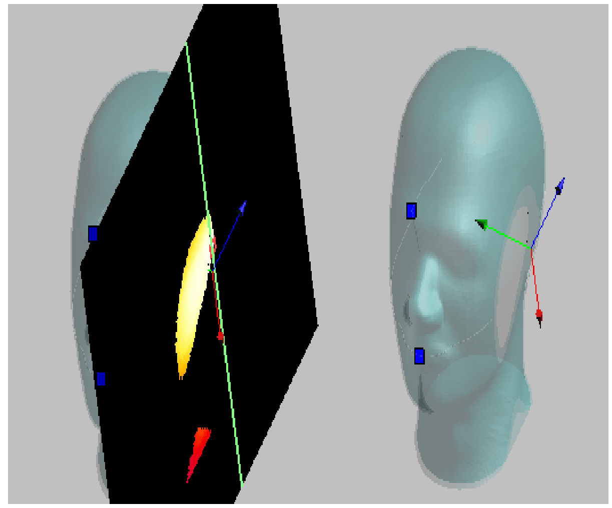

Fig. 3

As noticed Peak SAR appears near human ear.

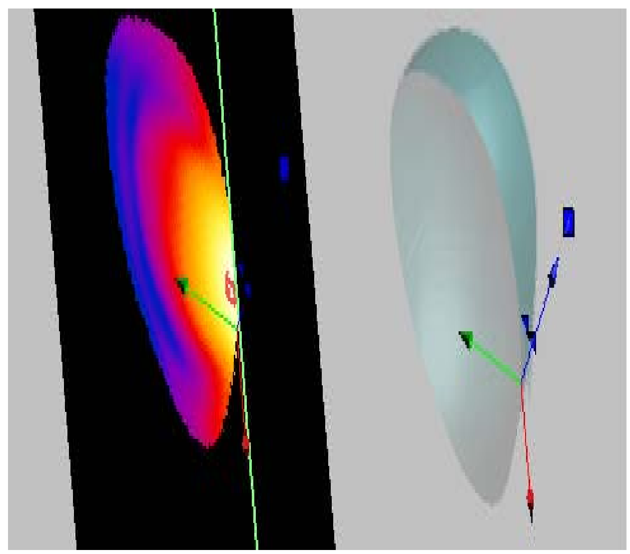

Fig. 4

Surface field view (represented by contours) for Spatial Peak SAR averaged over 1g of human head tissue is given in Figure 5.
As noticed, higher values of SAR are distributed on points near the source of radiation.
Analyzing dielectrical properties of human eyes biological tissues, and also having in mind that eyes are external organs without direct blood supply, it would be interesting for next studies to analyze SAR distribution on human head if the source of radiation is placed near human eyes.
Apart from electromagnetic modeling the thermal modeling may be considered [27].

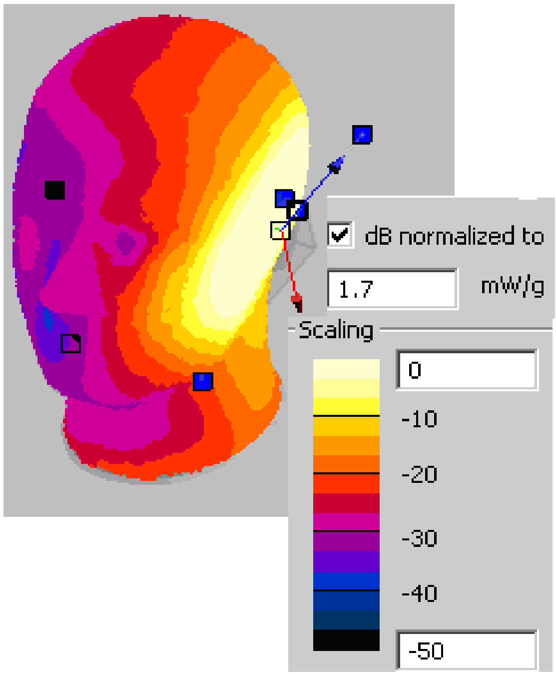

Fig. 5

4 Assessment of SAR in child exposed to mobile phone electromagnetic fields

Interaction of GSM electromagnetic fields and human head can be influenced by many parameters: distance of phone from head, position of phone and antenna, type of biological tissue, tissue distributions, geometry of head, etc.

Assessment of SAR on child head exposed to radio frequency electromagnetic fields raises few questions regarding parameters that influence induced SAR in child, possible difference on radio frequency energy deposition between child and adult, and also questions whether actual compliance with international safety standards testing methods are valid for children as well.

The issue has been studied by many researchers [10], [11], [19], [20], [22] that came up with contradictory results. The reason for result divergence is due to different preconditions defined.

Some have assumed the same dielectrical parameters for adults and children, others have built child head based on uniformly down-scaled adult head, some others have used magnetic resonance imaging data to built more representative child head, few have normalized results to a constant radiated power others to constant antenna current etc

Differences in approach have brought to differences in results.

Geometric (size not shape) and dielectrical parameter differences between the adult and child were considered at our simulations to some extent being aware that they do not represent an all inclusive real life child exposures.

According to [1], rat biological tissues show a general dielectric properties decrease with age. The variations in dielectric properties of rat's brain and muscle were within 31% and 28 % in permittivity and 36 % and 31% in conductivity, from birth up to an age of 70 days at 900 MHz.

Even though there is no evidence of extrapolating these results to human biological tissues, fitted parameters for humans based on tissue maturity and water content may be calculated.

Fitted child dielectrical parameters calculated as stated above at 1800 MHz are given on [21].

In order to assess impact of size and change of dielectrical parameters values on induced SAR, two child models were built and two exposure scenarios were run:

- Child A exposed to 900 MHz mobile phone electromagnetic fields,
  Child A head represents 80% of SAM head phantom with adult electromagnetic parameters,
  Mobile phone modeled as perfectly conducting box with monopole antenna as in paragraph 2,
  For this exposure scenario is calculated Spatial Peak SAR 1g and Spatial Peak SAR 10g.

- Child B exposed to 900 MHz mobile phone electromagnetic fields,
  Child head represents 80 % of SAM head phantom with increased dielectric parameters. Increase of 20 % on permittivity and 25 % on conductivity is assumed,
  Mobile phone modeled as perfectly conducting box with monopole antenna as in paragraph 2,
  For this exposure scenario is calculated Spatial Peak SAR 1g and Spatial Peak SAR 10g.

Differences between induced Spatial Peak SAR averaged over 1g and 10g of child body for Child A and Child B are given below:

900 MHz	SAR 1g W/kg	SAR 10 g W/kg
Child A	0.84	0.62

Table 3

900 MHz	SAR 1g W/kg	SAR 10 g W/kg
Child B	0.98	0.69

Table 4

Graphically on Figures 6 and 7 are shown comparative induced SAR in adult head represented by SAM phantom, where Child A and Child B are defined as above.

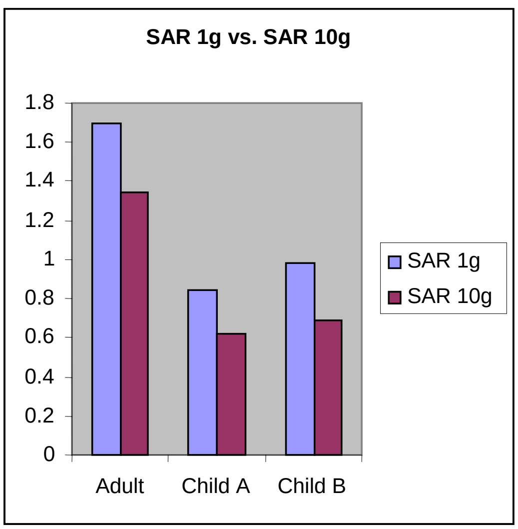

Fig. 6

The Child A and Child B models used here, according to their head size represent children older than 7 years. Even though there are studies that are addressing child exposure at different development stages from embryo, fetus, childhood until adolescence [26], according to surveys on child mobile phone usage mentioned on paragraph 1, the frequency of mobile usage is reported mostly for children over 7 years old, and thus the study is based on children older than 7.

Although not included in study, according to obtained results and analytical approach given on paper, the induced SAR in child model built with unchanged permittivity and increased conductivity would be higher than induced SAR in child with adult dielectrical parameters .

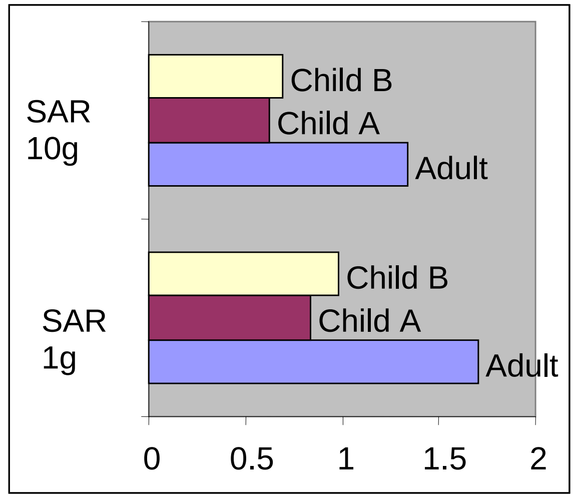

Fig. 7

The obtained results do not tell that induced SAR in children is lower than the one induced in adults since not all parameters that influence radio frequency energy deposition on biological tissues are considered. Moreover, many approximations are made.

Perfectly conducting box cannot represent real mobile phone.

More models of mobile phone with different structures and antenna types should be included as well.

The real child head is not represented as uniformly scaled-down adult head since the age related developmental changes in the anatomy of various organs follow a quite different growing course.

Also, more tissues have to be included representing different tissues of child head.

The distance from head to mobile phone and position of phone has to be considered too.

From obtained results it is confirmed that geometry variations impose changes on SAR, which means that SAR induced in children due to their difference in geometry compared with adults differs from SAR induced in adults.

The increase of dielectrical parameters is also causing increase of SAR values.
SAM phantom may be considered conservative for compliance with radio frequency exposure standards both for adults and children, which according to Figure 6 and 7 gives the highest SAR.

5 Conclusion

Modeling of electromagnetic fields inside a human body in general and child body in particular is a complex issue and more work should be done to answer actual research questions and provide an all inclusive approach that corresponds to real life exposure.
Analyzing results of practical measurements performed in limited number of locations meters away from base of antenna, ground level, the electrical field strength from GSM 900 MHz base station antenna never exceed the reference levels as per ICNIRP guidelines.
Calculated SAR for people living in houses near base station antenna are within basic restrictions of actual safety standards.
For adult exposure to mobile phone electromagnetic fields, for simplified model SAM phantom exposed to 900 MHz mobile phone, obtained results with FDTD simulations for Spatial Peak SAR averaged over 1g of body tissues is 1.7 mW/g for typical transmitting power of mobile phone 250 mW at frequency 900 MHz.
Obtained value for Spatial Peak SAR averaged over 10g of biological body tissue is 1.34 mW/g or typical transmitting power of mobile phone 250 mW at frequency 900 MHz.
Maximum SAR is noticed near human ear and near the source of radiation.
Since lately there has been a shift of communication from audio to visual and dielectrical properties of eye biological tissues are among highest, it is of high importance to address induced SAR in eyes when source of radiation is paced in front of eyes.
Assessment of induced SAR in two representative child models built for assessing impact of geometry and dielectrical properties on SAR has been included.
For two exposure scenarios:

- Child A represented as uniformly down-scaled adult head (SAM phantom) with adult electromagnetic parameters and
- Child B represented as uniformly down-scaled adult head (SAM phantom) with increased permittivity and conductivity,

both exposed to 900 MHz mobile phone radiation the SAR differences have been noticed and presented.
From comparative SAR assessment in adult and children based on studied parameters the following conclusions can be extracted:
There will be changes in induced SAR if changes in geometry of exposed body will be introduced. This argues that since geometry of children and adults differs, the induced SAR will also differ.
Increased values of dielectrical properties (permittivity and conductivity) will be followed with increased values of SAR, both 1g averaged and 10g averaged.
20% increase of permittivity and 25% increase of conductivity has resulted with 15% increase of SAR 1g and 10% increase of SAR 10g.
If age-dependence of dielectrical parameters of animal biological tissues will be extrapolated to humans, this will lead to the fact that to children, the induced SAR values will be higher compared to adults due to change on dielectrical parameters, for same exposure conditions.
Analyzing comparison between SAM exposure and child-like models exposure used in paper, the highest values of SAR appear in SAM.
Even though not an all inclusive approach is considered, obtained results give indications that SAM may be considered conservative for assessment of children exposure compliance to radio frequency electromagnetic fields.
At the end it is worth mentioning that even though all obtained results are within actual safety standards, few countries are setting country local limits and are taking precautionary measures for mobile communication usage especially for children.
When to all above mentioned facts is added that children have longer life time exposure to radio frequency electromagnetic pollution in comparison with adults, it is worth repeating that it is better safe than sorry!
Our children are exposed to electromagnetic pollution during different development stages, since childhood and even before they are born. At this regard, fetus exposure to radio frequency electromagnetic fields remains one of main challenges of field.

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