

Article

Analyzing the SAR in Human Head Tissues under Different Exposure Scenarios

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Abstract: This paper deals with the assessment of induced specific absorption rate (SAR) in various human models under different exposure scenarios, including both laboratory measurements and simulations. Firstly, SAR values were measured in a standardized SAR laboratory using a phantom for two radiofrequency electromagnetic field (RF-EMF) sources at 900 MHz and 1800 MHz. These laboratory measurements served as a reference for SAR calculations conducted on a specific anthropomorphic mannequin (SAM) using a computer simulation technology (CST) program, thus enabling the determination of antenna location and excitation signal levels for further evaluation. Subsequently, simulations were carried out with CST to evaluate average SAR for the head and for specific head tissues such as the brain, muscles, and fat. Realistic computational human models were also used alongside SAM in CST to explore the influence of gender, age, and tissue type on SAR. Various power levels representing low, moderate, and high RF-EMF exposure were applied to the human models to compare against basic restrictions and reference levels. The simulation results indicate significantly higher SAR values calculated for 1800 MHz compared with 900 MHz. The ratio of the highest SAR values at 1800 MHz to 900 MHz is approximately 1.70 for a baby, 2.59 for a child, and 2.84 for both adult female and adult male. While the SAR values for the brain, fat, muscle, and head are comparable at 900 MHz for the baby, the brain's SAR value at 1800 MHz stands out significantly from the other tissues. In contrast with the baby, the difference in SAR values between 900 MHz and 1800 MHz is more pronounced for the child, adult female and adult male. The lowest SAR values at 900 MHz and 1800 MHz were obtained for brain tissue in all human models, while the head has the highest SAR value. The maximum SAR change ratio between the brain and the head is calculated to be 4.44 for the male at 1800 MHz. The results reveal that, although the applied electromagnetic field levels were below reference levels for general public local exposure, some local SAR values exceeded the International Commission of Non-Ionizing Radiation Protection's basic restriction for the general public at certain power levels, particularly at 1800 MHz. The SAR analysis derived from this study is significant in understanding the impact of wireless technologies on health, establishing safety standards, guiding technology advancement, conducting risk assessments, and increasing public awareness.



Citation: Turgut, A.; Engiz, B.K. Analyzing the SAR in Human Head Tissues under Different Exposure Scenarios. *Appl. Sci.* **2023**, *13*, 6971. <https://doi.org/10.3390/app13126971>

Academic Editor: Alessandro Borgini

Received: 28 May 2023

Revised: 5 June 2023

Accepted: 7 June 2023

Published: 9 June 2023



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Keywords: specific absorption rate; SAR laboratory; human head tissues; CST; RF-EMF

1. Introduction

The communication industry is of great importance nowadays, and is expected to be of even more importance in the future. Therefore, the number of base stations, which are the basis of telecommunications networks, continues to increase. Base stations cause electromagnetic field (EMF) exposure in radiofrequency (RF) and people are becoming concerned about the possible health effects of this exposure. It is very important to measure radiofrequency EMF (RF-EMF) levels in the environment that are emitted by base stations. There are international guidelines to protect humans from the potentially harmful effects

of RF-EMF. These guidelines are specified by institutions such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [1] and the Institute of Electrical and Electronics Engineers (IEEE) [2]. Limits set by these institutions, so-called “basic restrictions”, are originally derived using the metric of the average specific absorption rate (SAR) for a part of the human body or entire body. SAR measurement procedures are mostly applied to mobile phones. Although base station antennas are installed in places far from the public, this distance has become shortened with the increasingly dense use of wireless technologies.

The rapid growth in cellular phone use has resulted in an increase in the number of base stations installed and an increase in public debate about potential health risks associated with electromagnetic energy absorption. Although many recent studies [3–8] have shown that ambient RF-EMF levels are below established limits, it is essential to carefully determine the doses absorbed by the human body in order to fully evaluate the potential health implications. Understanding electromagnetic pollution and SAR is essential for conducting thorough risk assessments, establishing safety guidelines, guiding technology advancement, and promoting public awareness regarding the potential health effects of RF-EMF exposure. Continued research in this field helps ensure that individuals can make informed decisions about their RF-EMF exposure and adopt measures to minimize potential risks.

1.1. Related Works on SAR

In the literature, there is a considerable amount of research on RF-EMF absorption and SAR values for different tissues and organs. The summary of these studies is provided in Table 1. The distribution of the electric field in a human head is presented in [9], while SAR and temperature distribution in a child head model was investigated through simulations and is reported in [10]. Studies [11–15] investigated age and tissue-dependent exposure and reported a higher SAR in children’s head and brain compared with adults, while [16] found no significant SAR differences between the child and the adult head. In [17], SAR calculations were performed, and showed that the averaged SAR of adults vary, and that for child models it was over the fundamental safety limits. In [18], adult male head region SAR values caused by base stations were investigated. In [19], SAR evaluations were undertaken for a pregnant women model and found showed that SAR values were higher than the specified limits. In [20], whole-body average SAR values were evaluated using flat phantoms. SAR values of anatomical human models and box-shaped phantoms were compared. In [14,21], it is stated that absorption level differences may be because of device usage patterns. The role of the position of the radiation source has been determined for both children [22], and for a computational human body model [23]. SAR values in different human tissues as a result of varying source-to-antenna distances and radiated powers were evaluated using ANSYS in [24], and a positive correlation between operation frequency, radiated power and SAR values was shown. The SAR values of 2G, 4G, and 5G mobile phone antennas were simulated in [25] using a SAM model and an anatomical head model, and the usage of a new head model for the SAR evaluation of 5G mobile was suggested. Ref. [26] investigated the effects of different commercial cell phone RF wave exposures on brain, eye, and skin tissues under laboratory conditions. Localized SAR values were then calculated based on the temperature increase in the selected tissue and were found to be below ICNIRP limits. The SAR levels from 900 MHz electromagnetic waves in different departments of several hospitals were evaluated in [27], the highest electric field strength and the corresponding SAR values were measured in a radiology department. In [28], SAR and heat transfer in human head tissues (skin, bone, brain) were assessed for different frequencies, antenna types, and antenna separation distances. Their results reveal that SAR values due to mobile phones was higher than those due to Bluetooth and to Wi-Fi devices.

Table 1. A Summary of SAR studies presented in the literature.

Ref.	Human Model	Parts/Organs/Tissues	Frequency (MHz)	Key Highlights
[9]	Adult	Head	900	SAR and radiation source distance relation
[10]	Child	Head	900	Relation between SAR and distance from the source of radiation
[11]	Adult, child	Head/eye	900, 1800	Head size and SAR relation
[12]	Adult (male), child (boy, girl)	Head/brain/eye	900, 1800	Age dependent-tissue specific exposure differences
[13]	Adult (male, female), child	Head/brain	900, 1800, 2100, 2400	Comparisons between adults' and childrens' SAR distributions
[14]	Adult, child	Head/fat/skin/bone/brain/eye	900	Effect of overexposure as well as age and radiated power on the SAR
[15]	Adult, child	Head/whole body	800, 900, 1800, 2100	Modeling daily RF dose in brain regions and the whole body in children and adolescents
[16]	Adult, child	Head	900, 1747, 1950	Investigates the SAR difference in the heads of children and adults using realistic EMF sources
[17]	Adult, child	Whole body/head/torso	20 to 2400	Variability analysis of SAR for different body models used in numerical dosimetry studies
[18]	Adult	Head	900, 1800	SAR evaluation in case of overexposure
[19]	Pregnant woman/fetus in uterus	Torso/whole body	900, 2100, 2450, 2600	SAR differences of fetus and pregnant woman
[20]	Adult, child	Whole body	788, 3500	Comparison of SAR measurement procedure results with numerical simulations
[23]	Adult	Whole body	98 to 2450	Location-based exposure assessment
[24]	Adult	Head/torso	850, 900, 2100, 2600, 5100	SAR values in different human tissues by varying source-to-antenna distance and radiated powers
[25]	Adult/SAM	Head/brain/muscle	900, 2500, 3500	SAR assessment for 5G mobile phones through numerical simulations
[26]	Adult phantom	Brain/eye/skin	2300 to 2400	SAR and thermal change analyses in case of prolonged exposure to mobile phone radiation
[27]	Adult	Brain/skin/fat/bone	900	SAR and electric field strength assessment in a hospital
[28]	Adult	Head/skin/bone	900, 1800	SAR comparison for different antenna types and services (e.g., Bluetooth, Wi-Fi)

1.2. Research Gaps of Previous Work on SAR

SAR studies have often utilized simplified human models, which may not adequately account for the potential variability of SAR, including age groups, genders, and anatomical variations, across different demographics. Further research is necessary to investigate these variabilities and their implications for SAR assessment. Additionally, there is a need to explore the variations in SAR among specific population groups, such as babies, children, and women, to ensure that safety guidelines are appropriately tailored to protect these vulnerable groups. This study can contribute significantly to a more comprehensive

understanding of SAR in human tissues under different exposure scenarios, ultimately leading to the development of improved safety guidelines and enhanced protection of human health.

1.3. Contribution of This Paper

In this study, different from existing studies, our aim was to provide a more comprehensive understanding of the factors that influence SAR. The effect of age, gender, tissue type, frequency, and exposed RF-EMF levels on SAR values were determined through both laboratory measurements and simulations. Measurements at different electric field values and two different frequencies (900 MHz and 1800 MHz) were conducted in a SAR laboratory in accordance with standards and then simulated in an electromagnetic field solver for four different computational human models. Simulations were carried out with CST to evaluate SAR 10g values in specific head tissues such as the brain, muscles, and fat. The head model in CST includes all tissues and organs present in the head region, such as air inside the body, blood, bone, eye bulb, eye lens, esophagus, salivary glands, skin, teeth, thyroid, tongue, tonsils, and more, in order to offer a realistic representation of a person. The simulations also accounted for the dielectric properties of these tissues and organs. The main contributions of this study can be summarized as follows:

- The study analyzed the impact of different exposure scenarios, such as varying frequencies, electric field levels, and age/gender, on the SAR distribution within the head tissues.
- The SAR analysis in human head tissues provides valuable insights into the potential effects of electromagnetic radiation and contributes to the development of safety measures for protecting human health.
- The analysis of SAR values in the head helps identify potential vulnerabilities or variations in different populations.
- The study investigated the effect of tissue type on SAR, aiding in the assessment of specific risks associated with different organs and body parts.
- Examining the effect of frequency on SAR values helps identify potential variations in energy absorption across frequencies used in current and emerging wireless technologies.
- SAR analysis facilitates the assessment of potential risks associated with different power levels, allowing for comparison against established safety guidelines.
- The results obtained in this study can help in designing and optimizing wireless communication devices, electromagnetic safety standards, and guidelines to minimize exposure-related health risks.

The paper is organized as follows. Measurement setup and SAR calculation are given in Section 2, measurement and calculation results are presented and discussed in Section 3. The paper is concluded in Section 4.

2. Materials and Methods

The ICNIRP releases the guidelines for EMF exposure and states the limits for an electric field (E), magnetic field (H), or power density (S). Recommended reference levels within the frequency range of 400 MHz–2000 MHz are $1.375\sqrt{f}$ (f is the frequency in MHz) [1]. For the frequencies of 900 MHz and 1800 MHz, the limits are 41.25 V/m and 58.34 V/m, respectively, for E.

In the present guidelines, SAR is also a basic restriction which is defined as the amount of electromagnetic energy that biological tissue absorbs, and is calculated using (1):

$$SAR = \frac{\sigma |E|^2}{\rho} \quad (1)$$

where σ and ρ are the conductivity and the mass density of the tissue, respectively, and E is the root mean square of the internal electric field. Specifically, SAR 10g presents the power

absorbed over a 10g cubical mass while whole-body average SAR is the amount of power absorbed over the entire body. SAR limits recommended by ICNIRP for the whole body, local head/torso, and local limb are given in Table 2 [1].

Table 2. SAR limits.

Exposure Scenario	Frequency	Whole Body Average SAR (W/kg)	Local Head/Torso SAR (W/kg)	Local Limb SAR (W/kg)
General Public	100 kHz–6 GHz	0.08	2	4

2.1. SAR Laboratory Measurements

The objective of this study is to calculate the SAR from measurement data obtained from two different signal generators operating at 900 MHz and 1800 MHz (Everest GSM Simulators 900CW4 and 1800CW2 [29]) and then assess the SAR on different tissues such as muscle, brain, and fat through simulations. SAR measurements were conducted at a standardized SAR laboratory [30], and signal generators with monopole antennas were used as RF-EMF sources with different frequencies. The laboratory is $4 \times 4 \times 5 \text{ m}^3$ in dimensions and has three surfaces covered with insulating material as shown in Figure 1.

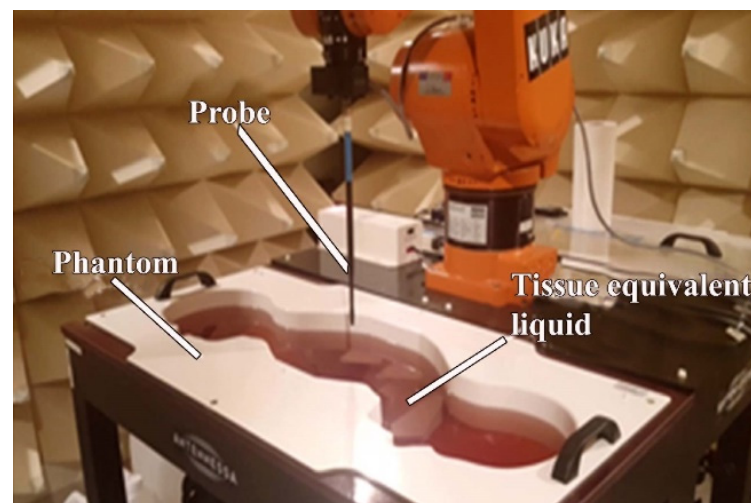


Figure 1. SAR laboratory and phantom.

There are tissue-equivalent fluids in the laboratory that allow SAR measurements at different frequencies. In this study, 900 MHz and 1800 MHz tissue equivalent fluids were used based on a specific recipe. Before using these fluids, a liquid calibration test must be performed according to the relevant standards. The relative permittivity and conductivity values of these liquids must be in accordance with these standards with a maximum tolerance of 5%. The results of the test were validated using a vector network analyzer.

The real part of the relative permittivity (ϵ'), the imaginary part of the relative permittivity (ϵ''), and the conductivity (σ) values of two different liquids that were used in the laboratory and the simulations are given in Table 3 and are in accordance with the standards.

Measurement setup consists of monopole antennas for 900 and 1800 MHz and generators. Monopole antennas of the generators are placed to the head region of the phantom with an angle of about 15° . In the SAR laboratory, an electric field probe is positioned on the six-axis robot arm. Data are then collected in x, y, and z coordinates. The robot software defines the area to be scanned by the electric field probe, including the tracing paths and axial steps. Surface scanning is then conducted at 123 points with 8 mm intervals between

each scan. First, the highest SAR value in the phantom is determined with the help of field scanning. Afterward, the scanning process is continued by performing three-dimensional cube scanning. SAR values of different output powers are obtained for the fixed antenna position with the help of openSARV4 software. This process is performed separately for the 900 MHz and 1800 MHz frequencies.

Table 3. Dielectric properties of materials used at the laboratory and the simulations.

	Frequency (MHz)	Relative Permittivity (Real Part)	Relative Permittivity (Imaginary Part)	Conductivity (S/m)
SAR Lab.	901.95	39.77	18.53	0.93
	1803.20	38.30	13.87	1.39
CST	900	41.50	19.37	0.97
	1800	40.00	13.98	1.40

2.2. SAR Simulations

In order to investigate the effects of exposure to RF-EMFs of various intensities on the human head and tissues, we used a specific anthropomorphic mannequin (SAM) which has the same geometry as described in IEEE 1528–2013 standard [31] and computational human models. Because it is aimed at determining the effect of an electric field on tissues, the SAR values obtained at the laboratory were transferred and used as a reference for simulations. The equivalent of the phantom and tissue equivalent fluids used in the laboratory are found in CST program under the name SAM, and its relative permittivity and conductivity values are given in Table 2. As seen from the table dielectric properties of SAM are very similar to liquids used in the laboratory.

CST's SAM head model is a simplified homogeneous human model that consists of the outer shell and the tissue-equivalent liquid. Its dielectric parameters are determined by averaging the dielectric properties of an anatomical head. The relative permittivity and conductivity values of the outer shell are independent of frequency ($\epsilon_r = 3.5$, $\sigma = 0.0016$ S/m). However, tissue equivalent fluid's dielectric properties change by frequency. In order to use SAR laboratory measurement results as a reference, SAR calculations were performed for SAM in CST, and correct antenna position and excitation signal levels were determined for further evaluations.

As this study aims to determine the SAR on different tissues; computational human models, which have been developed from tomographic data of real individuals, were used in simulations beside SAM. These models are a mathematical description of the envelope of the human body shape as well as the borders of the internal tissues and organs. In the CST voxel family, there are seven human models of different ages, sizes, and gender [32].

In computational human models, each biological organ and tissue is defined by electromagnetic properties that vary with frequency. Detailed information about the electromagnetic properties of biological tissues and organs is necessary to understand the interaction between electromagnetic fields and the human body. These electromagnetic properties are available only for the 100 MHz and 900 MHz frequencies in CST. The electrical properties of the tissues for 1800 MHz were adjusted according to the values given in [33].

It is very important to determine the number of cells when working with computational human models. A thinner network means more elements and more accurate results but may, however, require more powerful hardware. The calculation time changes depending on the number of cells used. Therefore, an appropriate balance must be found between the accuracy and calculation time.

To model the RF-EMF source in the simulations, two monopole antennas that have the same properties as the antennas of the generators were designed for 900 and 1800 MHz. The designed antenna models consist of feeding pins, ground planes, copper wires as radiating elements, and Teflon coatings for insulation. The antenna is fed through a 50 Ω

connector. A three-dimensional view of the designed antenna is shown in Figure 2 and the geometrical dimensions of the antennas for the 900 and 1800 MHz frequencies are provided in Table 4. Human (e.g., adult male) interaction with the antenna is depicted in Figure 3. In SAR simulations, the antenna is typically placed in a location that represents its actual position on the mobile phone, considering factors such as distance from the body and its specific position.

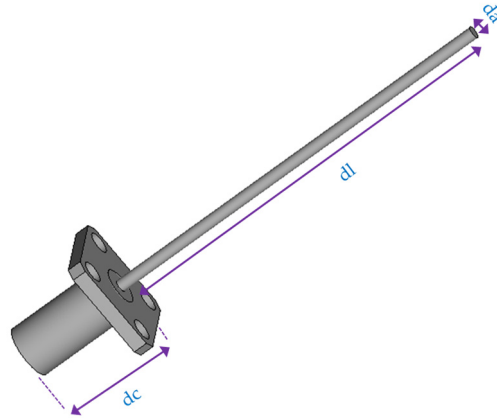


Figure 2. The antenna geometry used in the simulations.

Table 4. Dimensions of the antenna used in the simulations.

Frequency (MHz)	Antenna Dimensions (mm)		
	da	dl	dc
900	1.5	117	12.9
1800	1.5	50	12.9

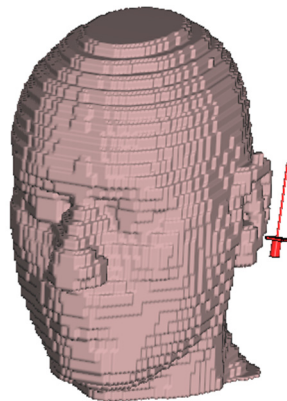


Figure 3. The interaction of a human with the antenna.

In the simulations, the excitation signal level is determined according to reference SAR values measured at the laboratory for the tissue equivalent fluids. SAR values in different tissues were calculated using CST where Maxwell's equations were solved through the finite integration technique (FIT) [34]. E distribution in the head region [35] is calculated by using the simplified Maxwell's equation as given in (2):

$$\nabla \times \mu_r^{-1} \nabla \times \mathbf{E} - k_0^2 \epsilon_r \mathbf{E} = 0 \quad (2)$$

where, μ_r , ϵ_r and k_0 represent the relative permeability, relative permittivity, and wave number, respectively. Additionally, hexahedral mesh type and perfect boundary approximation are applied. In order to adjust accuracy and simulation duration, automatic mesh

generation with an acceptable ratio limit is used. SAR values are averaged according to the IEEE/IEC 62704-1 standard [36].

3. Results and Discussion

3.1. SAR Laboratory Measurements

SAR measurements are conducted in the laboratory using specialized equipment and techniques, following a series of steps. These steps can be summarized as the preparation phase, exposure settings, and SAR measurements. During the preparation phase, a phantom is used and filled with liquid of different properties specific to each frequency, such as 900 MHz and 1800 MHz. Liquid calibration is performed to ensure accurate measurements. Additionally, a noise experiment is carried out to establish a baseline. Next, the antenna is positioned on the phantom, and power adjustments are made to simulate realistic usage conditions. This step ensures that the electromagnetic field emitted by the antenna accurately represents the output of the device under test (DUT). Moving on to the exposure settings stage, measurements are taken on the twin phantom's right and left sides. The DUT is set to active mode, and surface scanning starts. Four tests are conducted during scanning, starting from the right cheek and the phantom's 15° angled position. The same procedure is then applied to the left phantom. Next, the location with the highest SAR value is determined, and two additional volume scans are conducted at this specific position. Each measurement is completed in approximately 20 min, and this measurement procedure ensures a comprehensive and reliable assessment of SAR levels.

In this study, after determining the compliance of the liquids with the standards, SAR measurements are performed for 900 MHz and 1800 MHz frequencies in the laboratory. The output power values of the generators were set to six different levels for 900 MHz and five different levels for 1800 MHz, representing the low, moderate and high doses of electromagnetic exposure. The power values used in the laboratory measurements for 900 MHz and 1800 MHz and the measured electric field strength (E), and SAR values are provided in detail in Table 5. Average 10g SAR values (both laboratory and simulation) and corresponding E for 900 MHz and 1800 MHz are shown in Figure 4 and saved for future reference. As seen from the table and figure, a number of the SAR values are above the general public exposure limits set by ICNIRP [1]. The SAR value measured at 4 W power for 900 MHz and at 1.25 and 1.5 W power for 1800 MHz exceeds the 2 W/kg value determined by ICNIRP.

Table 5. The power, E and SAR values of the laboratory measurements at 900 MHz and 1800 MHz.

Frequency (MHz)	900	Power (W)	0.5	1	1.5	2	3	4
		E (V/m)	2.89	13.75	19.18	27.33	38.01	50.18
		SAR 10g (W/kg)	0.0077	0.1752	0.3410	0.6919	1.3386	2.3327
	1800	Power (W)	0.25	0.5	1	1.25	1.5	-
		E (V/m)	10.29	21.68	35.50	42.64	47.45	-
		SAR 10g (W/kg)	0.1468	0.6629	1.7483	2.5222	3.1227	-

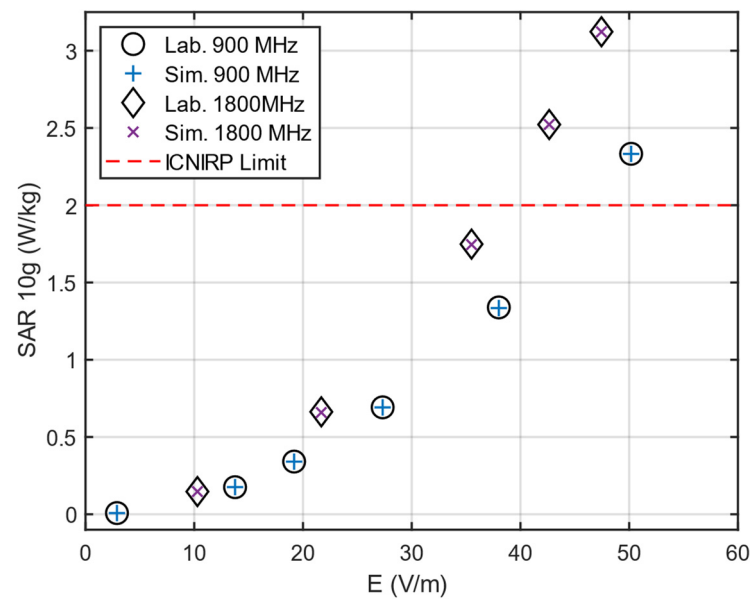


Figure 4. SAR laboratory and simulation results for 900 MHz and 1800 MHz.

3.2. SAR Simulations for SAM

In order to determine the excitation signal levels for simulations, the SAR values that were measured at the laboratory were used as a reference. In the simulations, SAM with relative permeability and conductivity values approximately equal to those of the phantom fluid in the laboratory and a monopole antenna were used. Taking into account the plastic surrounding the antenna used in the laboratory, a distance of 10 mm was maintained between the antenna and the SAM in the simulations. Furthermore, the antenna location and angle in the simulations were adjusted to match those in the laboratory using the reference lines of the SAM models. In simulations, different excitation signal levels were set according to measured SAR values and were indexed. Simulation results for 900 MHz and 1800 MHz are also given in Figure 4. It can be clearly seen from Figure 4 that measured and simulated SAR values follow each other closely, ensuring accuracy.

In order to visualize the SAR distribution in the head region a sample color scale image is shown in Figure 5. The sample images are given for simulations performed for moderate doses of exposure at 900 MHz and 1800 MHz respectively. It can be observed from the figures that the highest SAR values are obtained around the radiation source, and the values decrease significantly by distance from the source.

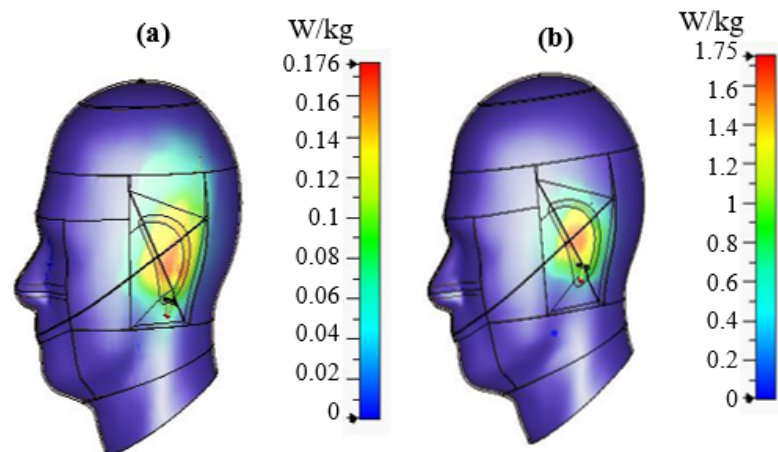


Figure 5. SAR 10g distribution over SAM, (a) 900 MHz and (b) 1800 MHz.

3.3. Simulation Results for Computational Human Models

All measurements performed at the laboratory provide information about the average SAR value in the head region. In order to determine the SAR in the tissues of interest, it is necessary to measure the SAR over the equivalent liquid belonging to that tissue. Since this process is difficult and costly, the calculations can be made through simulations and using realistic computational human models. Since these models offer the opportunity to work with human models of different ages, gender, and heights, simulations with these models can provide more detailed calculations. In the simulations, realistic computational human models with different ages and genders were considered from the CST voxel family to investigate the effects of age and gender. Additionally, the dielectric properties of the tissues in these models were adjusted based on the operating frequency (900 MHz and 1800 MHz). In order to examine the effects of SAR on tissues in the head region, it is necessary to replace the SAM with a computational human model head while keeping the excitation signal level and the antenna position the same. The SAR 10g distribution of the whole head region of adult males is given in Figure 6 as an example. The SAR 10g values are calculated, and the peak SAR 10g values are saved and given for the head and for the selected tissues of all models.

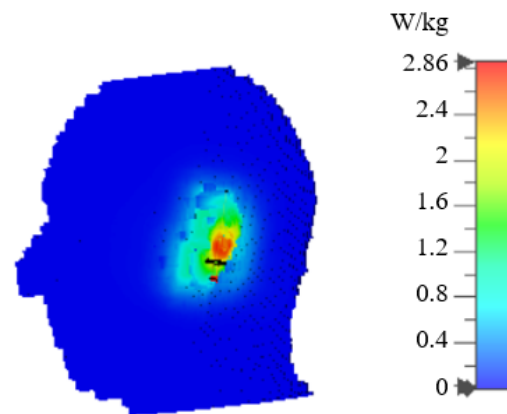


Figure 6. SAR 10g distribution over the adult male computational human model.

In order to determine how the same SAR affects other tissues of the head region, additional SAR calculations are made. The change of the SAR 10g as a function of E for the baby brain, fat, and muscle tissues at 900 MHz and 1800 MHz are shown in Figure 7a,b, respectively. As seen from Figure 7a, while all SAR 10g values are close to each other, there is a significant difference between the SAR 10g of the brain and the other SAR 10g values for 1800 MHz. The baby whole head and muscle tissue has the highest SAR compared with other tissues at 900 MHz and the lowest SAR can be observed over baby brain tissue at 1800 MHz, all of which were below the ICNIRP's limits. The highest SAR 10g is 1.02 W/kg and 1.75 W/kg for the head at 900 and 1800 MHz, respectively. It can also be concluded from the figures that the change in the frequency affects the SAR levels over tissues. The increase was at most 80% for the tissues of fat, muscle, and the whole head.

Figure 8 shows the SAR 10g values of the child head and selected tissues at 900 MHz and 1800 MHz. As seen from the figure, the SAR 10g of child brain tissue is lower than other tissues and the head for 900 MHz and 1800 MHz. Furthermore, SAR 10g values of fat, muscle, and head are roughly the same. The head has the highest SAR 10g values of 1.42 W/kg and 3.67 W/kg at 900 MHz and 1800 MHz, respectively. It can also be concluded from the figure that the SAR 10g value of the head is 1.76 times higher than brain tissue for 900 MHz and 2.60 times higher for 1800 MHz. SAR 10g values of brain, fat, muscle, and head are below the limits for 900 MHz while some SAR values (i.e., 2.05, 2.85, 2.95, 3.34, and 3.67 W/kg) are above the determined limits for fat, muscle and head at 1800 MHz.

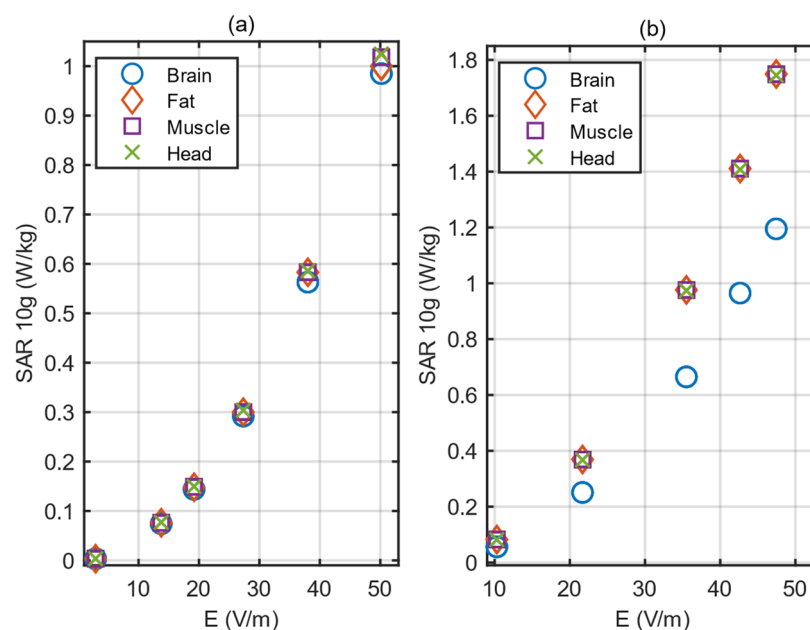


Figure 7. SAR 10g values of head and selected tissues of baby, (a) 900 MHz and (b) 1800 MHz.

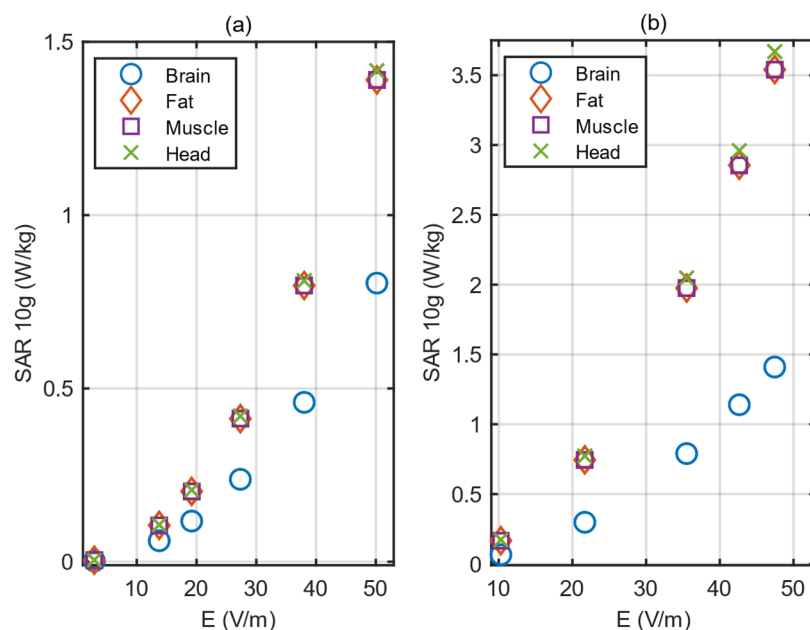


Figure 8. SAR 10g values of head and selected tissues of a child, (a) 900 MHz and (b) 1800 MHz.

SAR 10g values of the adult female are illustrated in Figure 9. Some of the SAR 10g values are also above the limits at 1800 MHz, similar to the child SAR 10g. As can be seen from the figures, and contrary to those of baby and child, the SAR 10g values differ from each other. The highest SAR 10g is observed for the head at 1.57 and 4.46 W/kg for 900 MHz and 1800 MHz, respectively, as obtained from the baby and child head. The brain tissue SAR 10g value is the lowest among them.

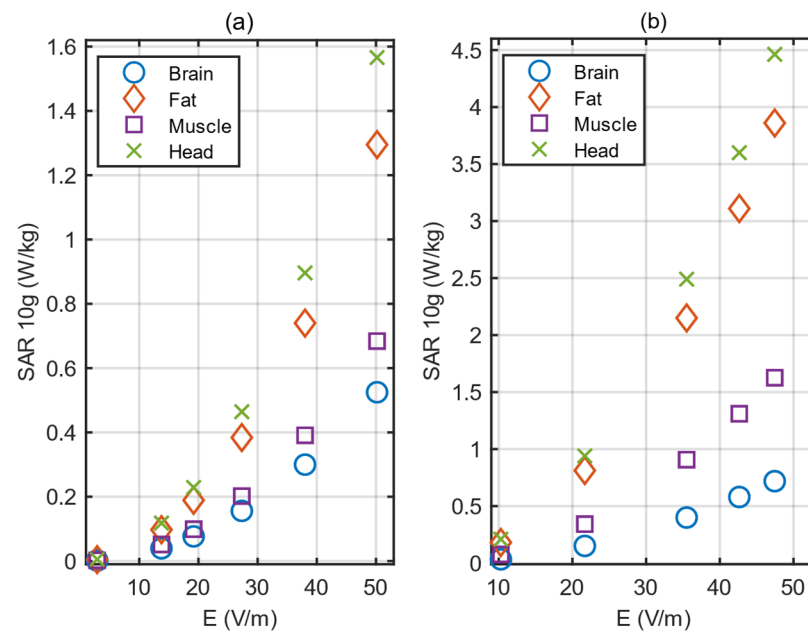


Figure 9. SAR 10g values of head and selected tissues of adult female, (a) 900 MHz and (b) 1800 MHz.

Adult male SAR 10g values for selected tissues and whole head are given in Figure 10. It can be concluded from the figure that there is no SAR 10g above limits at 900 MHz while some of the SAR 10g values are above the determined ICNIRP limit at 1800 MHz. The peak SAR 10g is 5.15 W/kg, the highest among all SAR 10g values. Fat tissue exhibited the highest SAR value at 1800 MHz with a value of 4.80 W/kg. The maximum of the ratios between SAR 10g values of head and brain tissue is 4.44.

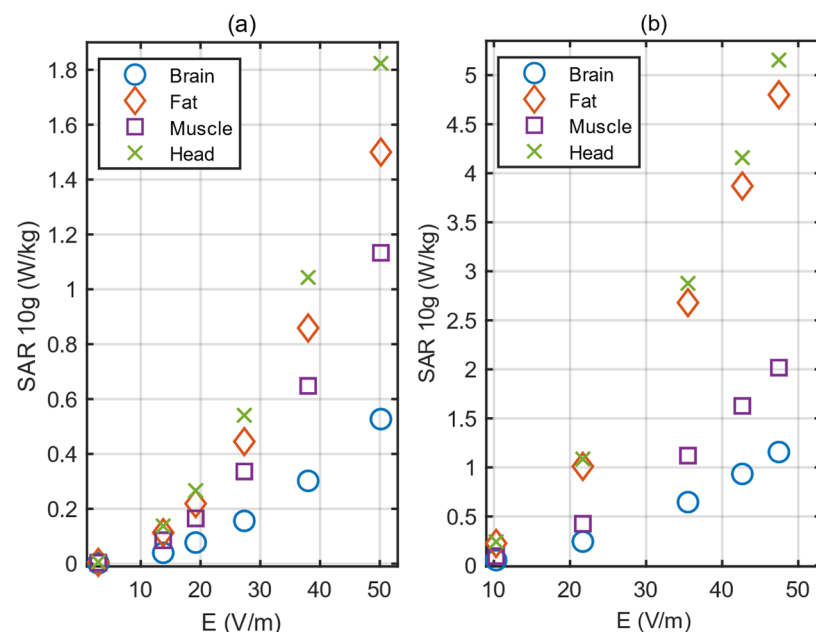


Figure 10. SAR 10g values of head and selected tissues of adult male, (a) 900 MHz and (b) 1800 MHz.

Figure 11 shows the box graphs for all SAR 10g results for 900 MHz, and 1800 MHz. In the figure, the red line represents the median value, while the green diamond represents the mean value. The mean SAR values of brain, fat, muscle and head tissues at 900 MHz are 0.248, 0.453, 0.368, and 0.509 W/kg, respectively, with standard deviations of 0.268, 0.466, 0.393, and 0.533 W/kg, respectively. At 1800 MHz, the mean SAR values of the tissues are

0.588, 1.828, 1.171, and 1.971 W/kg, respectively, with standard deviations of 0.441, 1.4620, 0.956, and 1.603 W/kg.

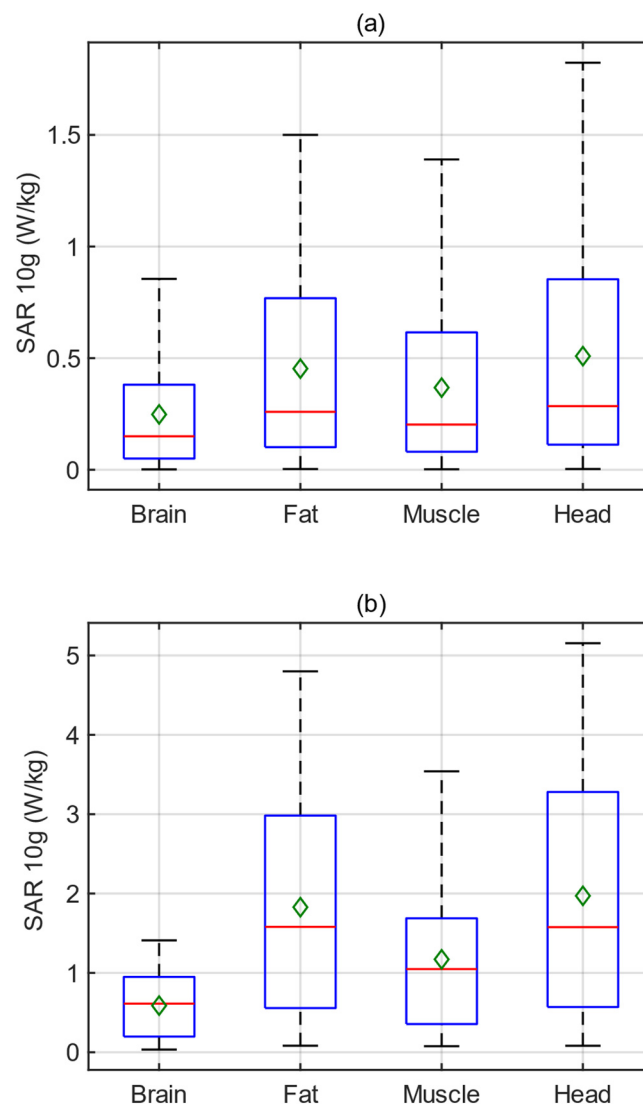


Figure 11. Box graph for SAR 10g, (a) 900 MHz and (b) 1800 MHz.

When evaluating the simulation results as a whole, it is observed that at 900 MHz, no SAR value exceeds the basic restriction for general public exposure. However, at 1800 MHz, the limit is exceeded only for the whole head in children at the 3rd power level (1 W). Moreover, at the 4th (1.25 W) and 5th (1.5 W) power levels, the SAR values for fat, muscle, and head tissues also exceed the limit. In both female and male, the limit is surpassed in the fat and head tissues after the 3rd power level. Additionally, in males, the muscle SAR value at the 5th power level also exceeds the limit.

3.4. Comparison of Results with Existing Studies

The overall evaluation of laboratory and simulation results reveal that children and baby brain tissue SAR 10g values (1.41, 1.20 W/kg) are higher than those induced in adult female and male (0.72, 1.16 W/kg). These results are in accordance with [11,12]. The assessment of the SAR 10g in different tissues of the head has shown that the brain of the baby has the highest values, contrary to the whole-head SAR. The maximum of the ratios of brain overhead SAR 10g for baby is 0.69 while the values are 0.38, 0.16, 0.22 for child, female and male, respectively, at 1800 MHz. This result supports the findings of [10], wherein

decreased head size yielded an increase in EM energy absorbed in the brain. Results show that, similar to [14,16,18,23], frequency, tissue type, the morphological specifications, and age/gender associated differences in electrical properties of tissues affect the induced SAR values.

In addition, a comparison based on parameters such as frequency, age, tissue, and key results based on SAR was made and the results are given in Table 6.

Table 6. Comparison of this work with existing studies.

Ref.	Year	Frequency (MHz)	Different Ages	Different Tissues	Results
[11]	2004	900, 1800	Yes	Yes	The peak SAR decreases with decreasing head size but percentage of the energy absorbed in the brain increases.
[13]	2008	900, 1800, 2100, 2400	Yes	Yes	The maximum SAR 10g in the head models of the adults and children are almost the same, while SAR of brain tissues of child models is higher than that of adults.
[17]	2008	20 to 2400	Yes	Yes	The standard deviation of whole-body averaged SAR of adult models can reach 40%, which proves the variability of adult models. Additionally, the whole-body average SAR of children is over the relevant limits.
[12]	2010	900, 1800	Yes	Yes	Age dependences of dielectric tissue properties do not lead to systematic changes of the peak spatial. However, major age-dependent changes were observed for the exposure of particular tissues.
[24]	2019	850, 900, 2100, 2600, 5100	No	Yes	Regardless of the frequency, if the antenna radiated power is low, temperature increase within the human tissues is low, and hence the SAR. However with the increase in radiated power, SAR also increases, and in the same cases, exceeds the limit in all head tissues.
[19]	2020	900, 2100, 2450, 2600	Yes	No	Based on the near-field exposure results, the SAR values vary for the antenna type and pregnant model type, and for some scenarios the SAR values are not within the limits.
[15]	2021	800, 900, 1800, 2100	Yes	Yes	Adolescents experience higher modeled RF doses in the whole-brain compared with children, while children are exposed to higher RF doses in the whole body.
This Study	2023	900, 1800	Yes	Yes	Frequency, radiated power, gender, age, and tissue type each have an effect on induced SAR levels. Local SAR values exceed the limits under some exposure scenarios.

3.5. Limitations and Further Studies

The results provided here pertain solely to the SAR analysis conducted at 900/1800 MHz frequencies and specific head tissues (such as the brain, muscles, and fat) using human models representing babies, children, adult females, and adult males. With the help of the method proposed in the study, SAR values can be calculated at different frequencies for

different morphology and parts/tissues of the body. Therefore, comparisons with limits of exposure and recommendations for acceptable SAR limits which takes age (baby, children) into account can be made.

4. Conclusions

In this study, the effect of RF-EMF radiation from 900 MHz, and 1800 MHz sources on the human head, and specific tissues in the human head, were investigated for varying antenna powers which cover all exposure levels. SAR 10g values that were measured at a standardized SAR laboratory using signal generators were used to evaluate SAR 10g distribution. The experimental setup was then simulated in CST using these SAR values as a reference. In order to determine how SAR is related to age, gender, and tissue type, different exposure scenarios were applied to baby, child, adult female, and adult male models. The highest SAR 10g values for 900 MHz and 1800 MHz were obtained for the adult male, followed by an adult female, child, and baby over the whole-head region. SAR 10g values vary depending on the excitation signal level, type of the model, and tissue.

At 900 MHz, the SAR values for the baby range from 0.003 to 1.02 W/kg, while for the child, female, and male, the ranges are 0.003–1.42 W/kg, 0.002–1.57 W/kg, and 0.002–1.82 W/kg, respectively. When evaluating the same parameters at 1800 MHz, the SAR ranges for the baby, children, female, and male are 0.06–1.75 W/kg, 0.07–3.67 W/kg, 0.03–4.46 W/kg, and 0.05–5.15 W/kg, respectively. The ratio of the highest SAR values at 1800 MHz to 900 MHz for the baby, child, female, and male are 1.71, 2.59, 2.85, and 2.83, respectively.

The SAR analyses conducted in this study help determine whether the operating frequency and power levels pose potential health risks by exceeding established limits for different populations. Additionally, the measured SAR values contribute to the protection of public health and the development of regulations addressing potential risks associated with wireless communication devices.

The results of this study show that wireless technologies produce different SAR effects on different demographic groups. The fact that the SAR value also increases with increasing operating frequency indicates that SAR values from wireless 5G/6G devices using millimeter wave frequencies, which will soon become prevalent in our lives, will also increase. The information presented in the study can significantly contribute to understanding the impact of wireless technologies on health.

As this study allows us to determine realistic SAR values through computational human models, it also enables us to make dosimetric studies without using live subjects.

Author Contributions: Conceptualization, A.T. and B.K.E.; methodology, A.T. and B.K.E.; software, A.T.; validation, A.T. and B.K.E.; formal analysis, A.T.; investigation, A.T.; resources, A.T. and B.K.E.; data curation, A.T. and B.K.E.; writing—original draft preparation, A.T. and B.K.E.; writing—review and editing, A.T. and B.K.E.; visualization, B.K.E.; supervision, B.K.E. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by Ondokuz Mayıs University Research Fund, Graduate Thesis Support Program with project number PYO.MUH.1904.18.008.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors would like to thank Aysegul Akar, Ondokuz Mayıs University, Faculty of Medicine, Department of Biophysics for providing signal generators.

Conflicts of Interest: The authors declare no conflict of interest.

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