

Averaging Method for Epithelial/Absorbed Power Density in Irregular Skin Models for 5G Antennas

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Abstract—This paper provides a novel averaging method for calculating the epithelial/absorbed power density (EPD/APD) in irregular body parts to evaluate the electromagnetic field (EMF) exposure irradiated by 5G handset antennas. The irregular skin model is divided into voxels based on a defined step size, with different weights assigned to surface voxels to determine the integral region. A typical ear model and a patch array antenna were utilized for dosimetry analysis. The results show that the SAR distribution is more dispersed on irregular skin surfaces. In addition, the choice of three different locations for post-processing the power absorption integral volume may cause deviations in the averaged EPD/APD values. As the antenna-to-skin distance increases, these values are gradually converged due to the clustered EMF power distribution.

I. INTRODUCTION

The IEEE International Committee on Electromagnetic Safety (ICES) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP) have revised their standards and guidelines in 2019 and 2020 [1], [2], respectively. The dosimetric reference limit (DRL) and basic restrictions (BR) were derived with large safety margins to prevent whole-body and localized tissue heating. Below 6 GHz, the DRL/BR for local exposure is the specific absorption rate (SAR), averaged over 10 g of body tissue. Above 6 GHz, owing to reduced penetration depth, the corresponding metric is the epithelial/absorbed power density (EPD/APD).

For EPD/APD assessment, plane waves [3] and antennas [4], [5], as sources of radiation on simplified skin models have been investigated. However, for localized EMF exposure on complex body parts, there is still room for breakthroughs in the spatially averaged EPD/APD (hereafter referred to as *sAPD*) post-processing, to achieve a higher correlation with the resultant skin temperature elevation. Reference [6] discusses methods for averaging APD on nonplanar models for localized EMF exposure at 10–90 GHz. Reference [7] evaluated the APD and temperature rise of nonplanar body models above 6 GHz and compared different voxelization schemes for APD calculation. Reference [8] applied an averaging technique to calculate APD for a realistic ear model exposed to plane waves, and compared the APD definitions in the ICNIRP and IEEE standards.

In this study, a novel method for post-processing *sAPD* on an irregular skin surface is proposed and validated with a realistic ear model in a call scenario. The *sAPD* obtained using the proposed algorithm consistently provide more conservative and highly accurate values, which will be useful

for developing compliance test systems for MMW user equipment.

II. ANALYTICAL MODEL AND AVERAGE METHOD

A. Ear model and 5G Handset Antenna

In this study, we consider a realistic 3D geometry from the Bio Models Library of CST Studio Suite 2023, as shown in Fig. 1(a) and (b). The dimensions of the model match those of an adult head, with the length and width of the ear model set to 77.9 mm and 50.3 mm. The permittivity and conductivity of the model correspond to human dry skin at 28 GHz: $\epsilon_r = 16.55$, $\sigma = 25.82$ S/m [9].

Fig. 1(c) shows the antenna configuration mounted on a 5G handset used in this work. The substrate is Rogers RT/Duroid 5880 with a dielectric constant of $\epsilon_r = 2.2$ and a substrate thickness of $H = 0.252$ mm. The 1×4 patch array are placed on the substrate layer with an 8 mm spacing between each patch, and dimension of each patch is $3.2 \text{ mm} \times 3.2 \text{ mm}$. The operating frequency is set at 28 GHz, the rotation angle θ is set at 15° , and the antenna total input power is set to 10 mW.

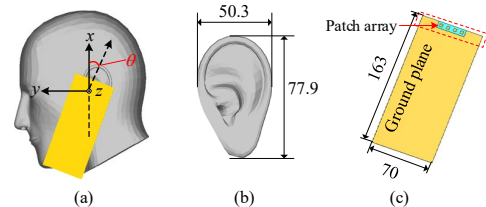


Figure 1. Human model and antenna configuration. (a) The human model. (b) The realistic ear model. (c) The configuration of 1×4 patch array.

B. Averaging Method of APD in Irregular Models

According to ICNIRP 2020 [2], The calculation method of the *sAPD* is as follows:

$$sAPD = \frac{1}{A} \iint_A dx \cdot dy \int_0^{z_{\max}} \rho(x, y, z) \cdot SAR(x, y, z) dz \quad (1)$$

where z is the depth of the skin, the body surface is $z = 0$, $z_{\max}$ is much larger than the penetration depth, A is the averaging area, and ρ and SAR represent the human tissue mass density (kg/m^3) and the local SAR (W/kg) at location (x, y, z) , respectively.

A method for estimating the surface area of the 3D nonplanar model was proposed in [7], which assigns surface area weights to each boundary voxel. In this study, we further

apply the proposed voxelization method to complex and irregular skin models.

Fig. 2(a) shows the longitudinal map of the model after voxelization. The gray squares are located in the average area A to be calculated. The red square is situated in the center of the model. L_1 is determined by the shape of the model surface, L_2 , L_3 and L_4 are parallel to the grid axis. Fig. 2(b) shows a projection of the surface area of the model. The A increases to the reference area A_S by extending outward from the center by the length l , where A_S is equal to 1 cm^2 and 4 cm^2 .

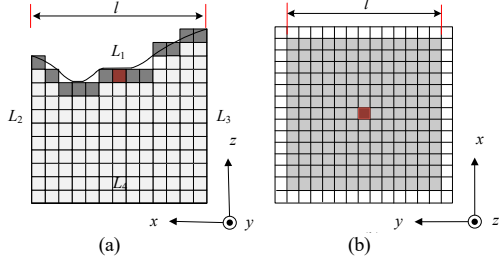


Figure 2. Integral area of the voxelization model. (a) Longitudinal map. (b) Surface projection map.

The average area A is the sum of the uppermost boundary voxels shown in Fig. 2. Five types of boundary voxels are available: s_1 , s_2 , s_3 , s_4 , s_5 . The surface area weight corresponding to each type of boundary voxel is w_k , where $k = 1, 2, 3, 4, 5$. The area of each boundary voxel can be expressed as follows:

$$S(x, y) = w_k \times dx \times dy \quad (2)$$

where the weights are $w_1 = 0.894$, $w_2 = 1.3409$, $w_3 = 1.5879$, $w_4 = 2$, $w_5 = 2.6667$ [10]. Then, the surface area in the APD calculation can be expressed as follows:

$$A = \sum_{i=1}^N S(x, y) \quad (3)$$

where N represents all voxels in the integral area.

In this study, we examine $sAPD$ for three locations of SAR aggregation on the ear model, Location 1 is directly below the center of the antenna. Location 2 is the peak SAR. These two locations are most likely having the maximum $sAPD$. However, on the complex and irregular surface, the peak SAR is likely to appear at sharp points, where SAR aggregation does not occur. Therefore, we also consider Location 3, where the EMF energy is the most concentrated, aside from Location 1 and Location 2.

III. ANALYTICAL RESULTS

Figure 3 shows a box plot of the calculated $sAPD$ variation with distance for three locations and compares the variation induced by the three locations at different distances. Figs. 3(a) and (b) illustrate the results of $sAPD$ for 1×4 patch array with $A_S = 1 \text{ cm}^2$ and 4 cm^2 , respectively. In Fig. 3, the heights of the rectangular boxes represent the interquartile range (IQR). The error lines represent 95% confidence interval (CI), and values within this range are considered normal. In Fig. 3, for the $1 \times$

4 patch array, as d increases, the IQR gradually reduction from 3.45 to 1.39, indicating that the $sAPD$ values at the three locations are gradually converging.

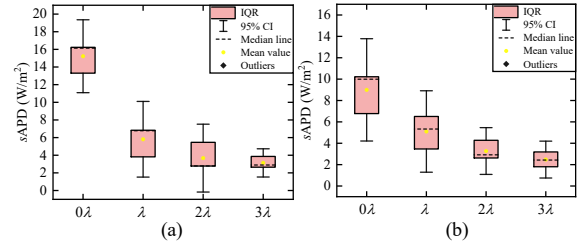


Figure 3. $sAPD$ as a function of antenna-to-skin distance d (λ) considering the variation caused by different locations. (a) $A_S = 1 \text{ cm}^2$. (b) $A_S = 4 \text{ cm}^2$.

IV. CONCLUSION

In this paper, a novel APD averaging method based on a voxelization model is proposed, which can be used to calculate APD for arbitrarily complex and irregular human models. Using a call scenario as an example, the EM radiation from the array antenna to the human ear is investigated. We consider three key locations to examine the effect of location on $sAPD$, and the results show that the IQR for $sAPD$ at the three locations gradually decreases as the distance increases, indicating an increasing concentration of EMF energy.

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