



Dosimetric assessment in the brain for downlink EMF exposure in Korean mobile communication networks

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ABSTRACT

Because the position and direction of the human body is not fixed in an actual environment, the incidence direction of the electromagnetic field (EMF) from mobile communication base stations, WiFi access points, broadcasting towers, and other far-field sources is arbitrary. To analyze the overall health effects of radio frequency EMF exposure, the dosimetric assessment for such environmental exposures created from an unspecified number of sources in daily life, along with exposures from specific EMF sources, must be quantified. This study is aimed at numerically evaluating the time-averaged specific absorption rate (SAR) of the human brain for environmental EMF exposure in the frequency range of 50–5800 MHz. Whole-body exposure to EMFs that are evenly incident spatially is considered. By comparing the results of several incidence directions and the number of polarizations, an optimal calculation condition has been derived. Finally, based on the results measured in Seoul at the end of 2021, the SAR and daily specific energy absorption (SA) in the brains of both a child and an adult for downlink exposures from 3G to 5G base stations are reported. Comparison results of the daily brain SA for exposure to DL EMF in all 3G to 5G mobile networks and exposure to a 10-min voice call (uplink EMF) using a mobile phone connected to a 4G network show that the SA from the downlinks is much higher than that from the uplinks.

1. Introduction

Numerous epidemiological studies have looked for an association between brain tumors and exposure to radio frequency (RF) electromagnetic fields (EMFs) (Cardis et al., 2007; Aydin et al., 2011; Castaño-Vinyals et al., 2022). In Interphone and MOBI-Kids studies, the specific absorption rate (SAR) in the human brain was quantified for various types and frequencies of mobile phones, based upon which the EMF exposure of study subjects was evaluated. In other words, only an uplink (UL) EMF radiated from a mobile phone was considered in previous epidemiological studies.

In a mobile communication network, the term uplink refers to a transmission (access link) from user equipment such as a mobile phone (mobile station) to a base station (fixed station), whereas the term downlink indicates a transmission from a base station to user equipment.

Owing to the continuous development and changes in mobile communication technologies, downlink (DL) EMF radiation from base stations is becoming increasingly complex as networks from different generations of communication technologies (e.g., 3G through 5G)

coexist in a single space. Such radiation is not a matter of individual choice and can be present at any time. Not all exposures to DL EMF are of the same frequency and intensity, and depending on the country or region, the mobile communication technologies serviced differ as do the start and end times of a specific service. Therefore, the long-term cumulative exposure of individuals living in different regions may be different. Lifestyle, such as location (e.g., outdoors, at home, or in a school or vehicle) and duration of stay also affect one's cumulative exposure.

The final goal of our study is to evaluate EMF absorption in the detailed brain structures of both a child and an adult for DL EMF exposure in an arbitrary real environment, along with UL EMF exposure owing to mobile phone use within the RF range. To do so, the following two databases (DBs) must be implemented: (1) a DB consisting of the normalized SAR distributions for far- and near-field exposures at the frequencies of interest in the brain at different ages and (2) a DB of the DL and UL exposure levels through large-scale measurements in a real environment. The first DB consists of SAR distributions, normalized to an electric field (E-field) of 1 V/m, as well as spatially uniform and SAR

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distributions, normalized to the maximum power of the mobile phone when held against the ear. The former SAR distributions are used for DL exposure evaluations, and the latter SAR distributions are used for UL exposure evaluations. The DL and UL exposures can be treated as far- and near-field exposures, respectively. The second DB consists of DL EMF levels and UL power levels measured for each technology. In addition, network and global positioning system (GPS) data at the measurement points are also provided in the DB. Therefore, if these two types of DBs are given, it becomes possible to derive and integrate detailed doses of the brain for real exposure to DL and UL EMFs at various frequencies.

The mobile phone types and SAR distributions related to UL exposure owing to the use of mobile phones, and the UL power level of mobile phones in a real environment have previously been reported (Lee et al., 2016; Lee et al., 2017; Lee et al., 2019; Lee et al., 2020; Lee et al., 2021). These previous studies generated the SAR distributions in the brain of 6- and 9-year-old children, a 15-year-old adolescent and a 22-year-old adult for mobile phone exposure and the SAR distributions become part of the first DB. The SAR level of the distributions corresponds to the values when the output power of the mobile phone is at maximum, which has been determined for each type of commercial mobile phone model based on a statistical analysis of more than 1400 SAR test reports. Therefore, given the UL power level of a particular mobile phone in a real environment, the SAR of the detailed brain structure of the corresponding age can be obtained for the specific phone radiation (UL exposure).

To develop the second DB, the authors carried out drive test measurements evaluating the DL and UL EMF levels within the residential areas of Seoul, South Korea (conducted for a limited biennial period and in limited locations, i.e., mostly on side streets) (Lee et al., 2020; Lee et al., 2021). Various methods have been used to measure and statistically analyze the EMF levels radiated from sources such as FM and TV broadcast towers, WiFi access points, and base stations (Birks et al., 2018; Choi et al., 2018; Calvente et al., 2016; Zeleke et al., 2018; Aerts et al., 2018; Sagar et al., 2016). In this paper, the far-field EMF radiated from sources in a real environment is referred to as “environmental EMF” and treated as spatially uniform far-field radiation.

Because different frequencies generate different dose levels in the human body, even when the same EMF levels at different frequencies outside the human body are given, it becomes necessary to provide them in a dose form for an exposure assessment, for instance, as an SAR value rather than as an EMF value.

To simulate EMF exposure, the first DB includes brain SAR distributions for UL EMF (near-field) exposure through mobile phone use and for the incidence (far-field exposure) of a spatially uniform E-field of 1 V/m. This paper focuses on the brain SAR for a far-field exposure. The same human head models that were considered numerically for UL exposure in previous studies (Han et al., 2018; Lee et al., 2019) were used in this research, allowing the integration of mobile phone and base station exposures. To simulate a whole-body exposure, each head model was combined with a body part below the neck appropriate for the corresponding age, which is discussed in Section 2.

The posture of a live human body continuously changes, and at the same time, various electromagnetic waves are present around the body. Therefore, a long-term averaged environmental EMF exposure can be regarded as exposure to multiple plane waves arriving from random directions at the corresponding frequency. Throughout this study, this is numerically considered by assuming plane waves uniformly incident to the human body. The number of incident directions and the number of E-field polarizations of plane waves incident from the outside surrounding the human body were analyzed (Section 3.1) to determine the most suitable combination of incident directions and polarizations for a dosimetric assessment of environmental EMF exposure.

Using the incidence configuration determined in Section 3.1, as the first step, the dose in the brain of both a 6-year-old child and an adult is calculated as the SAR for environmental EMF exposures with an E-field

strength of 1 V/m within the frequency range of 50 MHz to 5.8 GHz, at which FM and TV broadcasting towers, WiFi access points, base stations for mobile communications, and other RF sources radiate EMF. The SAR normalized to 1 V/m can be applied to estimate a specific absorption energy (SA) for the far-field radiation of an individual source or frequency using the corresponding E-field strength and exposure duration in a real environment. As the next step, the SA in the brain in a real DL environment of 3G–5G networks in Seoul is evaluated and compared to the SA of the exposure to the UL EMF of a mobile phone in Voice over Long Term Evolution (VoLTE) mode. These series of results are addressed in Section 3.

2. Material and methods

2.1. Implementation of whole-body voxel models

The anatomical morphology of the human head at different ages has been investigated using MRI data from hundreds of Koreans, including young children beginning their mobile phone use to adults (Han et al., 2018). Average head models with detailed brain structures based on the average morphology for the selected age groups of 6-, 9-, 15-, and 20–24-year-old Korean males have been implemented using a total of 70 head structures. The head models were labeled KR-6, KR-9, KR-15, and KR-22. Using these models, the age-dependency of brain exposure for mobile phone use was previously reported (Lee et al., 2020; Lee et al., 2019).

Dosimetric exposure levels should be quantified in the same head model to integrate exposure to the human brain for various environmental EMFs as well as EMFs from local sources such as mobile phones. Therefore, the KR-6 and KR-22 head models are employed in this study. The whole-body models for KR-6 and KR-22 had to be implemented because the exposure of plane waves to only a head model may yield a different brain SAR from that exposed to its whole-body model. Much earlier, the authors developed a whole-body model in a standing posture using magnetic resonance imaging (MRI) data of a 7-year-old child volunteer (Lee et al., 2009), and the 7-year-old model was nonlinearly reformed to produce models at other ages based on external dimensions of the body obtained from the Korean Anthropomorphic Survey (Lee and Choi, 2012).

To implement the whole-body models with KR-6 and KR-22, the following technique was employed in this study. First, the external dimensions of the body part below the neck of the 7-year-old model were non-linearly modified to fit the bodies of 6- and 22-year-old individuals. The heads of the modified models were then replaced with KR-6 and KR-22, respectively. The 6- and 22-year-old whole-body models were implemented using a voxel size of $1 \times 1 \times 1 \text{ mm}^3$ or $2 \times 2 \times 2 \text{ mm}^3$, hereafter referred to as KR-6-WB and KR-22-WB, respectively. From the left, KR-6-WB, the internal structures of KR-6 and KR-22-WB, and the internal structures of KR-22 are shown in Fig. 1, respectively.

2.2. Numerical method

The finite-difference time-domain (FDTD) method was used to calculate the SAR of the whole-body models KR-6-WB and KR-22-WB in the frequency range of 50 MHz to 5.8 GHz. In the frequency ranges of 50 MHz to 3 GHz and 3 GHz–5.8 GHz, uniform cell sizes of $2 \times 2 \times 2 \text{ mm}^3$ and $1 \times 1 \times 1 \text{ mm}^3$, respectively, were employed in the computational domain. A perfectly matched layer condition (Berenger, 1994) was employed for the absorbing boundary condition. A human voxel model was located at the center of the computational space for an isolated condition. In the authors' previous study (Lee and Choi, 2012), variations in the WBA SAR owing to changes in the dielectric properties based on age were checked for certain child models within the frequency range of the γ dispersion, and the differences were found to be marginal. Thus, in this study, the SAR was calculated using adult tissue properties according to a 4-Cole–Cole dispersion model (Gabriel et al., 1996).

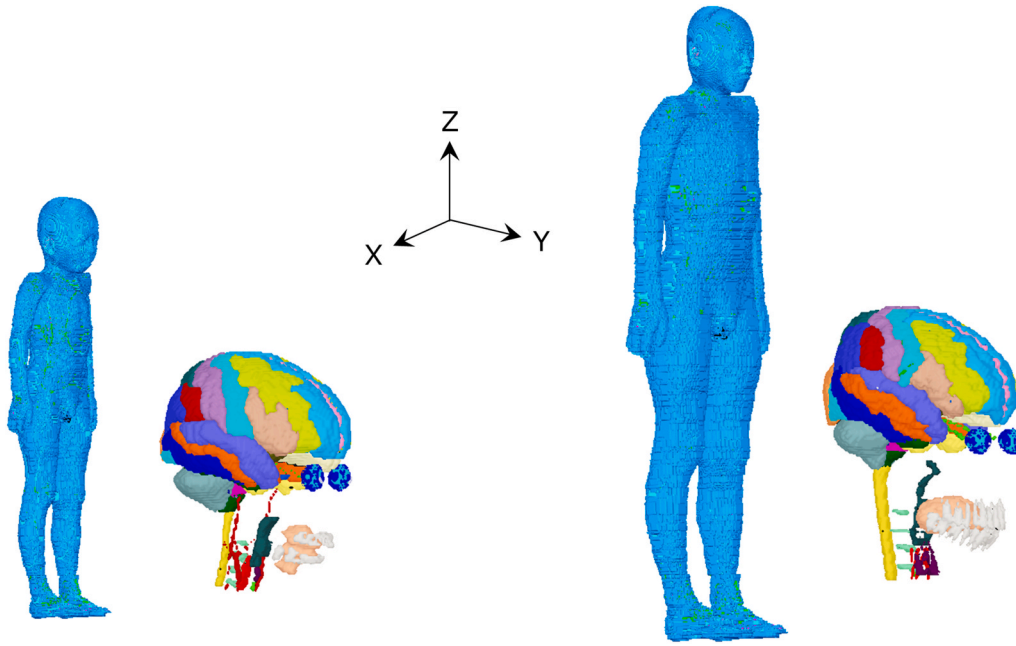


Fig. 1. Whole-body models KR-6-WB and KR-22-WB ($2 \times 2 \times 2 \text{ mm}^3$) implemented with head models KR-6 and KR-22.

As has been reported by many researchers, it is well known that a vertically polarized E-field incidence to the anterior region of the body brings about the highest whole-body average SAR ($\text{SAR}_{\text{wbody}}$) at most frequencies in comparison with other polarizations and incident directions. This is despite the fact that a horizontal polarization produces a higher WBA SAR in the region above 2 GHz (Dimbylow et al., 2010; Bakker et al., 2010; Hirata et al., 2010).

However, to evaluate the time-averaged SAR in the brain of a human body in unfixed postures and under exposure to a number of EMF sources surrounding it in a living environment, an infinite number of spatially uniform incident fields with different polarizations and incident directions should be considered at each frequency. Because it is impossible to conduct an infinite number of numerical simulations, an effective configuration with a finite number of plane wave incidences is required.

Meanwhile, the method proposed in (Taflove and Hagness, 2005) was employed to define the propagation direction and polarization of an incident plane wave, as shown in Fig. 2. Using the spherical coordinates,

the incident unit wave vector $\hat{\mathbf{k}}_{\text{inc}}$ is oriented with an angle θ relative to the +z-axis of the space lattice, where $0^\circ < \theta < 180^\circ$; in addition, with an angle ϕ relative to the +x-axis of the space lattice, where $0^\circ \leq \phi < 360^\circ$ (Eq. (1)). To specify the incident-wave polarization, a reference direction $\hat{\mathbf{k}}_{\text{inc}} \times \hat{\mathbf{z}}$ is defined in the plane of the wavefront. An orientation angle Ψ for $\mathbf{E}_{\text{inc}}$ is specified relative to this direction, where $0^\circ < \Psi < 360^\circ$.

$$\hat{\mathbf{k}}_{\text{inc}} = \hat{\mathbf{x}} \sin \theta \cos \phi + \hat{\mathbf{y}} \sin \theta \sin \phi + \hat{\mathbf{z}} \cos \theta \quad (1)$$

For a spatially uniform field incidence, the distances between neighboring field incident points on a virtual spherical surface should be the same. Incidences from the vertices of regular polyhedrons, such as tetrahedron, octahedron, and icosahedron, meet this requirement. There can be a number of combinations of incident directions and polarizations for constructing a spatially uniform incidence of the plane waves. In this study, the vertices of regular octahedron and icosahedron structures are employed as incident directions. The SAR of KR-6-WB was calculated and compared for three configurations of plane waves incident from the vertices. Details of the three configurations and a comparison of the results are described in Section 3, through which the optimal configuration was selected.

Using the selected incident wave configuration, the $\text{SAR}_{\text{wbody}}$, whole-brain average SAR ($\text{SAR}_{\text{wbrain}}$), and SAR averaged over 1 g of a brain are calculated as the ratio of the power dissipated in all voxels consisting of tissues of the corresponding body part divided by its total mass. The psSAR is defined as the maximum SAR averaged within a local region based on a specific averaging mass, e.g., any 1 or 10 g of tissue (IEC/IEEE, 2020). Hereafter, the psSAR averaged over a mass of 1 and 10 g is referred to as psSAR_{1g} and psSAR_{10g}, respectively. In this paper, the psSAR_{1g} of the brain was calculated according to IEC/IEEE 662704-1 (IEC/IEEE, 2017).

2.3. SAR and SA estimation for real exposure

The total brain exposure to DL and UL EMFs is derived within mobile communication networks in this paper. Using the 1-V/m normalized SAR distribution of a brain calculated according to the method described in Section 2.2, the SAR for each mobile communication technology and the integrated SAR are estimated for DL EMFs in real 3G, 4G, and 5G

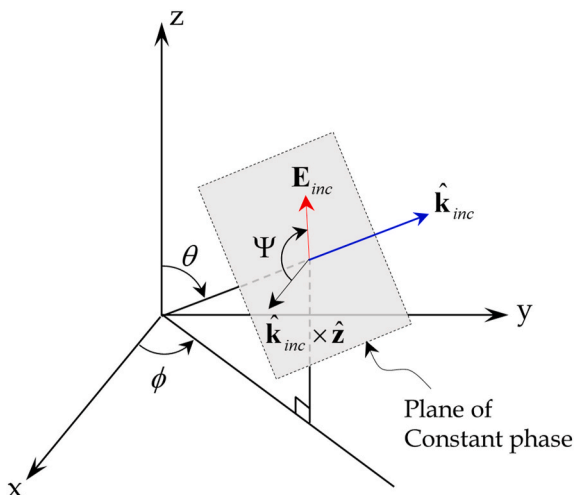


Fig. 2. Propagation direction and polarization of an incident wave (Taflove and Hagness, 2005).

networks.

The DL E-field strengths applied to the SAR estimation for real networks are from the results measured in 2021 using a previously reported method (Lee et al., 2020; Lee et al., 2021). Because this paper focuses on SAR and SA estimations for DL EMF, the measurement approach applied is only briefly summarized. As the measurement equipment used to evaluate the DL EMF for each individual network, an RF scanning receiver (PCTel Hbflex, 10 MHz to 6 GHz) was employed. The received E-field samples from a total of 18 frequency bands related to 3G through 5G networks were recorded along with the GPS data and time information. Meanwhile, an OPTis-M(II) system (Innowireless Co., Ltd.) consisting of a device and control software was used to collect UL power samples provided by the chipset of each mobile phone. Several mobile phones were connected to the measurement system, and UL power samples were recorded during voice calls using 3G and 4G networks and during the uploading and downloading of files in 5G NR networks. Power and field samples provided by the mobile phones and the scanning receiver, respectively, were collected every second while driving along the side streets in residential areas for a longer than 40-min period. The measurements were conducted over approximately a 3-month span, and 0.7×10^6 to 1.0×10^6 samples were collected for each link of each network in Seoul, South Korea.

The second database mentioned in Section 1 consists of the above measurement results for UL and DL exposures. The normalized SAR distributions for the UL exposure of various types of mobile phones were largely derived in previous studies, as mentioned in Section 1. Therefore, given the normalized SAR distributions for the DL exposure covered in this paper, actual doses from UL and DL exposures in networks used in Seoul can be integrated. The daily accumulated energy or SA for 24-h exposure to DL EMFs is compared with that of exposure to UL EMF, assuming a total of 10 min of voice calls on a mobile phone per day. The SAR and SA results estimated for real mobile networks are described in Section 3.

3. Results

3.1. Comparison of three incident wave configurations

As mentioned in Section 2.2, to simulate a spatially uniform plane wave incidence, the SAR was calculated and compared for three configurations with different incident directions and polarizations. The three configurations shown in Fig. 3 (a), (b), and (c) are applied to KR-6-WB and compared at 900, 1850, 2650, and 3000 MHz, which are the main frequencies related to the mobile communication technologies.

- (A) With the Octa-2pol configuration, the incidence directions are from the origin toward six vertices of the octahedron (where the origin of the octahedron coincides with the origin of the coordinate system) surrounding the whole body and in each incidence direction, and two plane waves propagate respectively with mutually orthogonal polarizations (Fig. 3 (a)). The 12 SAR values obtained at each voxel of the body model for a total of 12 plane wave incidences (= 6 directions $\times$ 2 polarizations) are averaged.
- (B) With the Icosa-2pol configuration, the incidence directions are toward 12 vertices of the icosahedron (where the origin of the icosahedron coincides with the origin of the coordinate system), and in each incidence direction, two plane waves with mutually orthogonal polarizations are respectively considered (Fig. 3 (b)). The 24 SAR values obtained for a total of 24 plane wave incidences (= 12 directions $\times$ 2 polarizations) are averaged at each voxel.
- (C) With the Icosa-5pol configuration, the incidence directions are from the origin toward 12 vertices of the icosahedron, and in each incidence direction, five plane waves with linear polarizations at 72° intervals are considered (Fig. 3 (c)). The 60 SAR values

obtained for a total of 60 plane wave incidences (= 12 directions $\times$ 5 polarizations) are averaged at each voxel.

Configuration (A) has been used for an SAR evaluation of animals exposed to EMF in a reverberation chamber (Gong et al., 2017). It was also recently employed for a far-field exposure assessment of a human body (Liorni et al., 2020). However, the effects on the number of incidence directions and/or polarizations have yet to be reported. Table 1 compares the calculation results on the SAR_{wbody} and whole-brain average SAR (SAR_{wbrain}) of KR-6-WB for the three configurations. It can be seen that the difference in the SAR between the Octa-2pol and Icosa-2pol configurations clearly increases with an increase in frequency. The Icosa-2pol and Icosa-5pol configurations provide higher results than the Octa-2pol configuration in most cases, and the difference between the Icosa-2pol and Icosa-5pol configurations is insignificant ($<0.2\%$). Based on these results, the SARs of a child and an adult (KR-6-WB and KR-22-WB) in the 50 MHz to 5.8 GHz band were calculated using the Icosa-2pol configuration.

3.2. Normalized SAR_{wbody} and SAR_{wbrain} (50 MHz–5.8 GHz)

This section reports the SAR_{wbody} and SAR_{wbrain} of child and adult models (KR-6-WB and KR-22-WB, respectively), normalized to 1 V/m within a wide frequency range of 50 MHz to 5.8 GHz, and then compares them with those for a single wave incidence.

The resonant frequency depends on the outer shape of the body viewed from the direction in which the plane wave travels. Fig. 4 shows SAR_{wbody} values generated by 24 incident waves according to the Octa-2pol configuration. When the direction (or polarization) of an E-field vector is projected onto the body, the path of the plane wave along $\hat{k}$ coincides with the longitudinal direction of the body, and the corresponding plane wave yields the highest SAR_{wbody} within the frequency range of 100–110 MHz, where the 1.144-m height of KR-6-WB corresponds to approximately 0.4-times the wavelength, as reported in previous studies (Lee and Choi, 2012; Dimbylow, 2002). As shown in Fig. 4, this corresponds to the plane waves polarized at $\Psi = 90^\circ$ for incident directions $\hat{k}_2$ through $\hat{k}_{11}$. Because the electrical length of the body viewed from the incident direction is shortened and diversified, all waves with $\Psi = 0^\circ$, including those incidences from the soles of the body ($\hat{k}_1$) and the top of the head ($\hat{k}_{12}$), produced a relatively gentle resonance over a wider and higher frequency band.

Figs. 5 and 6 show the SAR_{wbody} and SAR_{wbrain} of KR-6-WB and KR-22-WB, respectively, exposed to environmental EMF. They were obtained by averaging the SAR values at each voxel for the 24 individual wave incidences, as stated in Section 2, and then calculating the SAR of the whole body and the entire brain.

The whole-body resonance frequency of KR-6-WB (Fig. 5) is consistent with those of single waves polarized at $\Psi = 90^\circ$ for incident directions $\hat{k}_2$ through $\hat{k}_{11}$ (Fig. 4); however, the resonance amplitude (Fig. 5) is much lower than that for the single plane wave, i.e., $39.7 \mu W/kg/(V/m)^2$ at 110 MHz for KR-6-WB and $29.5 \mu W/kg/(V/m)^2$ at 70 MHz for KR-22-WB.

Fig. 6 shows the frequency characteristics of the SAR_{wbrain} of the child and adult models. As reported by Lee et al. (2019), KR-6 and KR-22 showed only a 4% difference in brain (white matter and grey matter) volume, i.e., 1219 mm^3 (KR-6) and 1270 mm^3 (KR-22), respectively. Because the shape of the brain is not long in any particular direction, the brain resonance occurred in a relatively wider frequency range than that of the whole body, i.e., in the frequency range of 300–1000 MHz, with a mean of 27.8 and standard deviation (SD) of 0.86 dB for KR-6-WB and a mean of 26.0 and SD of 0.64 dB for KR-22-WB. In addition, as the frequency exited this frequency band (lower and higher frequencies), a larger SAR difference in SAR_{wbrain} between the child and the adult was observed. For example, in the range of 300–1000 MHz, the SAR_{wbrain} levels were similar to each other; however, at 2 GHz, SAR_{wbrain} of the

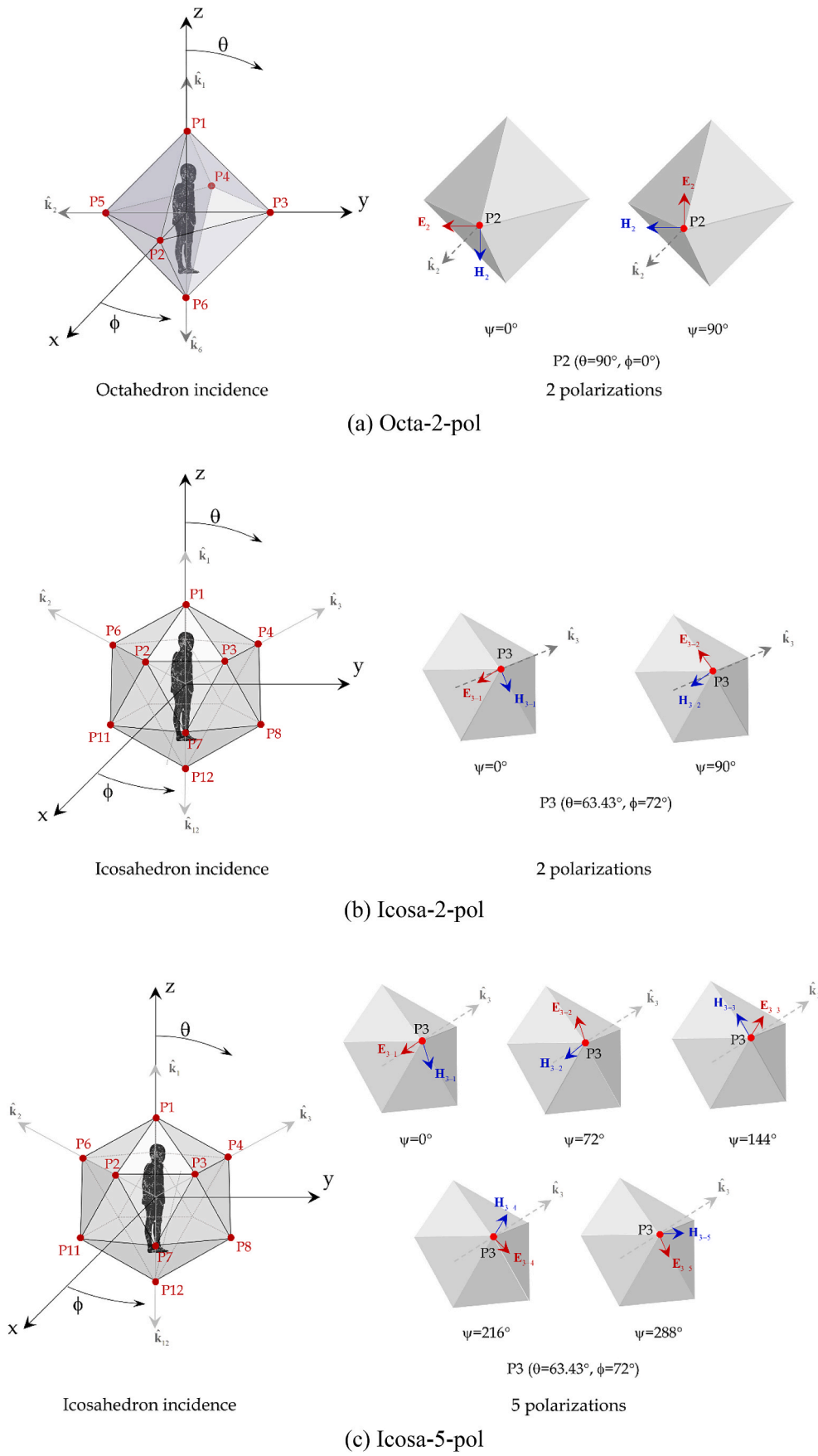


Fig. 3. Three configurations used to numerically simulate spatially uniform EMF incidence.

Table 1

SAR comparison between the configurations for uniform EMF incidence (KR-6-WB). The incident E-field strength is 1 V/m.

(a) SAR _{wbody}				SAR unit: (μW/kg)	
Frequency (MHz)	Octa-2pol (A)	Icosa-2pol (B)	Icosa-5pol (C)	Difference (%)	
				(B) – (A) ^a	(B) – (C)
900	22.137	22.053	22.021	−0.38	+0.18
1850	18.941	19.867	19.862	+4.78	+0.06
2650	16.684	17.982	17.967	+7.48	+0.08
3000	15.683	17.063	17.043	+8.43	+0.12

(b) SAR _{wbrain}				SAR unit: (μW/kg)	
Frequency (MHz)	Octa-2pol (A)	Icosa-2pol (B)	Icosa-5pol (C)	Difference (%)	
				(B) – (A)	(B) – (C)
900	27.672	27.215	27.168	−1.67	+0.17
1850	19.675	19.971	19.970	+1.49	0.00
2650	10.908	11.255	11.255	+3.13	0.00
3000	8.331	8.681	8.681	+4.12	0.00

$$^a \text{Diff (\%)} = \frac{(B) - (A)}{\left(\frac{(B) + (A)}{2}\right)} \cdot 100$$

child was approximately 50% higher than that of the adult. A similar tendency in the psSAR was reported for mobile phone exposure at 835 and 1850 MHz (Lee et al., 2019). This similar tendency occurred because the distance from the head surface to the peripheral region of the child brain is closer compared to that of the adult brain, and the penetration becomes shallower than at a higher frequency. At low frequencies of less than 300 MHz, SAR_{wbody} of the adult was higher than that of the child owing to the resonance of the adult body, and SAR_{wbody} for both the child and adult models increases sharply over a relatively narrow frequency range.

3.3. DL exposure dose in the brain within a real environment (Seoul, 2021)

Fig. 7 shows the SAR distributions on the surface of the whole brain and a cross-section at the mid-height of the brain of KR-6-WB and KR-22-WB for the incidence of a 1-V/m E-field at the six representative frequencies related to a DL used for mobile communication. It is notable that the SAR distributions at low and high frequencies are extremely different. At 900 and 1000 MHz within the resonance frequency region, a high absorption of electromagnetic energy can be observed in deep areas of the brain, such as the midbrain and thalamus. When the

frequency exits the resonant region, the absorbed energy is gradually attenuated from the surface of the brain to the inside, resulting in an extremely low absorption at the center. The higher the frequency, the faster the attenuation that is observed.

As described in Section 2.3, the authors measured the power of DL channels radiated from base stations. In this section, based on the above SAR results, the SAR in the brain of the child and adult models is estimated and presented for a real DL EMF exposure. Table 2 shows the mean E-field strengths for all DL channels operating in 3G–5G networks in 2021. They were obtained by analyzing the channel power samples collected while driving along the side streets in residential areas of Seoul, as previously reported (Lee et al., 2020; Lee et al., 2021). The E-field strength for each frequency band is labeled as $E_{f,n}$, where the subscripts f and n represent the frequency (MHz) and its serial number, respectively, as shown in the second column from the right. Among the six frequencies (Fig. 7) where the SAR was calculated, the frequency is that closest to the channel frequency.

The SAR distributions at the six frequencies shown in Fig. 7 were used for an integrative dosimetric evaluation in the brain of KR-6-WB and KR-22-WB for 3G–5G DL exposures, i.e., the SAR at 900 MHz for 4G B5 DL, the SAR at 1850 MHz for 4G B3 DL, the SAR at 2150 MHz for UMTS2100 and 4G B1 DL, the SAR at 2650 MHz for 4G B7 DL, and the SAR at 3550 MHz for 5G DL. The following integrative SAR distribution was obtained:

$$\begin{aligned} \text{SAR}_{\text{integrative}}(x, y, z) = & \hat{\text{SAR}}_{900}(x, y, z) \cdot \sum_{n=1}^2 E_{900,n}^2 + \hat{\text{SAR}}_{1000}(x, y, z) \cdot \sum_{n=1}^1 E_{1000,n}^2 \\ & + \hat{\text{SAR}}_{1850}(x, y, z) \cdot \sum_{n=1}^3 E_{1850,n}^2 \\ & + \hat{\text{SAR}}_{2150}(x, y, z) \cdot \sum_{n=1}^6 E_{2150,n}^2 \\ & + \hat{\text{SAR}}_{2650}(x, y, z) \cdot \sum_{n=1}^3 E_{2650,n}^2 \\ & + \hat{\text{SAR}}_{3550}(x, y, z) \cdot \sum_{n=1}^3 E_{3550,n}^2 \end{aligned} \quad (2)$$

where $\hat{\text{SAR}}_f(x, y, z)$ is a normalized value for an E-field strength of 1 V/m at a three-dimensional point (x, y, z) in biological tissue, of which the present authors focused on brain tissue. The subscripts f and n represent the SAR-calculated frequency (MHz) and the serial number of the sub-frequency regions for the DL within a frequency f of $\pm 5\%$, respectively. For instance, when f is 1850, there are total three sub-frequency

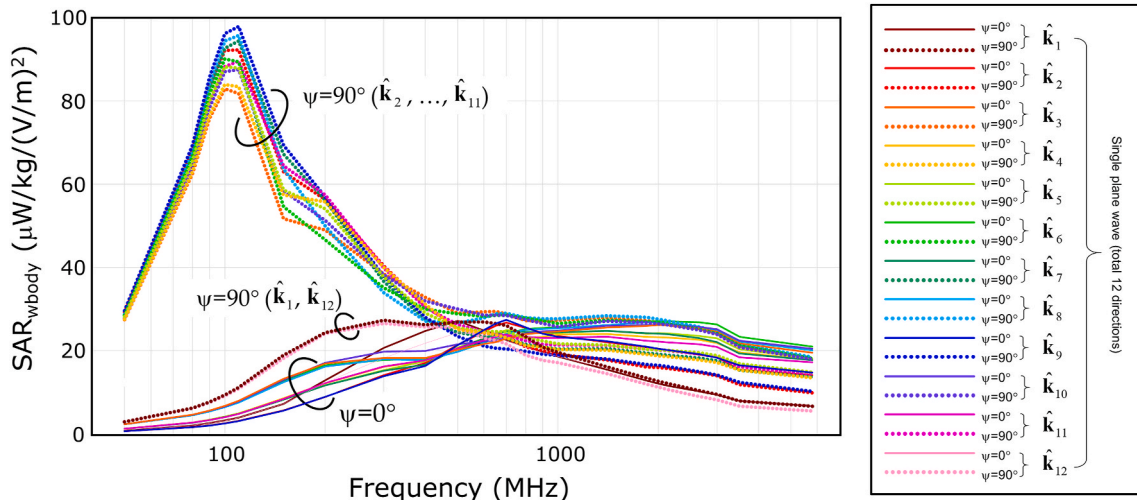


Fig. 4. SAR_{wbody} of KR-6-WB for 24 single plane wave exposures. It was normalized to an incident E-field strength of 1 V/m at each frequency.

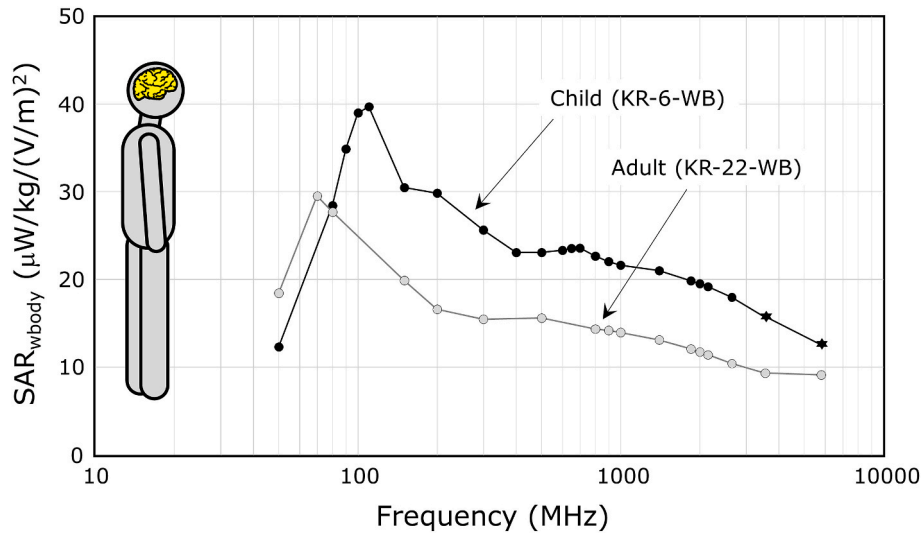


Fig. 5. SAR_{wbody} of the child and adult models (KR-6-WB and KR-22-WB) for environmental EMF exposure. At 3.5 and 5.8 GHz, a voxel size of $1 \times 1 \times 1 \text{ mm}^3$ was used for KR-6-WB, whereas a voxel size of $2 \times 2 \times 2 \text{ mm}^3$ was used for KR-22-WB owing to an excessive computation time.

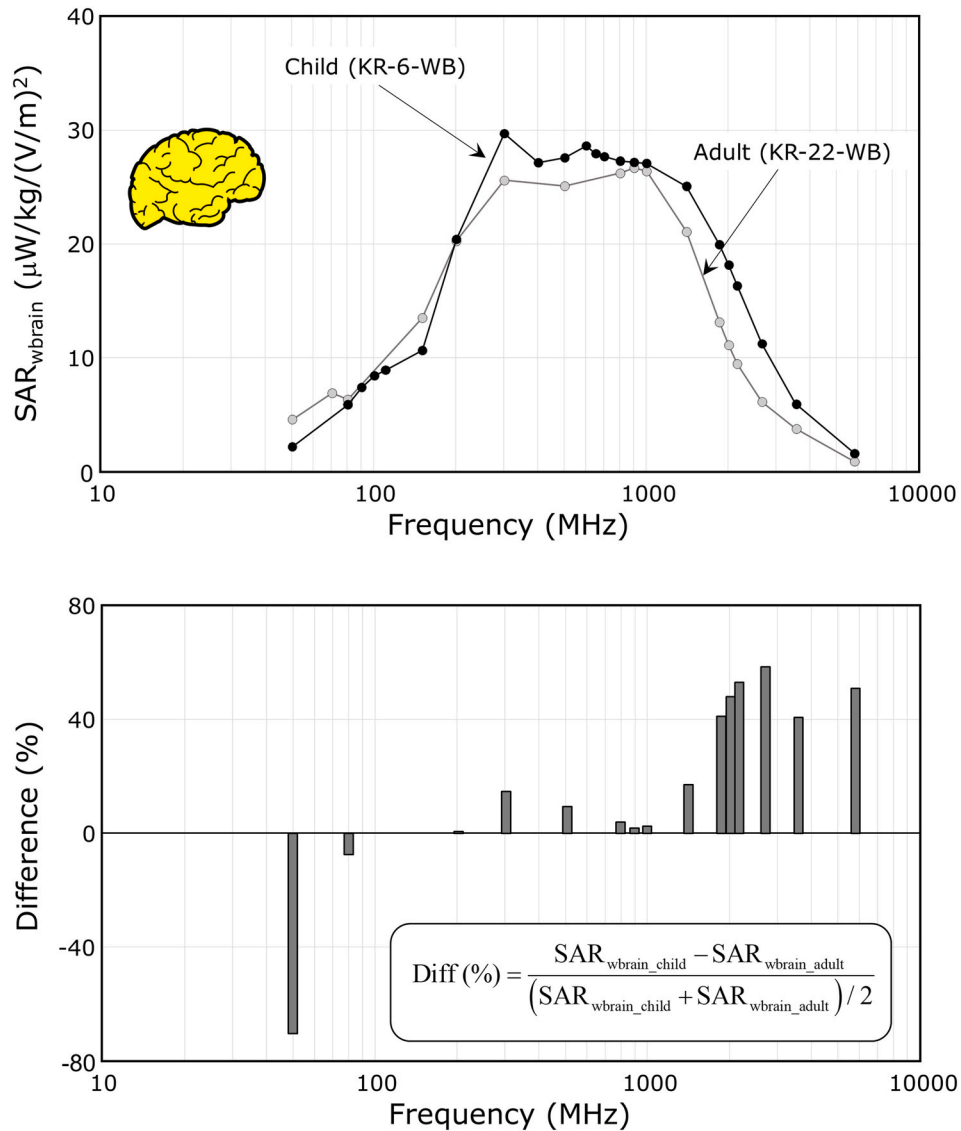


Fig. 6. SAR_{wbrain} of the child and adult models for environmental EMF exposure.

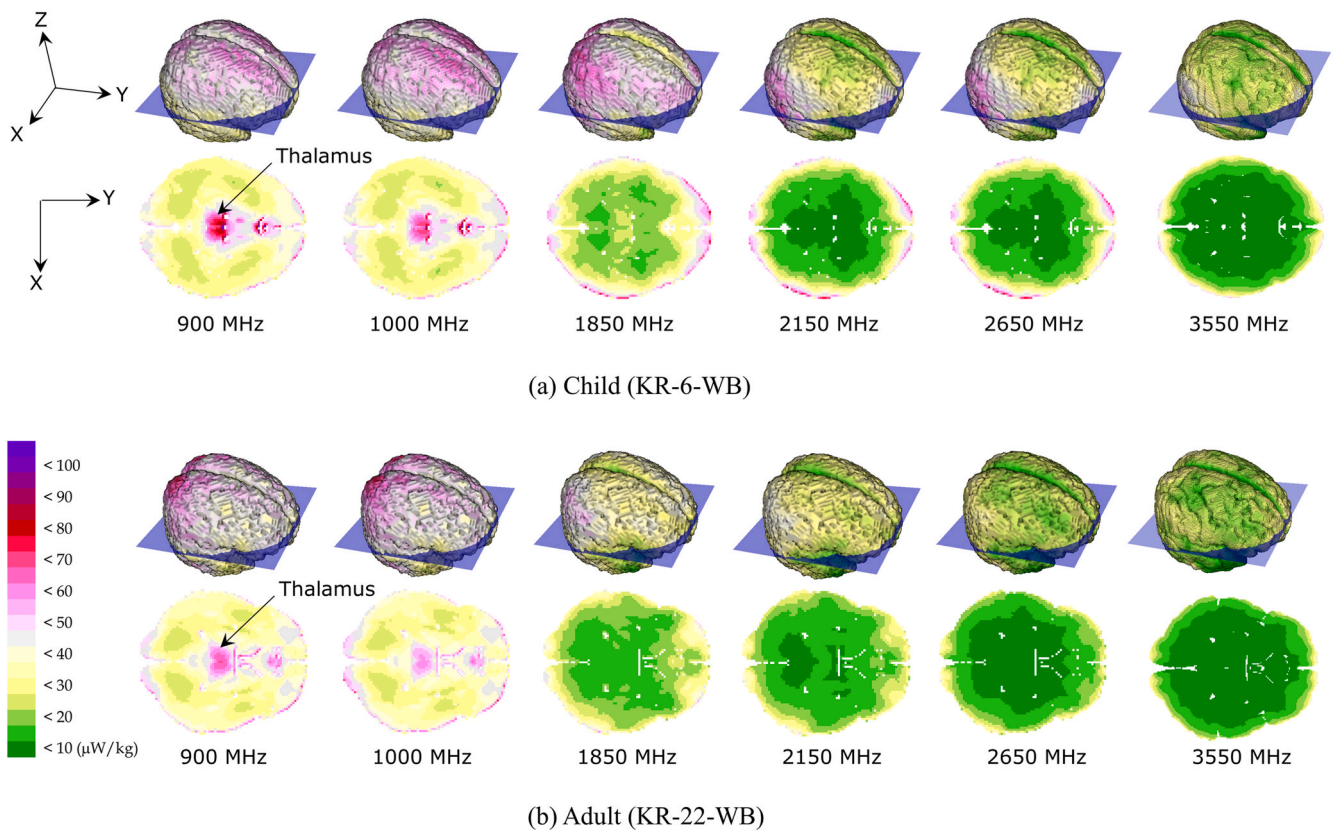


Fig. 7. Brain SAR distributions of KR-6-WB and KR-22-WB at frequencies related with mobile communication systems. The E-field strength is 1 V/m at each frequency.

Table 2

Mean E-field levels for DL channels of 3G, 4G, and 5G networks (Seoul, 2021).

Technology	Operator	Allocated freq. (DL) (MHz)	Band name ^a	Channel no. ^a	E-field strength (linear mean) (mV/m)	
3G (WCDMA)	O _A	2145–2150	UMTS 2100	10737	E _{2150,1}	105
		2160–2170	UMTS 2100	10812	E _{2150,2}	52
				10836	E _{2150,3}	99
4G (LTE-FDD)	O _A	2130–2145	B1	275	E _{2150,4}	106
		1810–1830	B3	1350	E _{1850,1}	130
		874–884	B5	2500	E _{900,1}	116
		2620–2640	B7	2850	E _{2650,1}	84
		2660–2670	B7	3200	E _{2650,2}	52
	O _B	2150–2160	B1	450	E _{2150,5}	70
		1830–1850	B3	1550	E _{1850,2}	117
		1850–1860	B3	1694	E _{1850,3}	99
	O _C	950–960	B8	3743	E _{1000,1}	165
		2110–2130	B1	100	E _{2150,6}	112
		884–894	B5	2600	E _{900,2}	132
		2640–2660	B7	3050	E _{2650,3}	76
5G NR ^b (TDD)	O _A	3600–3700	n78	640001–646666	E _{3550,1}	23
	O _B	3500–3600	n78	633334–640000	E _{3550,2}	25
	O _C	3420–3500	n78	628000–633333	E _{3550,3}	68

^a It indicates UARFCN⁺ for WCDMA, EARFCN⁺⁺ for LTE, and NR-ARFCN⁺⁺⁺ for 5G NR. ⁺UMTS Absolute radio-frequency channel number, ⁺⁺EUTRA Absolute radio-frequency channel number, ⁺⁺⁺NR-Absolute radio-frequency channel number.

^b Time-averaged SSB radiation. The sum of the SS-RSRPs of all SSB beams of O_C was used to calculate the time-average SSB power of O_C.

bands ($n = 1, 2$, and 3) within $1850 \text{ MHz} \pm 5\%$, as shown in Table 2.

Liorni et al. (2020) described the concept of integrative exposure for multiple RF sources based on normalized SAR results for various human body models. The evaluation method, which overlaps the SAR distributions at different frequencies, as shown in Eq. (2), was also reported in IEC/IEEE 62209-1528 (2020) to be the most accurate method for

evaluating the combined SAR under situations in which the human body is simultaneously exposed to different sources.

Fig. 8 shows the SAR distributions of child and adult brains in the DL EMF environment of each technology and the environment where the DL EMFs for all 3G, 4G, and 5G NR network technologies are integrated. The mean E-field strength in Table 2 was applied to Eq. (2). The

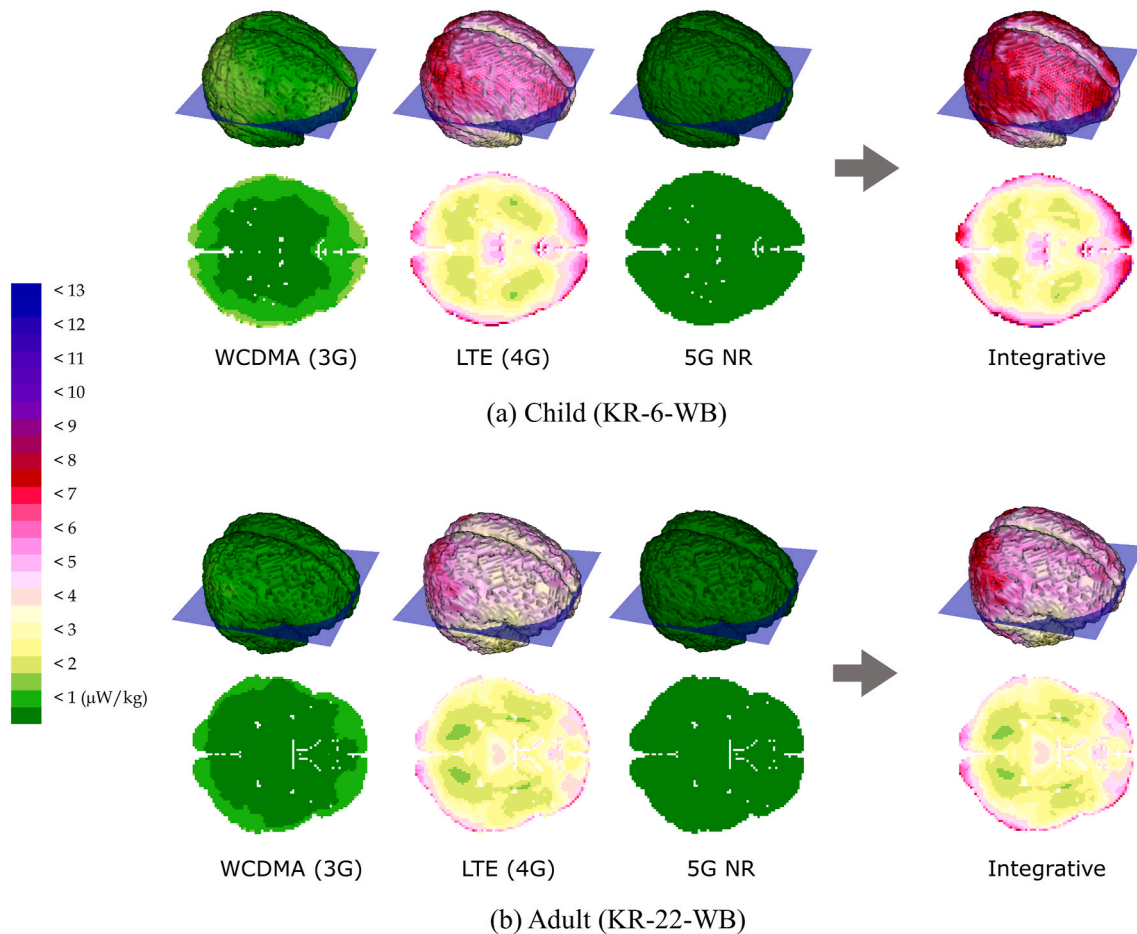


Fig. 8. Brain SAR distributions for DL exposure in 3G, 4G, and 5G NR networks (Seoul, 2021).

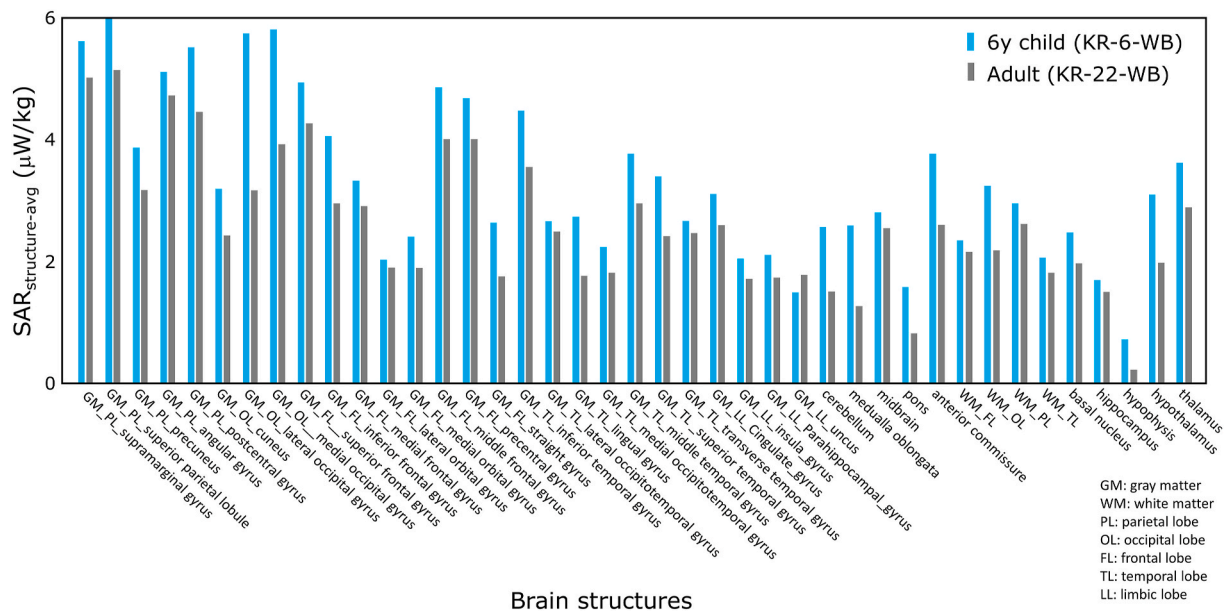


Fig. 9. SAR averaged over each structure consisting of a brain for exposure to the mean E-field strengths (DL) measured in 3G, 4G, and 5G NR networks (Seoul, 2021).

integrative SAR distribution on the far-right side of Fig. 8 is extremely similar to the SAR distribution of only 4G networks. The DL exposure within the mobile communication environment of Seoul in 2021 was

primarily contributed to by the LTE networks rather than the others.

As can be observed visually in Fig. 8, the brain SAR of KR-6-WB was approximately 25% higher than that of KR-22-WB, i.e., the $SAR_{w\text{brain}}$

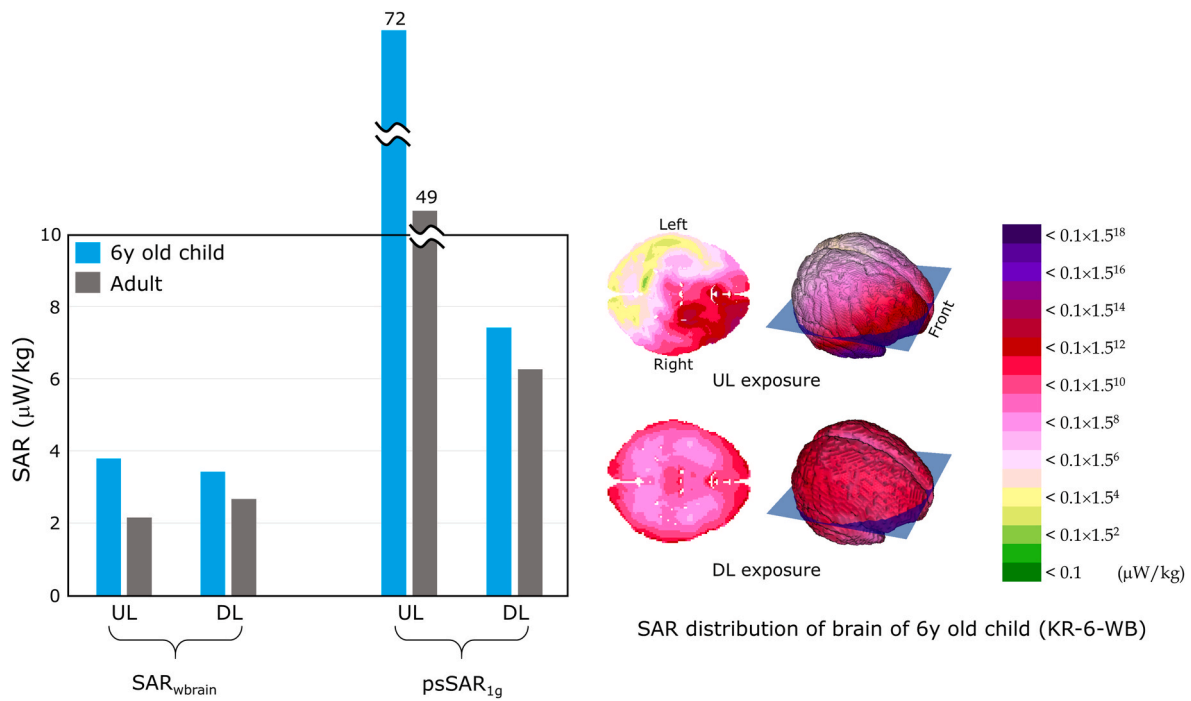


Fig. 10. Brain SAR of the child and adult models (KR-6-WB and KR-22-WB) in real networks (Seoul, 2021).

was 3.45 and 2.69 $\mu\text{W/kg}$ for KR-6-WB and KR-22-WB, respectively. The head part of these models was segmented into a total of 69 structures, and in particular, the grey matter of the cerebral cortex was subdivided into 27 gyri (Han et al., 2018; Lee et al., 2019). Fig. 9 compares the SAR values for detailed structures of the brain between KR-6-WB and KR-22-WB for the above DL environment (integrated). Excluding the uncus of the limbic lobe, the brain structure-averaged SAR (SAR_{structure-avg}) of KR-6-WB was 27.4% higher on average compared to that of KR-22-WB in 40 of the 41 structures considered (see Fig. 9).

3.4. Dose comparison and integration of DL and UL exposures

The SAR_{wbrain} and brain psSAR_{1g} for UL and DL exposures are shown in Fig. 10. The SAR results for UL exposure are for voice calls when using a mobile phone connected to the 4G network of operator O_A, which has the largest number of mobile subscribers in South Korea as of 2021. The SAR was evaluated using the same approach applied by Lee et al. (2020), where the brain SAR for EMF exposure was caused by user voice calls on mobile phones, i.e., UL EMF exposure was assessed under all available mobile communication networks of the corresponding operator in Seoul.

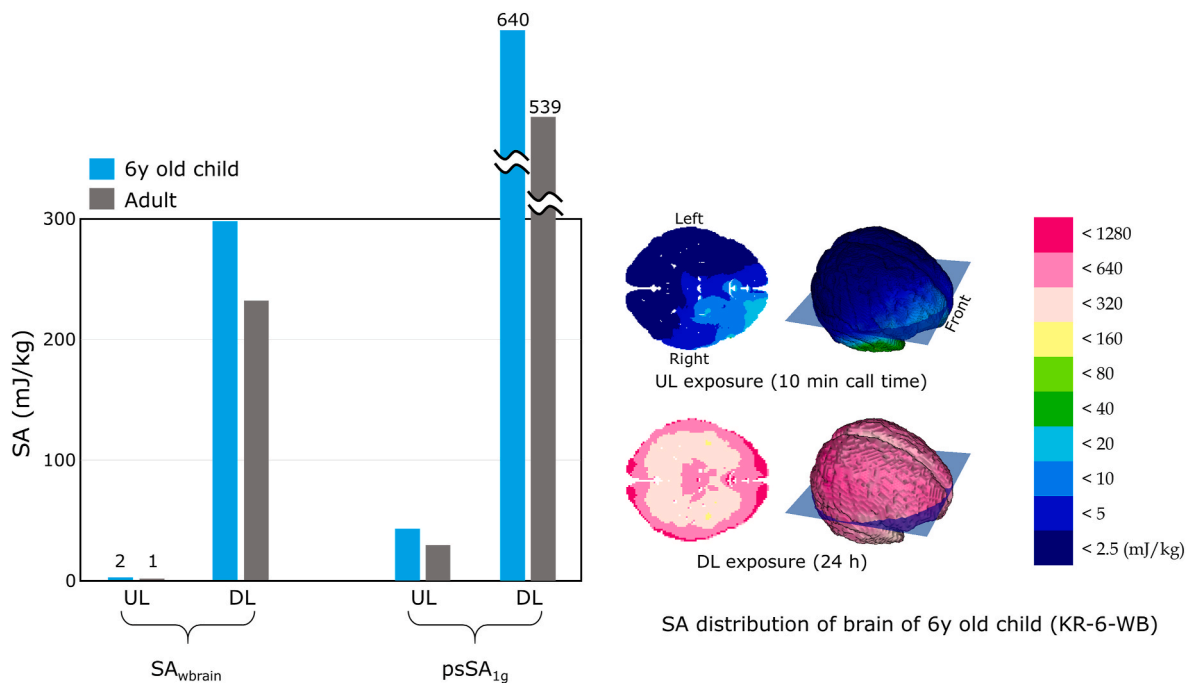


Fig. 11. Daily brain SA of the child and adult models (KR-6-WB and KR-22-WB) in real networks (Seoul, 2021). Differences of more than 10 fold are shown in the SA between the EMF exposures of UL and DL.

As mentioned in Section 1, exposure to UL EMF alone has been considered in many previous epidemiological studies seeking out an association between brain tumors and RF EMF. It has been confirmed that DL exposure cannot be overlooked in the evaluation of EMF exposure in mobile communication networks through a comparison of the brain dose (SAR and SA) levels for UL and DL exposures, as shown in Fig. 10. The brain $psSAR_{1g}$ for UL exposure is much higher than that for DL exposure, whereas SAR_{wbrain} shows similar levels for both exposures. The considered UL exposure is the most probable case; that is, the transmitting antenna of the mobile phone was located at the bottom, and when calculating the SAR, the measured connection ratios among the LTE frequency bands of O_A were applied as weights (Lee et al., 2020). The mean of the measured UL power samples of a mobile phone was used, which was within the range of approximately 0.1–0.25 mW for the LTE bands of B1, B3, and B5. The UL frequency bands allocated for B1, B3, and B5 are 1940–1950, 1715–1735, and 829–839 MHz, respectively. In addition, it was assumed that the user makes a call by placing the mobile phone on the right side of the head. Therefore, the SAR of the right temporal and frontal lobes of the brain was dominantly high, as shown in the SAR distribution of KR-6-WB in Fig. 10.

The assessment of the health effects of RF EMF in many studies (Cardis et al., 2011; Castaño-Vinyals et al., 2022; Calderón et al., 2022) has been tried on a cumulative dosimetric quantity over time, which is likely related to EMF exposure. The time-cumulative physical quantity of SAR (W/kg) is often expressed as SA (J/kg). The daily SA averaged over the whole brain (SA_{wbrain}) and the peak spatial-averaged SA over 1 g of tissue ($psSA_{1g}$) in the brain are shown in Fig. 11.

The SA for DL exposure was obtained by multiplying the above DL SAR by 86,400 s ($3600 \text{ s/h} \times 24 \text{ h}$) because the human body is in general continuously exposed to DL EMF regardless of the will of the person being exposed. However, for the SA of UL exposure, as an example comparison with the dose from DL EMF, the UL SAR was multiplied by 600 s for both KR-6-WB and KR-22-WB, assuming a total call time of 10 min per day. In Castaño-Vinyals et al. (2022), the median total call durations reported in age groups of 10–14 and 20–24 years were 53 and 655 h, respectively. It was estimated that the 20–24-year-old age group spent approximately 10.7 min on voice calls per day, assuming they have used a mobile phone during the past 10 years. In the case of a 6-year-old child, although the duration of the call might be much shorter than that of an adult, the 10-min call time was applied to both the child and adult models. Contrary to the SAR results shown in Fig. 10, it can be seen that the daily cumulative energy in the brain is much higher for DL than for UL.

Although the mean E-field strengths for DL EMFs across the Seoul area were applied to the exposure assessment in this study, in the future, it will be necessary to differentiate the frequencies and E-field strengths when considering individual life patterns and small-scale differences in regional networks.

4. Summary and discussion

In this paper, evaluating the energy absorption of the human brain in an EMF environment radiated from the base stations, a spatially uniform exposure consisting of 24 incident plane waves was applied to numerically simulate environmental EMF exposure within the frequency range of 50 MHz to 5.8 GHz. This approach was determined by comparing the results of a few configurations of plane wave incidences (see Section 3.1). The SARs for whole-body models (KR-6-WB and KR-22-WB) of a 6-year-old child and an adult were calculated, and SAR_{wbody} and SAR_{wbrain} normalized to 1 V/m were reported. The brain SAR was converted to that in a real exposure environment using the results of large-scale DL EMF measurements conducted in Seoul in 2021. Finally, the brain SA for 24-h exposure to the DL environment was obtained and the results were compared with those for a 10-min exposure to the UL power level of a

mobile phone. The UL data were collected for voice calls in an LTE network during the same time period as the DL EMF measurement.

The main findings and issues obtained from these processes are as follows.

- Frequency and SAR for environmental EMF exposure (see Section 3.2)

For the evaluation of a long-term exposure to far-field EMFs in real life, the environmental exposure was assumed to be a spatially uniform plane wave exposure. The whole-body resonance frequency was consistent with those of single waves vertically polarized when the whole-body models of a child and an adult were exposed to spatially uniform plane waves. The resonance frequency was approximately 110 and 70 MHz for KR-6-WB and KR-22-WB, respectively. However, the resonance amplitude of SAR_{wbody} was much lower than that for a single plane wave because the SAR results were averaged for exposures to plane waves of all polarizations and incident directions. The whole-brain resonance occurred within a relatively wider frequency range than that of the whole body because the shape of the brain is not long in one particular direction. The standard deviation was less than 1 dB in SAR_{wbrain} for each brain was shown in the frequency range of 300–1000 MHz.

- Age difference in brain SAR (see Sections 3.2 and 3.3)

In the frequency range of 300–1000 MHz, the SAR_{wbrain} levels of the child and adult models were extremely similar to each other; in other words, the frequency did not affect their SAR_{wbrain} . However, at the higher frequencies outside this frequency range, the SAR_{wbrain} of the child model gradually increased compared to that of the adult model because the distance from the head surface to the peripheral region of the child brain is shorter in comparison to that of the adult brain, and the penetration becomes shallower at a higher frequency. At frequencies lower than 300 MHz, SAR_{wbrain} of the adult was higher, which seems to be influenced by the whole-body resonance of the adult. The $SAR_{structure-avg}$ of the child in most brain structures and the SAR_{wbrain} of the child were approximately 27% and 25% higher, respectively, compared to the adult in a real DL EMF environment of Seoul (2021), where WCDMA, LTE, and 5G NR were being serviced.

- Difference in doses between UL and DL exposures (see Sections 3.4)

Although this paper is mainly focused on DL exposure calculations, the brain dose (SAR and SA) levels for UL and DL exposures were compared. The brain $psSAR_{1g}$ for UL exposure is much higher than that for DL exposure at the mean Tx (UL) power of a mobile phone in VoLTE mode; however, the SAR_{wbrain} shows similar levels for both exposures. The energy in the brain from an UL signal from a mobile phone when assuming a 10-min call time per day showed a much lower contribution to the integrated cumulative energy (SA) of all EMFs in the mobile communication networks, in comparison to that from DL signals (24-h exposure). Thus, it was confirmed that DL exposure cannot be ignored in the exposure evaluation for the studies seeking the association between chronic brain diseases and EMF exposure related to mobile communication services.

5. Conclusion

Many studies have investigated and reported the environmental EMF radiated from various far-field sources, such as broadcasting stations and mobile communication base stations. The authors previously implemented virtual head models with a statistically average structure for children, adolescents, and adults of various ages, and calculated and

reported the brain SAR for various mobile phone exposures. In addition, to quantify the total exposure to UL and DL EMFs in real mobile communication networks, the UL and DL exposure levels in all networks operating in Seoul have been evaluated every other year since 2015. The relationship between an EMF outside the body and the corresponding dose of a specific organ inside the body is not simple.

In this paper, the optimal configuration of the incident waves simulating human exposure to an environmental EMF, such as DL fields radiated from base stations was derived and applied to the SAR calculation for virtual whole-body models of both a child and an adult. By combining the calculated UL and DL SAR distributions with the UL and DL EMF levels measured in Seoul in 2021, it was shown that the cumulative dose for each detailed structure of the brain can be derived for the exposure of a specific person living in the corresponding environment.

Comparison of the cumulative doses from UL and DL EMF exposures showed that the DL exposure must be included in the comprehensive evaluation of the RF exposure. With the recent emergence of 5G NR, the resulting EMF exposure environment is becoming more complex than in the past, and it is therefore necessary to evaluate the rapidly changing environmental EMF in more detail in terms of time and space.

CRediT authorship contribution statement

Ae-Kyoung Lee: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing. **Hyung-Do Choi:** Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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