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Specific absorption rate assessment of fifth generation mobile phones with specific anthropomorphic mannequin model and high-resolution anatomical head model

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Abstract
With the spread and application of the fifth generation (5G) of mobile communication technology, the number of 5G mobile phone users increase rapidly. The traditional safety standard of electromagnetic radiation of mobile phones was set two decades ago, in which a homogeneous specific anthropomorphic mannequin (SAM) head model with standardized size and shape is utilized for specific absorption rate (SAR) evaluation. The SAM model has been proved conservative for SAR evaluation of 2G, 3G and 4G mobile phone antennas. However, it needs to be validated whether it is still suitable for SAR evaluation of 5G mobile phone antennas. A high-resolution anatomical head model with tissues including muscle, skull, cerebrospinal fluid and brain is developed in this paper. The SAR values of three different generation mobile phone antennas are simulated by utilizing both the SAM model and the high-resolution anatomical head model to assess their applicability. Numerical simulations show that the anatomical model may produce a higher SAR value than the SAM model for a 5G mobile phone antenna. So new head model may need to be developed for the SAR evaluation of 5G mobile phone antennas.

KEYWORDS
SAR, 5G, mobile phone antennas, head models, phantom

1 | INTRODUCTION

Mobile phones have become more and more indispensable in our daily life. They achieve mobile communication through sending and receiving electromagnetic waves. However, the electromagnetic wave radiated by the mobile phones is partly absorbed by human body, resulting in the increment of temperature tissues and organs. If we do not limit the maximum power density inside human bodies when a mobile phone is

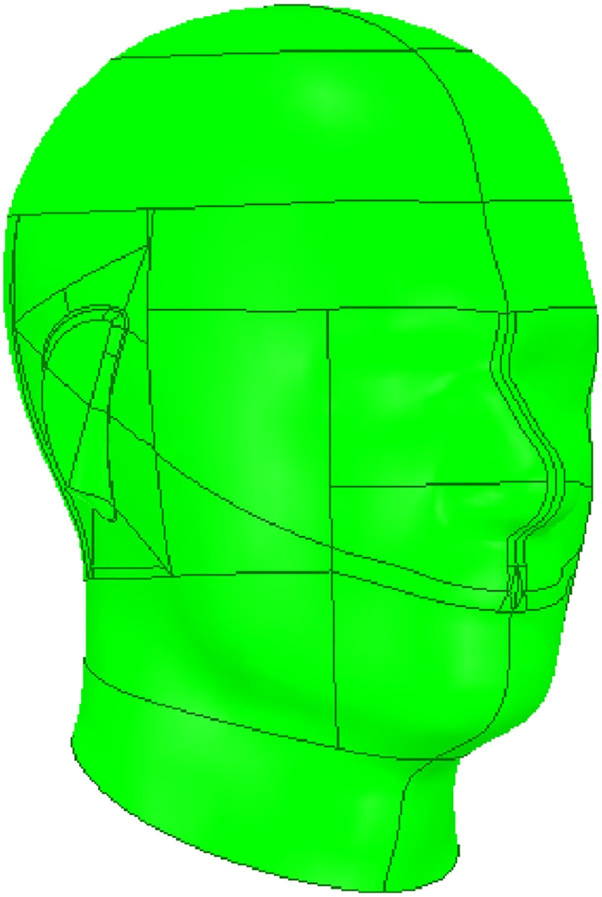

FIGURE 1 Specific anthropomorphic mannequin (SAM) phantom[7]

used, it may lead to damage of human tissues and organs.

In order to quantitatively evaluate the electromagnetic energy absorbed by human body, a term named specific absorption rate (SAR) is defined:

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

where σ is the tissue's conductivity, ρ represents the tissue's density, $\mathbf{E}$ is the electric field inside the tissue. SAR is a measure of the power absorbed by per mass of tissue.

Many countries and organizations have prescribed limits to peak spatial-average head SAR value and peak spatial-average body SAR value. Since the limit of head SAR is more stringent than body, we mainly focus on head SAR in this paper. According to IEEE Std C95.1-1991,[1] the limit of peak spatial-average head SAR value is 1.6 W/kg averaged over 1 g of tissue. While the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guideline stipulates the peak spatial-average head SAR value shall not exceed 2 W/kg, as averaged over any 10 g of tissue.[2] Later, the peak spatial-average head SAR value in IEEE Std C95.1-2005 and C95.1-2019 was changed to 2 W/kg to harmonize the restrictions with ICNIRP guidelines.[3,4] All premarket mobile phones must have measured head SAR values lower than the SAR limit.

TABLE 1 Electromagnetic parameters of SAM model[7]

Frequency (MHz)	Relative permittivity	Conductivity (S/m)
835	41.5	0.90
900	41.5	0.97
1450	40.5	1.20
1640	40.2	1.31
1750	40.1	1.37
1800	40.0	1.40
1900	40.0	1.40
2000	40.0	1.40
2100	39.8	1.49
2300	39.5	1.67
2450	39.2	1.80
2600	39.0	1.96
3000	38.5	2.40
3500	37.9	2.91
4000	37.4	3.43

Abbreviation: SAM, specific anthropomorphic mannequin.

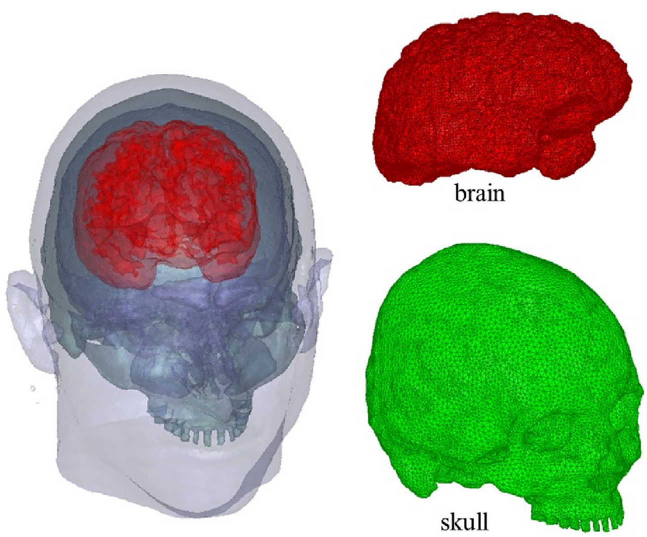

FIGURE 2 High-resolution anatomical head model

The detailed procedures for the SAR measurement is described in IEEE Std 1528-2003 firstly,[5] and then updated in IEEE Std 1528-2013[6] and IEC/IEEE Std

TABLE 2 Electromagnetic parameters of brain

Frequency (MHz)	Relative permittivity	Conductivity (S/m)
880	49.6	1.25
1100	48.4	1.35
1600	46.6	1.6
1900	45.9	1.77
2100	45.5	1.88
2500	44.7	2.13
3000	43.9	2.48
3300	43.4	2.71
3500	43.1	2.86
3800	42.7	3.11

TABLE 3 Electromagnetic parameters of skull

Frequency (MHz)	Relative permittivity	Conductivity (S/m)
880	20.8	0.335
1100	20.4	0.389
1600	19.6	0.527
1900	19.2	0.62
2100	19	0.685
2500	18.5	0.823
3000	17.9	1.01
3300	17.6	1.12
3500	17.4	1.2
3800	17.1	1.32

TABLE 4 Electromagnetic parameters of CSF

Frequency (MHz)	Relative permittivity	Conductivity (S/m)
880	68.7	2.4
1100	68.3	2.5
1600	67.5	2.79
1900	67.1	3
2100	66.8	3.15
2500	66.2	3.5
3000	65.4	4.01
3300	64.9	4.34
3500	64.6	4.57
3800	64.1	4.94

TABLE 5 Electromagnetic parameters of muscle

Frequency (MHz)	Relative permittivity	Conductivity (S/m)
880	55.1	0.936
1100	54.5	1.02
1600	53.8	1.24
1900	53.4	1.4
2100	53.2	1.51
2500	52.7	1.77
3000	52.1	2.14
3300	51.7	2.39
3500	51.4	2.56
3800	51.1	2.83

62 209-1528.[7] In these standards, the specific anthropomorphic mannequin (SAM) model is specified for head SAR measurement. This model has also been widely adopted for numerical simulation of SAR.[8–19] The SAM model is a homogeneous model with standardized size and shape. The main reasons of adopting a homogeneous model, rather than a heterogeneous anatomical head model with multiple tissues, including muscle, skull, brain, etc., can be summarized into three points: (1) It is much easier to manufacture a homogeneous model than a heterogeneous model. (2) It is difficult to apply an E-field probe in a heterogeneous model for SAR measurement. (3) A standardized homogeneous model can guarantee that the differences of SAR values obtained by different laboratories can be minimized.

However, the defects of the SAM model is also obvious. The SAR value obtained by using this model is definitely not consistent with the situation when the mobile phone antenna is put beside a real human head. It is proved conservative for SAR evaluation in the vast majority of cases.[10–15] Namely, the SAR value obtained by using the SAM model is usually higher than using the anatomical model. However, the working frequencies of the mobile phone antennas in[10–16] are all around 900 MHz and 1.9 GHz. With the gradual popularization of the fifth generation (5G) of mobile communication technology, it is necessary and urgent to reappraise whether the SAM model is still conservative for SAR evaluation for 5G mobile phones. In this paper, a high-resolution anatomical head model with tissues including muscle, skull, cerebrospinal fluid (CSF) and brain is developed. The SAR values of three different generation mobile phone antennas are simulated by utilizing both the SAM model and the anatomical head model to assess their applicability.

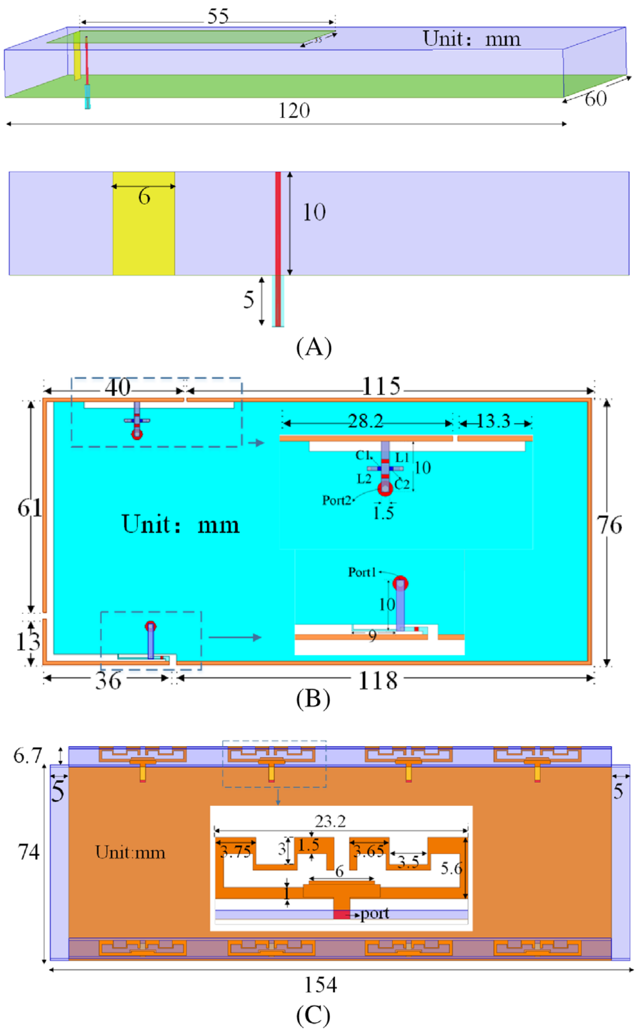

FIGURE 3 The geometry and dimension of three mobile phone antennas: (A) antenna 1, (B) antenna 2, and (C) antenna 3

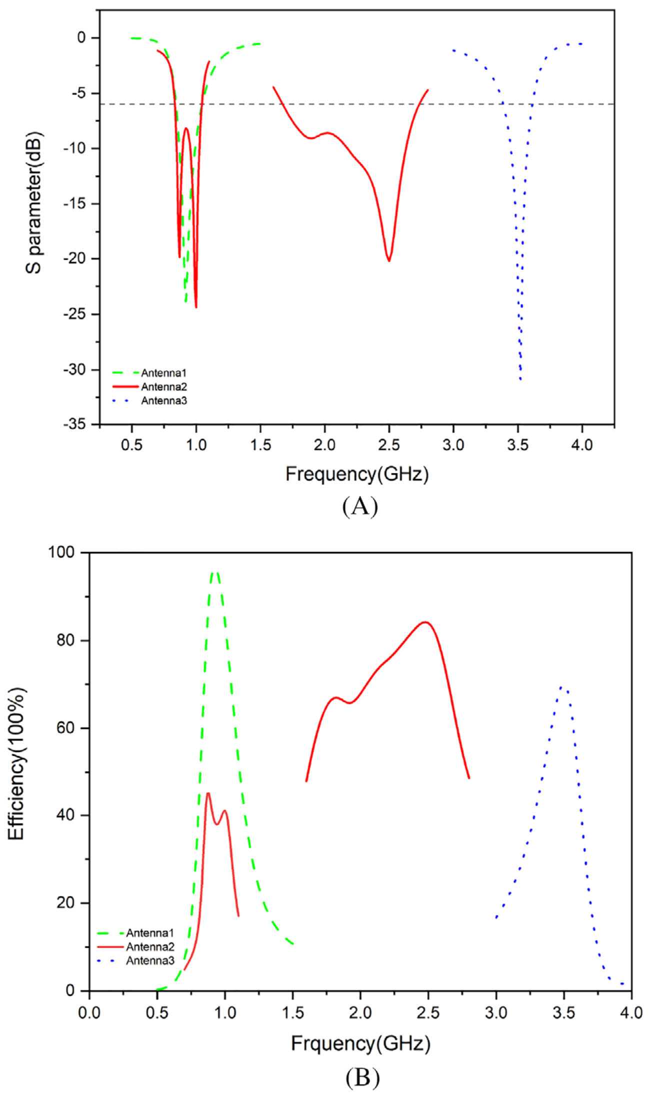

FIGURE 4 Simulated *S* parameters and efficiencies of the three antennas

The remainder of this paper is organized as follows. Both the SAM head model and the high-resolution anatomical head model are described in Section 2. Section 3 introduces the three mobile phone antennas for SAR evaluation. The simulation results of SAR values based on the SAM model and the anatomical model are presented and analyzed in Section 4. Some conclusions are drawn in Section 5.

2 | HEAD MODELS

2.1 | SAM head model

Figure 1 shows the SAM phantom model with standardized size and shape stipulated by IEC/IEEE Std 62 209-1528.[7] The SAM model was constructed by the IEEE Standards Coordinating Committee 34, Subcommittee 2, Working Group 1. The shape and dimension of this model are determined according to the 90th-percentile anthropometric data of many adult males' heads provided by the US Army. Note the anatomical ear on human head is replaced by an ear spacer with a low-loss dielectric material to facilitate head SAR measurements. The thickness of the ear spacer (6 mm) is much smaller than the distance between the rear edge of the anatomical ear and the head (typical 19–28 mm). Consequently, the antenna of a mobile phone would be placed much closer to the human head, resulting in an overestimated head SAR value. The permittivity and conductivity values of the SAM model ranging from 300 to 6000 MHz are given in Table 1.[7] The dielectric parameters are generally average values of several different tissue layers, which are also chosen to give overestimated head SAR values.

It can be concluded that the size, shape, material of the SAM model are chosen to achieve a relatively

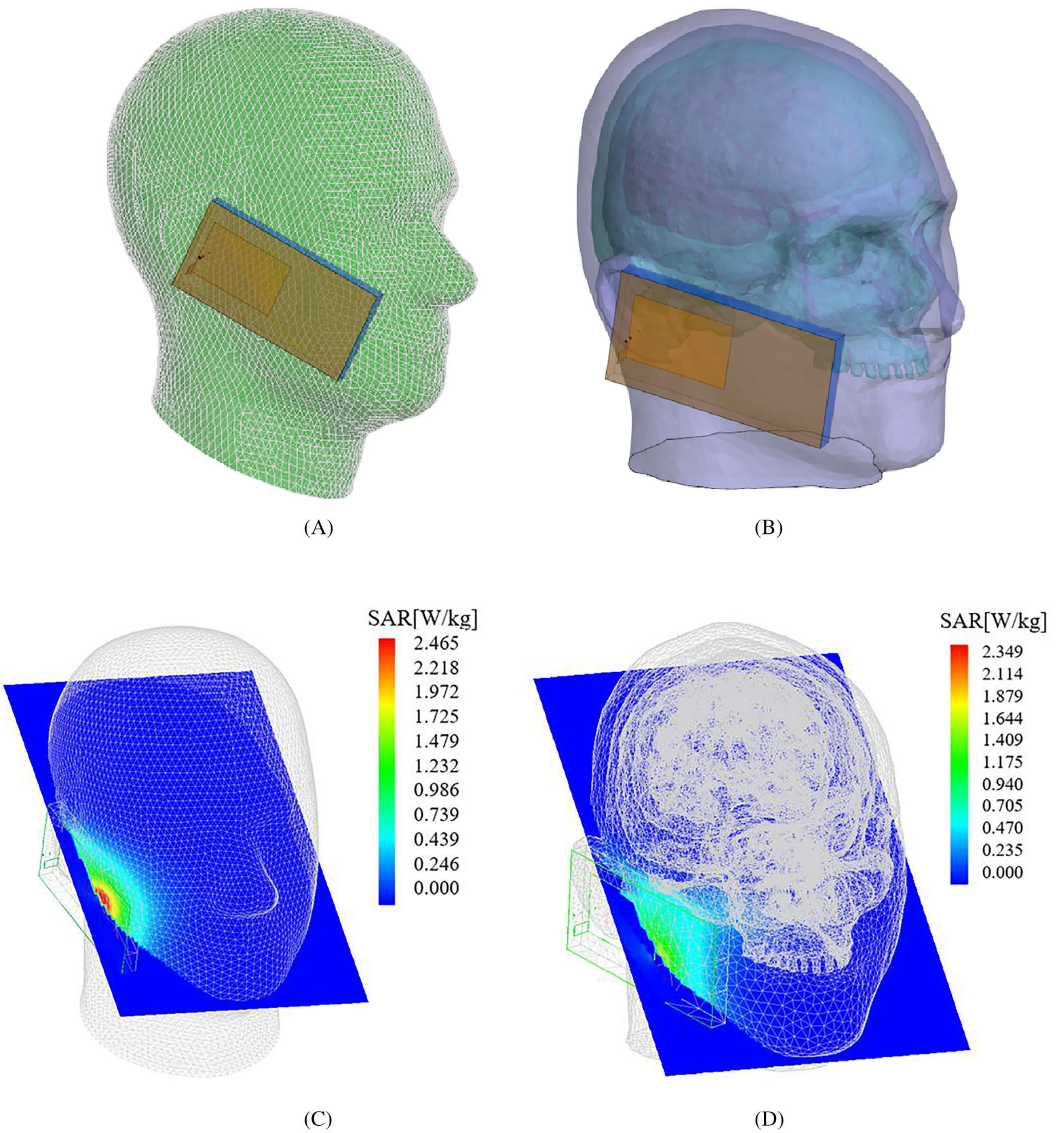

FIGURE 5 (A) The antenna 1 beside the specific anthropomorphic mannequin (SAM) head model, (B) the antenna 1 beside the anatomical head model, (C) the 1-g averaged 2-D specific absorption rate (SAR) distribution in a cutting plane of SAM model, and (D) the 1-g averaged 2-D SAR distribution in a cutting plane of anatomical head model

conservative estimate of the peak spatial-average SAR.[7] Thus the antennas designed based on this model have a relatively high safety margin of SAR values. Moreover, since the same standardized model is utilized, the differences of simulated SAR results between different laboratories can be minimized, which can guarantee the repeatability of simulation results.

2.2 | Anatomical head model

Figure 2 shows the high-resolution anatomical head model created from magnetic resonance image (MRI) data of volunteers with a resolution of $0.5 \times 0.5 \times 0.5$ mm^3. Note the original geometries of tissues obtained from MRI are too complex. A huge amount of

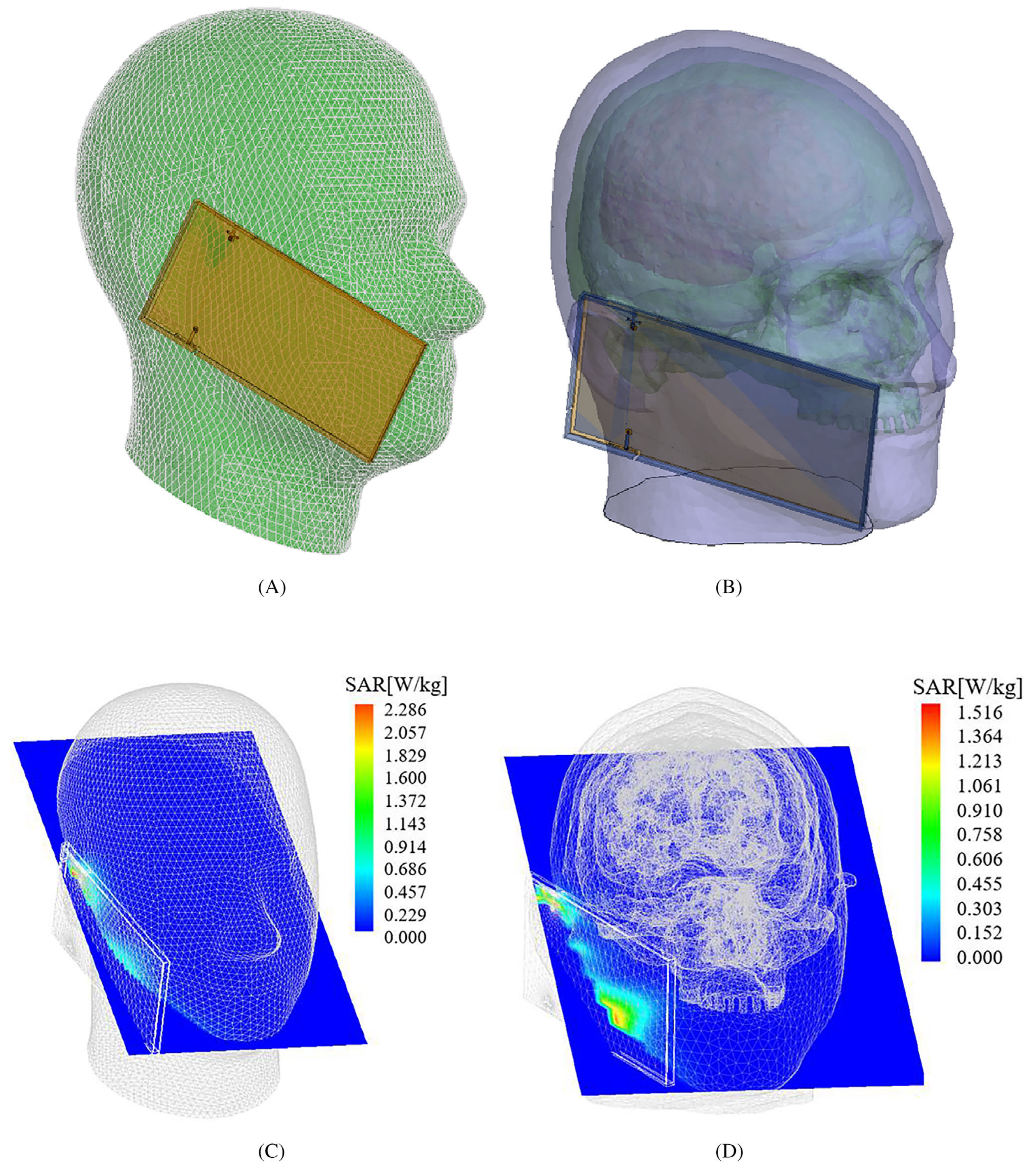

FIGURE 6 (A) The antenna 2 beside the specific anthropomorphic mannequin (SAM) head model, (B) the antenna 2 beside the anatomical head model, (C) the 1-g averaged 2-D specific absorption rate (SAR) distribution in a cutting plane of SAM model, and (D) the 1-g averaged 2-D SAR distribution in a cutting plane of anatomical head model

meshes will be generated when utilizing the electromagnetic simulation software to carry out SAR evaluation, resulting in unbearable demand of memory and CPU time. So for ease of electromagnetic simulation with mainstream third-party commercial software like FEKO,[20] CST and HFSS, the original geometries of tissues are simplified and optimized. The current version of high-resolution anatomical head model mainly

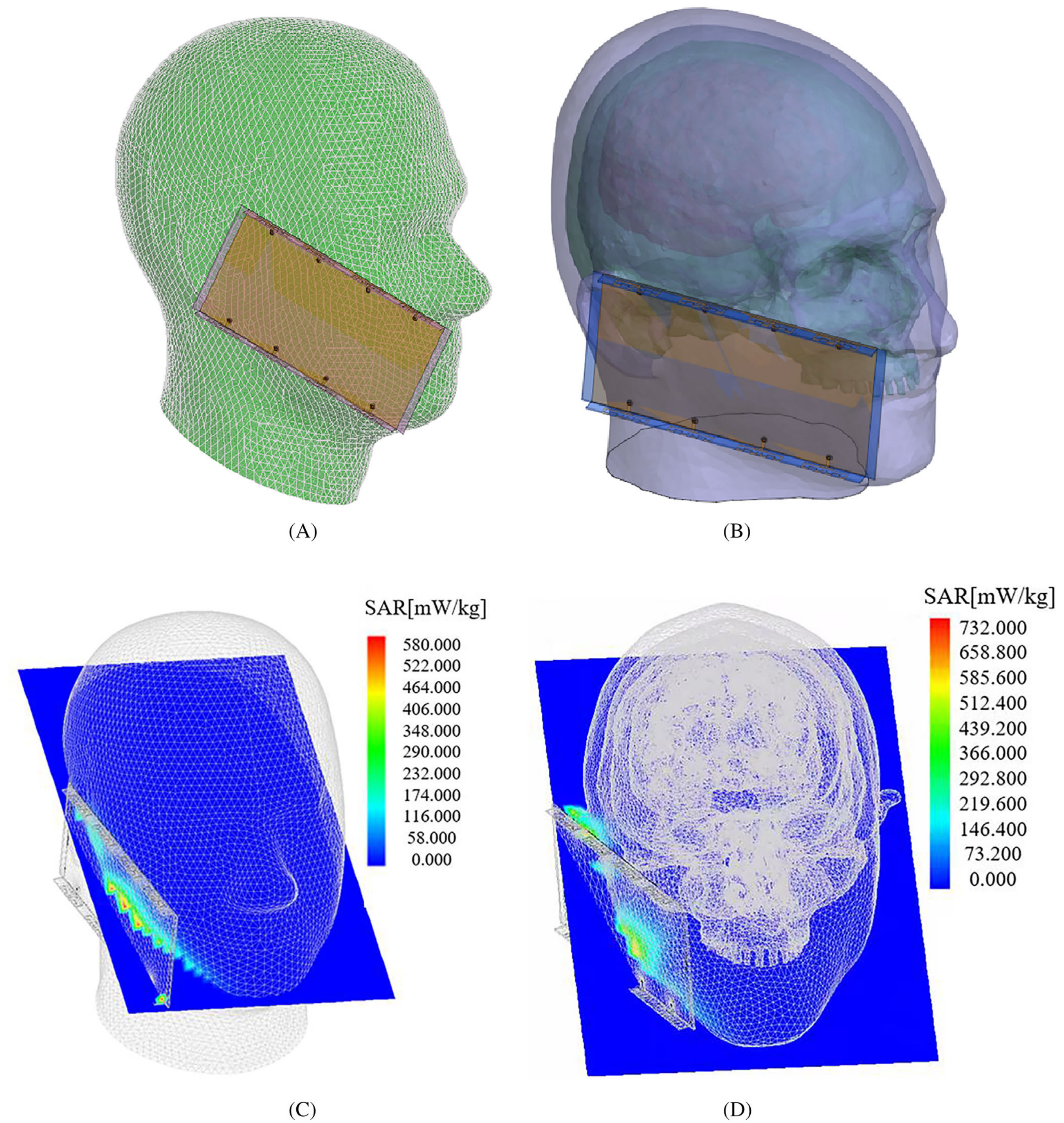

FIGURE 7 (A) The antenna 3 beside the specific anthropomorphic mannequin (SAM) head model, (B) the antenna 3 beside the anatomical head model, (C) the 1-g averaged 2-D specific absorption rate (SAR) distribution in a cutting plane of SAM model, and (D) the 1-g averaged 2-D SAR distribution in a cutting plane of anatomical head model

includes tissues of brain, skull, CSF and muscle. It is worth mentioning the geometric profiles of these tissues remain unchanged to the greatest extent during simplification. Moreover, the current version of high-resolution anatomical head model has anatomical ears compared with the SAM head model. So it is good enough to replace the real human head for SAR evaluation.

The permittivity and conductivity values of the brain, skull, CSF and muscle of the high-resolution anatomical head model ranging from 500 to 4000 MHz are listed in Tables 2–5.[21]

3 | MOBILE PHONE ANTENNAS

Figure 3A–C present the geometries and dimensions of three mobile phone antennas. Antenna 1 is a PIFA antenna, which is a typical mobile phone antenna in the stage of 2G mobile communication. Antenna 2 is a full-screen metal-rimmed antenna, which is a popular design in 4G mobile communication recent years. Antenna 3 is an eight-element MIMO array with couple-fed dipole antenna elements, which represents a 5G mobile phone antenna. In all these three antennas, the substrate of the PCB is FR4-epoxy with a relative permittivity of 4.4 and a loss tangent of 0.02, respectively.

The simulated S11 curves and efficiencies of the three designed antennas are shown in Figure 4. It can be observed that the −6 dB impedance bandwidth of antenna 1 can cover the frequency band of 880–960 MHz. The −6 dB impedance bandwidth of antenna 2 can cover the frequency band of 880–960 MHz and 1710–2690 MHz. That of antenna 3 can cover the frequency band of 3.4–3.6 GHz. In the above mentioned frequency bands, the efficiency of antenna 1 is higher than 88%. The efficiency of antenna 2 in its lower band is higher than 38%, while it is higher than 62% in its higher band. The efficiency of antenna 3 is higher than 48%. Note that the S11 curves and efficiencies are computed in absence of the head model.

4 | SAR EVALUATION

As shown in Figures 5A,B, 6A,B, and 7A,B, the three mobile phone antennas are put beside the SAM model and the anatomical head model to imitate the scenario that the human head is exposed to the EM radiation of the antennas. The mobile phone antennas are placed beside the SAM head model in the cheek position, which is a standard placement location defined in IEC/IEEE Std 62 209-1528.[7] The mobile phone antennas are placed beside the high-resolution anatomical head model in a similar manner. The input powers of antenna 1 and antenna 2 are 250 mW. For antenna 3, since the eight antenna elements simultaneously radiate, a total input power of 250 mW is divided equally to the eight ports of the antennas.

The 1-g spatial averaged SAR distributions of antenna 1, antenna 2, and antenna 3 at 900 MHz, 2.5 and 3.5 GHz are simulated by using the commercial software Altair FEKO 2021[20] The selected method for electromagnetic field and SAR simulation is method of moment (MoM). All the simulations are carried out on a workstation with Intel Xeon Gold 6248R CPU with 48 cores and 1 TB RAM. Each core supports two processes. The procedure for SAR simulation is aligned with IEC/IEEE Std 62 209-1528.[7] The results as demonstrated in Figures 5C,D, 6C,D, and 7C,D. It can be observed that the hotspots of the SAR distributions of the three antennas are around the surface of the human head. The simulation times corresponding to the two head models are compared in Table 6. Obviously, it takes much more CPU time to calculate the SAR value with high-resolution anatomical model.

TABLE 6 Comparison of simulation time between two models

Antenna	SAM	Anatomical
1	23 min	10 h
2	1 h 5 min	11 h 41 min
3	1 h 30 min	13 h 25 min

Abbreviation: SAM, specific anthropomorphic mannequin.

TABLE 7 Head SAR values of three antennas

		1 g SAR (W/kg)	
Antenna	Frequency (MHz)	SAM	Anatomical
1	900	2.46	2.34
2	2500	2.28	1.51
3	3500	0.53	0.73

Abbreviations: SAM, specific anthropomorphic mannequin; SAR, specific absorption rate.

The peak values of 1 g spatial average head SAR of the three antennas are summarized in Table 7. It can be found that the SAR values obtained by the SAM model are conservative compared with the high-resolution anatomical model for antenna 1 and antenna 2. However, for the 5G MIMO antenna 3, the SAR value obtained by using the high-resolution anatomical model is higher than using the SAM model, which implies that it may be improper to utilize the SAM model for the SAR evaluation of 5G mobile phone antennas.

5 | CONCLUSION

In this paper, a high-resolution anatomical head model with tissues including muscle, skull, CSF and brain is developed to assess the applicability of the traditional SAM model for SAR evaluation of mobile phone antennas. Three different generation mobile phone antennas are designed for SAR simulation. Numerical experiments show that the peak values of 1 g spatial average head SAR obtained by the SAM model are higher than the high-resolution anatomical model for 2G and 4G mobile phone antennas, which proves the conservativeness of the SAM model. However, the SAR value obtained by the anatomical head model is higher than the SAM model for a 5G mobile phone antenna. So new head model may need to be developed for the SAR evaluation of 5G mobile phones antennas. This paper can provide a reference for the update of standards and guidelines for SAR evaluation.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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