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Evaluation of Children's Exposure to Electromagnetic Fields of Mobile Phones Using Age-Specific Head Models With Age-Dependent Dielectric Properties

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ABSTRACT Given the rapid introduction of mobile phones and other portable wireless devices into society, and the increased possibility of young children using or being exposed to electromagnetic (EM) fields, a study of specific absorption rate (SAR) in the head of young children is becoming increasingly relevant. To accurately evaluate the exposure of children to electromagnetic fields, realistic head models, which consider the age-specific anatomical structure and age-dependent tissues dielectric properties, are developed. During postnatal development of human tissues, the number and size of cells increase while the proportion of water content decreases. Such changes result generally in significant changes in the dielectric properties of tissues. The SAR levels for different ages are investigated using the developed children's head models when young children or their parents use a standard mobile phone. The results show that the maximum SAR levels in brain tissues of young children (3 months) are higher by up to 61% and 78% than adults at the lowest (700 MHz) and highest (2600 MHz) investigated frequencies, respectively. The percentage absorption power in the heads of young children (3 months) is higher by up to 40.6% and 24% than the values for adults at 700 MHz and 2600 MHz, respectively. Our investigation shows that previous studies, which used scaled head models without considering the age-dependent variations in the head anatomy and/or age-dependent tissues' dielectric properties, underestimated SAR levels in the children's heads. The obtained results using the developed realistic head models indicate that for young children, a lower limit on radiated power might be required to meet the acceptable dosimetry levels.

INDEX TERMS Electromagnetic exposure, electromagnetic dosimetry, children's head model, specific absorption rate.

I. INTRODUCTION

There is a continuing public concern regarding the health risk of low-intensity EM radiation from mobile phones and other portable wireless devices. With the rapid development of wireless communication technology and falling costs of large-scale manufacturing, the use of wireless devices, such as smartphones and tablets, has increased dramatically and has become ubiquitous for communication, education, and entertainment. Many organizations including Institute of Electrical and Electronics Engineers (IEEE), International Commission on Non-Ionizing Radiation Protection (ICNIRP), and U. S. Federal Communication

Commission (FCC) have recommended limits on the radiation emitted by these devices to protect the public from over exposure to EM fields [1]–[3]. Many previous studies investigated the relation between the increased risk of brain tumors and the long-term frequent use of mobile phones [4]–[6]. While the level of risk is still a controversial issue, the health effects on children are of special consideration due to the greater sensitivity of their developing brains to the radiation from these devices [7], [8].

According to the Institute of Electrical and Electronics Engineering (IEEE), the basic safety limits for mobile phones are measured in specific absorption rate (SAR) averaged for

10 grams (g) of tissue at 2 W/kg [1]. In the past, exposure assessments in human heads were studied and analyzed using different adult and children head models [7]–[21]. According to those studies, the EM radiation levels in children are similar [21] or higher [5], [12]–[20] than those for adults.

Most children's head models used to assess the EM radiations [8], [9], [17]–[19] are scaled versions of an adult head, taking into account the age-dependent variations only in the shape and size of outer head geometry and dielectric properties (conductivity and permittivity) [12], [13]. In reality, the spatial tissue distributions also vary with age, and this is a factor that was not considered in previous EM dosimetry studies. Additionally, in order to accurately model the head of a child aged 3-years or younger, the anterior fontanels and its gradual decrease in the size with age needs to be reproduced in the numerical phantom. To date, this anatomical change has not been considered.

During growth phases of infants and children, several synchronized processes occur in the developing brain. Some of these developments are completed before birth, while others continue into adulthood. In the early years of life, rapid brain development occurs, significantly affecting the general geometry, dielectric properties, and tissue distribution within the head, and hence influencing EM dosimetry and safety assessment. By age two, a child's head typically achieves 80% of adult size [22], followed by a slower development achieving 95% of adult head size by the age of six years [23]. In addition to the variation of head shape, the dielectric properties of tissues are age-dependent [24]. However, previous EM dosimetry studies typically did not use age-dependent spatial distributions of brain tissue. Specifically, a significant decrease in the relative volume of total brain water occurs in the first two years, followed by significant remodeling of soft brain tissues (gray and white matter) in childhood. In adolescence and young adulthood, a stable reduction in the gray matter volume occurs, associated with a simultaneous increase in the cerebral spinal fluid (CSF) and white matter volumes [25].

The main objective of this study is to investigate EM energy absorption in the child's head at the age 3 months to 3 years. To this end, realistic head models are developed. Besides changes in the head geometry and age-dependent dielectric properties of tissues, age-dependent tissue distributions are considered to create age-dependent head voxel models. In addition, a derived formula is used to accurately estimate the dielectric properties of tissues at different ages using the dielectric properties of adult tissues and age-dependent water concentration. The developed head models are then exposed to EM radiation in a realistic simulator from a commercial mobile phone using a conventional Planar Inverted-F antenna (PIFA) operating at all of the frequency bands used in 3G and 4G systems. Different positions of the radiation sources (mobile phone) with respect to the head are investigated. For the 0-3 year's group, we assumed others held the phone as a proxy for exposure. The results indicate that the maximum SAR (10 g) and the total absorbed power in

children's head are higher than those predicted in previous studies using scaled adult head models.

II. MATERIALS AND METHODS

A. HEAD MODELS OF TARGETED AGES

An anatomically detailed voxel model Thelonious (6-year-old boy) of the virtual family [26], which was originally constructed based on high-resolution magnetic resonance (MR) images of healthy volunteers, is used as a base model to create children models of various ages with forty-four different types of head tissues. Here, three important age-related anatomical changes are considered in creating head models of children aged 3, 6, 12, 18 and 36 months, namely, the variations in the head size [25], the age-dependent tissue properties and the volumetric differences of brain gray and white matter [27], and the gradual decrease in the size of the anterior fontanels [28]. These were achieved by the following operations:

- 1) The Thelonious model was scaled down according to the ratios of the previously reported averaged head size measurements [25]. For ages of 3, 6, 12, 18 and 36 months, the scaling factors to the averaged 6-year-old boy (Thelonious) were found to be 0.9402, 0.9022, 0.8696, 0.8043, and 0.7554 respectively. The scaling effect is illustrated in Fig. 1.



FIGURE 1. Head models for children at different ages.

- 2) The scaled models were then further modified to take into consideration the volumetric changes of gray and white matter [27]. The volume of gray and white matter increase following similar patterns, that is, a rapid increase during the first two years after birth and a slower expansion thereafter. However, because the white matter volume is considerably smaller than that of the gray matter immediately after birth, the proportion of gray matter relative to white matter (gray-to-white matter ratio, or GWR) decreases dramatically over the period of 0 to 3 years [27]. To mimic the underdeveloped white matter of neonates, corresponding GWRs were introduced to the scaled models created in step (1) by applying three-dimensional (3D) morphological erosion of white matter and replacing the eroded regions with gray matter. The size of the erosion were determined manually so that GWRs of the created models become 6.1, 9.8, 16.2, 26.5, and 42 for 36, 18, 12, 6, and 3 months, respectively. The relative proportion of gray and white matter at these ages are illustrated in Fig. 2a, whereas the morphological erosions (with lower age) on the scaled white matter

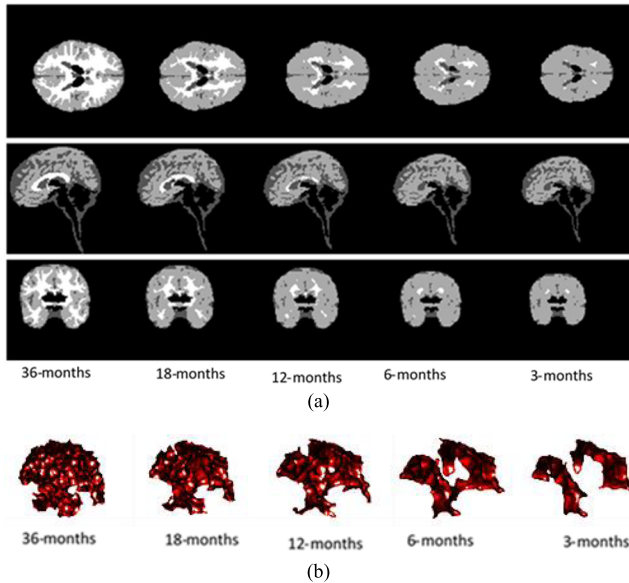


FIGURE 2. Children head models at age 36, 18, 12, 6, and 3 months showing (a) the three orthogonal slices of the development of the gray matter (gray color) and white matter (white color) with age, and (b) the morphological erosion on the scaled white matter volumes to correct the ratio of the white matter and gray matter with lower ages.

volume to correct the white and gray matters ratio are shown in Fig. 2b

- 3) Anterior fontanel of varied dimensions measured as oblique diameters of 20.4, 19.4, 12.5 and 9.1 mm, as extracted from previous report [28], was introduced to the 3-, 6-, 12- and 18-month, respectively, developed models created in step (2). The anterior fontanel was created by replacing sections of skull by tough membrane with corresponding dielectric properties. Fig. 3 shows the relative portion of the anterior fontanel for the corresponding ages.

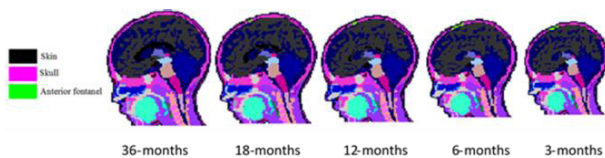


FIGURE 3. Two-dimension slices of children models at ages of 36, 18, 12, 6, and 3 months showing the variation of the anterior fontanel with age.

B. DIELECTRIC PROPERTIES OF AGING BIOLOGICAL TISSUES

Correct values for the dielectric properties are of crucial importance in studying age-dependent EM exposures as they define the maximum SAR. It is known that the differences in the water content of adults and children result in variation in the dielectric properties (permittivity and conductivity) [25], and total body water content among individuals may differ. Newborn infants have larger water content than older infants

and children, due, partially, to having less fat and viscera as a greater proportion of their body mass. The extracellular fluid (ECF) compartment comprises over half of the total body water at birth and contains a greater relative content of extracellular sodium and chloride. Although most of this neo-natal 'excess' ECF (approximately 5% to 10% of birth weight) is lost during the first ten days of life through perspiration, infants maintain a larger ECF than adults concerning the overall percentage of body water, until about two years of age.

Due to the lack of measured results for the dielectric properties of young children's tissues, a numerical relationship is used to extract the dielectric properties of children from those of adult tissues. Biological tissues are heterogeneous materials containing water and visceral organ. Assuming that the relative permittivity of an organ does not change, it can be derived from those of adult counterparts. Depending on the differences in the water content between adults and children [29]–[32], the real-valued relative permittivity of adult tissues was used to approximate those of younger, more water-rich biological tissues using the following formula [33]:

$$\varepsilon = \varepsilon_w^\gamma \varepsilon_{ro}^{1-\gamma} \quad (1)$$

where γ is the water concentration in each type of tissue, ε_w is the real-valued relative permittivity of water at 37° C (the body temperature) and is equal to 74.3 at 900 MHz [34], ε_{ro} is the real-valued specific relative permittivity of the tissue type. According to [32], [33], the total water content in the human body decreases with age and shows stability in the adult stage at an age between 30 to 50 years. Therefore, the tissue dielectric properties of a human adult over 30 years of age can be used as references to generate those of other age groups, including an infant, child, younger adult and the elderly.

To have the full details of the dielectric properties of tissues, the age-dependent conductivity can be calculated using the following formula [13]:

$$\sigma = \frac{\varepsilon_o \varepsilon}{\tau} \quad (2)$$

where ε_o is the permittivity of free space, and τ is the age-independent relaxation time of the biological tissue [13], [14].

To use the formulae (1) and (2), the water concentration (γ) for the tissues is needed. In this study, the relative water content (γ) as a function of age for the two main tissues in the head was gathered from different sources, including gray and white matter and of ages 10 months, 6 years, 9 years, 22 years, 34 years and 55 years [28]–[30]. These data were fitted to negative exponential models to describe the rapid decrease of body water content in the first years of age [28]–[32] as follows:

$$\gamma = a \exp(-b * Age) + c \quad (3)$$

where a, b, and c are the parameters of the fitting function.

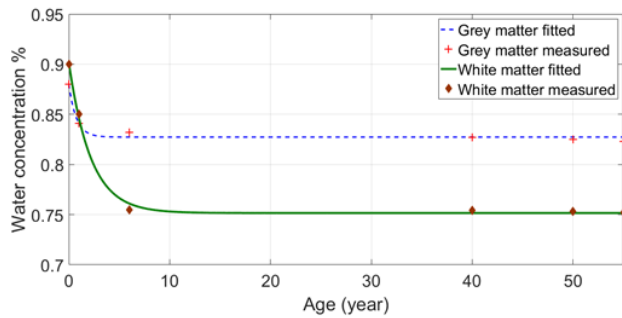


FIGURE 4. Water concentration values and its fitted data for human's gray matter and white matter.

Taking gray (white) matter as an example, with 95% confidence bounds, the following parameter values were found: $a = 0.05269$ (0.1503); $b = 1.345$ (0.4609); $c = 0.8273$ (0.7516). Fig. 4 shows the water concentration values and its fitted data for gray and white matters. The water concentration values at the target ages from the models (3) were then used to extract the complex dielectric properties (permittivity and conductivity) of the gray matter, and white matter, in human head using (1) and (2). The approximation formula by [13] was used to calculate the age-dependent dielectric properties for other head tissues (e.g., CSF, skull, and bone marrow) due to lack of information regarding their water concentration over time. As an example, the interpolated age-dependent dielectric properties of gray matter, white matter, and CSF are shown in Fig. 5. Those results indicate a good agreement with the measured data [24]. More details about the age-dependent dielectric properties can be found in [35].

C. SIMULATION SET-UP

EM simulations were performed using CST Microwave studio [36] with the time domain (transient) solver. Human voxel head models for an adult, the newly developed head models of young children, and children's head models scaled from adult, were exposed to a mobile phone (available in CST Microwave Studio) [35] as a near-field exposure source. The mobile structure included a PIFA antenna, battery, electronic circuit, keyboard, housing and a broadband matching circuit network.

The simulations were performed for all head models for adults and children without the hand holding the phones. The mobile were placed in a different Scenarios including: touching the ear (from the side of the head) and near the mouth (from the face of the head) as shown in Fig. 6. We also considered the scenario when the phone is held by a person, such as the parent, over the child's head, i.e. a person using the phone while carrying the child. For the first scenario, the standard mobile position (touch and tilted) that is defined in [37]–[39] were used. In this case, the mobile is naturally held against the ear and the cheek, and the body of the phone touches the ear when making call as explained [37]–[39]. A manual meshing feature was used to improve the accuracy of the simulation by taking into account the ratio between

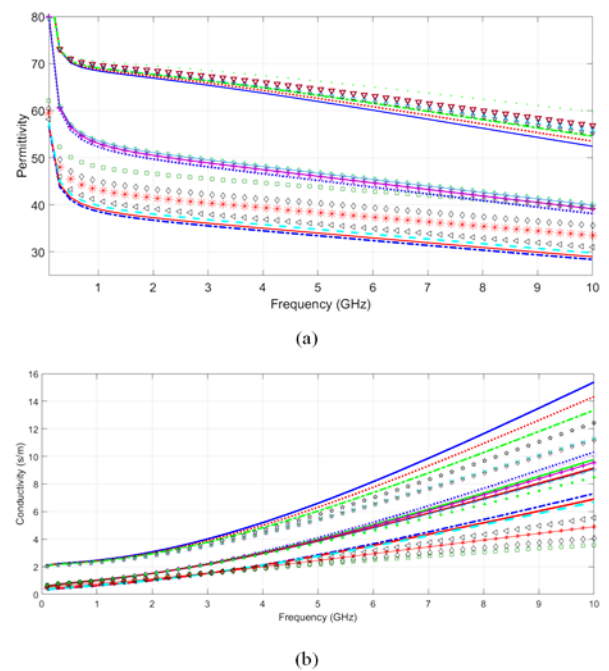


FIGURE 5. Measured and calculated dielectric properties of human head tissues including gray matter, white matter, and CSF. (a) Relative permittivity and (b) conductivity.

the largest and smallest distance between mesh lines at the low and high frequencies. To ensure accuracy, smaller cell size at the excitation port was used. For the low band frequencies from 700–800 MHz, and high frequency band from 2100–2600 MHz, meshes of size $1 \times 1 \times 1 \text{ mm}^3$ and $0.5 \times 0.5 \times 0.5 \text{ mm}^3$, respectively, were used. A matching circuit was used to change the working frequency of PIFA antenna to have more than 18 dB return loss at frequencies 700, 850, 900, 1800, 2100, 2300, and 2600 MHz for 3G and 4G mobile systems. The SAR was evaluated in the post-processing step using the averaging method specified in the IEEE C95.3 standards [2]. To obtain maximum SAR values of 2 W/kg over 10g for an adult head model the radiated power from the antenna was adjusted and found to vary between 0.28–0.6 W at all of the tested frequencies. The same radiated power at the same frequency then used to evaluate the SAR values for children at different ages over 10g for skin, gray matter, white matter, and CSF.

The dispersive dielectric properties of age-dependent brain tissues (white matter, bone marrow, and skull) as described previously were used according to the ages of the newly developed head models. The dispersive dielectric properties of adults were used for tissues that are not age dependent [24]. The dispersive data is loaded to the simulation environment as complex values (real and imaginary) across the required

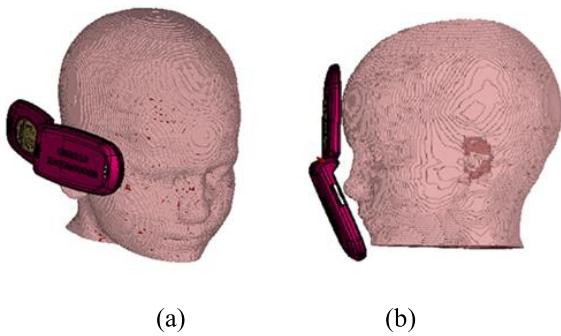


FIGURE 6. Simulation set-up where the mobile is placed (a) near the right ear, and (b) near mouth.

frequency band. The mobile phone was placed at two different positions, near and touching the ear tissue, and next to the mouth (10 mm away) as illustrated in Fig. 6. Additionally, a scenario was simulated for children less than 3yo, where another person, such as the child's parents, was holding the mobile near the children's head at distances of 10 and 30 mm from the top and side of the children's head.

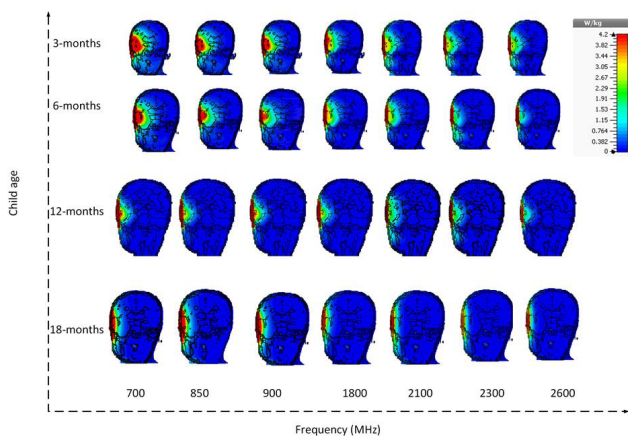


FIGURE 7. The SAR values when the mobile phone touches the ear of children aged 3-18 months. For fair comparison with age, the radiated power is selected to give maximum SAR values of 2 w/kg over 10g for an adult head model at all of the tested frequencies.

III. RESULTS AND DISCUSSIONS

For the developed realistic head models of children aged less than three years, the maximum SAR (10 g) values for the skin, CSF, gray matter, and white matter of the head were first calculated when the phone touches the ear. Fig. 7 shows SAR values in cross-sectional views of the heads of children aged 3-18 months at the widely used frequencies. For easy quantitative comparison, Fig. 8 shows the results in bar charts. It is quite clear, especially from Fig. 8 that the maximum SAR (10 g) values for skin, CSF, and gray matter decrease when the child's age increases. However, for the white matter, which has a quite small volume for young children, the maximum SAR (10 g) increases when the child's age increases until a 3yo child; after that, the SAR in the white matter decreases

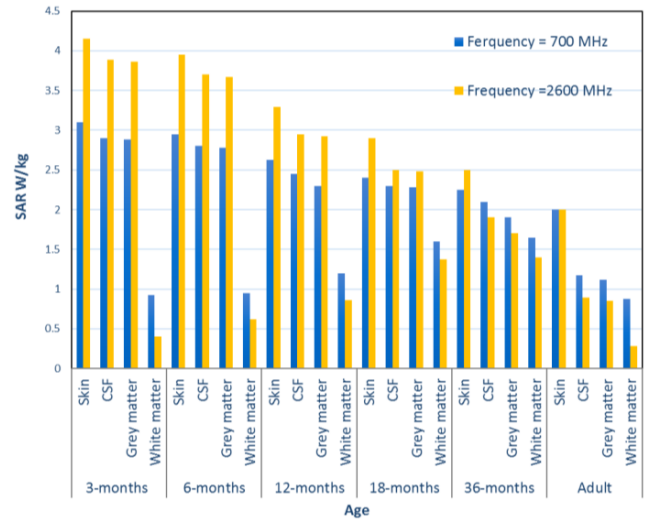


FIGURE 8. Maximum SAR values in the skin, gray and white matter of children aged 3-36 months and an adult when the phone touches the ear. The radiated power is selected to give maximum SAR values of 2 w/kg over 10g for an adult head model at selected frequencies of 700 MHz, and 2600 MHz.

with age. As indicative numbers, the maximum SAR (10 g) values for the skin, CSF, and gray matter are higher for a 3-months child's head by 23% and 35% than an 18-month child heads at the lowest (700 MHz) and highest (2600 MHz) investigated frequencies, respectively. Meanwhile, the maximum SAR values for the white matter are smaller by 42% and 70 % for a child aged 3 months than a child aged 18 months heads at the lowest (700 MHz) and highest (2600 MHz) investigated frequencies, respectively. This decrease in the SAR within the white matter with age is related to its structure, namely, more signal is able to reach the white matter since its volume increases, and it thus extends closer to the skull, with age.

The maximum SAR (10 g) values in children's heads are compared with the values of an adult using the same standard mobile orientation, i.e. phone touching the ear. For the adult model, a 34yo male, Duke, of the Thelonious virtual family [25] with $155 \times 305 \times 150$ cubics and a resolution of 2 mm was used. The relevant dispersive dielectric properties of adult tissues were loaded to the simulation. The results shown in Figure 8 indicate, as expected, that the maximum SAR (10 g) values for children and adults head models are always observed in the skin. Across the head tissues (skin, CSF, gray matter, and white matter), maximum SAR (10 g) values for young children is higher by up to (35%, 60%, 61%, and 5%) and (52%, 77%, 78%, and 30%) than the values for an adult heads at the lowest (700 MHz) and highest (2600 MHz) investigated frequencies, respectively. The decrease in values with age is related to the change in structure, size and properties of tissues with age. For example, in the bigger size of an adult head, the signal is dissipated in a larger volume of tissues and less signal is able to reach internal tissues.

The effect of using different frequencies on the maximum SAR (10 g) values of skin, CSF, gray matter, white matter,

and total absorbed powers for children aged 3-18 months and adults are studied using the same mobile position. For a fair comparison, the radiated power is selected so that a maximum SAR of 2 W/Kg over 10 g at each frequency is created at the skin of an adult. As revealed in Figure 8, the SAR in the skin, CSF, and gray matter for children aged 3 to 18 months increases with frequency. Meanwhile, our study indicates that for the white matter of young children, the SAR decreases with frequency due to its small volume and lower penetration depth of higher frequencies. The maximum SAR (10 g) values for internal head tissues (CSF, and gray matter) increase by 34%, 33%, 25%, and 20 % for children aged 3, 6, 12, and 18 months, respectively, for an change in frequency from 700 to 2600 MHz. For white matter, the maximum SAR (10 g) values decrease by 34%, 56%, 34%, 28%, and 14.3% for children aged 3, 6, 12, and 18 months, respectively, for the same frequency change. For children aged 3 years and above, the trend of variations in SAR with frequency starts to change. For example, for children aged above 3 years and adults, the maximum SAR (10 g) in the internal tissues (CSF, gray matter, and white matter) decreases with frequency. This trend of variation is related to the significant increase in the head size, maturity of the white matter and change in signal penetration with frequency, i.e. higher frequency penetrates less due to much higher losses in the bigger heads.

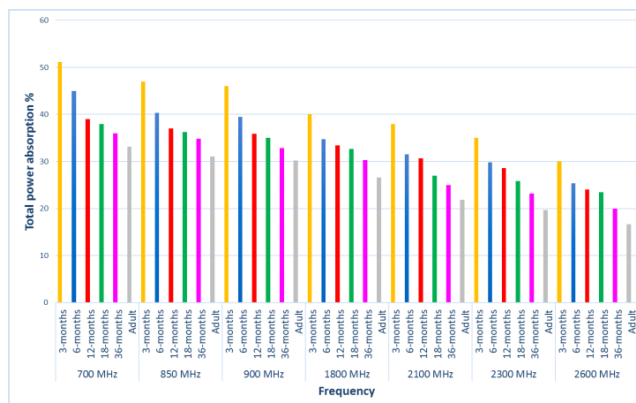


FIGURE 9. The total power absorption in children aged 3-36 months using the developed model when the phone touches the ear for all the investigated frequencies.

The percentage absorption power using the developed children head models are evaluated in comparison with the absorption rates in an adult's head at all the investigated frequencies as shown in Fig. 9. The results indicates the total absorbed power by children's heads decreases when age and frequency increase. For example, the total absorbed power by a child's head aged 3 months is larger by 30% and 40% than an 18-month child and an adult, respectively, at the investigated frequencies. Concerning the effect of frequency, changing the frequency from 700 MHz to 2600 MHz results in a reduction in the total absorbed power by 70.3% and 89% for children aged 3 and 36 months, respectively.

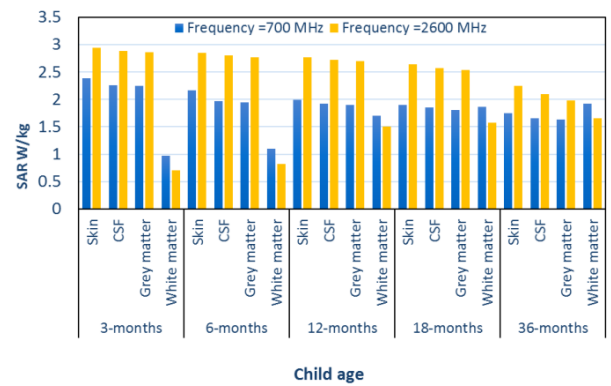


FIGURE 10. Maximum SAR values in the head models of children aged 3-36 months at selected frequencies when the mobile is held 10 mm next to the child's head.

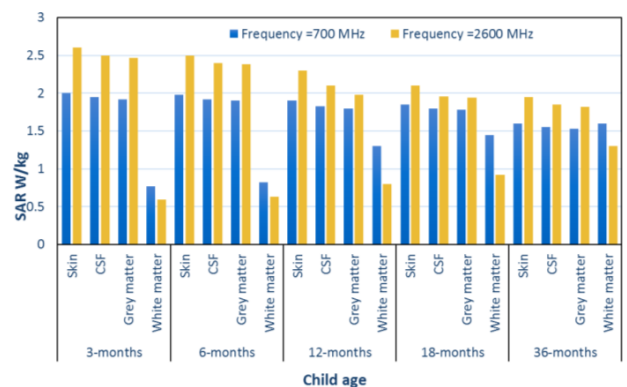


FIGURE 11. Maximum SAR values in the head models of children aged 3-36 months at selected frequencies when the mobile is held 10 mm above the child's head.

To investigate the dose levels for children aged less than 3yo in other realistic scenarios relevant to those young children, the phone was placed at two locations: The top and side of the head. These positions represent scenarios when the phone is held by a person, such as the parents carrying the child. The maximum SAR (10 g) values of skin, CSF, gray and white matters were evaluated over 10g for both cases with two head-mobile distances of 10, and 30 mm. In general, the results show an increase in the SAR values when the mobile is held at the side of the head compared to above the head. In our study, the antenna was located in the upper part of the mobile and therefore, the distance between the child's head and the antenna is longer when the mobile is located in the second posture. Fig. 10 and Fig. 11 show the maximum SAR (10 g) in the head tissues at selected frequencies (700 and 2600 MHz) for both mobile positions at 10 mm distance between the child head and mobile. The evaluated SAR values indicate that for children aged 3-6 months, a decrease in the maximum SAR (10 g) value of 18% and 9.3% is observed when the distance is increased by a factor of 3 for the top and side mobile positions, respectively.

The SAR values in this study were compared with the other studies [13], [15]. The study in [15] used realistic MRI-derived head models for a child aged 3yo but assumed the adult dielectric properties for this model. In the other study [13], an adult-scaled head model with age-dependent dielectric properties was used to investigate SAR for 3yo child. For the purpose of comparison, the Duke adult head model [25], a scaled version of 3yo child from Duke adult models, and the modified realistic head models of 3yo child developed in this study were compared in the same simulation framework. The results show a close agreement with the previous results for the SAR values of an adult head model in both studies. However, an increase of up to 4.5% for a 3yo child is observed in the SAR values of skin, CSF, and gray matter, meanwhile a decrease of up to 13.5 % is observed in the white matter using our realistic head model in comparison with the study presented in [15]. An increase of up to 3% is observed in the SAR values of skin, CSF, and gray matter, whereas a decrease of 22% is observed in the SAR value of white matter using our realistic head model in comparison with the study presented in [13]. Potential explanations for the differences come from the following reasons: The first study neglected age-dependent variations in dielectric properties, whereas the second study did not consider tissues' age-related morphological changes.

IV. CONCLUSION

Electromagnetic dosimetry in the heads of children aged 3 to 36 months has been investigated. Children of this age group are rapidly developing and gray and white matters have strong age-dependent relative volumetric proportions, besides total head size and skull thickness. There has been no previous studies on the dosimetry levels for those children, who are being increasing subjected to electromagnetics either by directly using wireless portable devices or due to the use of those devices by their parents. Moreover, previous studies on children dosimetry, which only investigated children above 3 years old, did not include age-dependent spatial tissue models and/or dielectric properties. This paper addresses these issues with realistic head models, where age-dependent tissue dielectric properties and anatomy are included.

Using the developed models, several scenarios were investigated including: (1) Young children holding mobile phones near their ear and mouth, (2) young children holding mobile phones at certain distances from the ear, and (3) a person holding a mobile phone near a child's head. It is concluded that 10g SAR values in the heads of young children are significantly higher than those for adults. Moreover, the 10g SAR values using the developed, more realistic children head models are noticeably higher than the scaled models used in previous studies that looked at the dosimetry for children aged above 3 years.

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