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Safety Consideration for Emerging Wireless Technologies - Evaluations of Temperature Rise in Eyes for RF Radiations up to 10 GHz

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***Abstract*—The study of temperature rise distribution in the human eye under plane electromagnetic wave exposure up to 10 GHz is presented in this paper. The effects of different frequencies and different blood perfusion rates of sclera to thermal calculations are investigated by finite difference method. The results reveal that the changes in the thermal parameter produce a maximum relative standard deviation of ~15% in the temperature rise in lens.**

***Keywords*—electromagnetic safety; radio frequency; thermal parameter**

I. Introduction

Due to the widespread use of wireless communication devices, there is an increasing concern of human safety issues related to Electromagnetic (EM) energy absorption in sensitive human organs [1]. Previous wireless technologies commonly use frequency band below 6 GHz, recently, there is a trend of adopting higher frequencies for wireless communications to support wider bandwidth, hence higher data transfer rate.

The human eyes, as a temperature-sensitive organ, have attracted many research attentions over the last decade. It has been shown that the formation of cataracts is related to acute radio frequency (RF) radiation [2]. It has also been summarized by international commission on non-ionizing radiation protection [3] that, under intense electromagnetic exposure, significant thermal damage would occur in sensitive tissues such as the eyes and the testis. Tissue heating effect in this frequency band, extending to 300 GHz, has been recognized by international standards as the basis for limiting the exposures.

Studies on the EM power absorption and temperature rise in human eyes have been investigated previously using numerical methods. In these numerical calculations, precise values of the EM and thermal parameters of human tissues are required. However, different datasets have revealed varied parameters, for example, the blood perfusion rate of sclera are different between [4] and [5]. The changes in thermal parameters of human tissues will alter the heat transfer rate between eyeballs and surrounding tissues, hence affects the results of temperature calculations.

In addition, previous studies mainly focus on frequencies below 6 GHz, due to the limited spatial resolution of human models. In this study, with a refined human eye model, the effect of different blood perfusion rates of sclera on the thermal evaluations have been investigated for RF EM exposure up to 10 GHz.

II. Models and Methods

A. Human Head Model

Voxel human models have been widely used in previous dosimetry studies, but the spatial resolutions of these models are not fine enough for numerical EM calculations up to 10 GHz. In this paper, the generic eye model developed in [6] is adopted. This eye model is discretized to 0.25 mm resolution and then inserted into the Japanese head model [7], which is first resampled at 0.25 mm resolution, and hence forms a closed-eye human head model with spatial resolution of 0.25 mm.

B. Methods

Finite-difference time-domain (FDTD) method is adopted for the evaluations of SAR. The radiation source is a plane-wave with a power density of 100 W/m^2, radiates from the front of the head model. The SAR in different tissues of the head is calculated using following equation:

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

where σ, ρ are the conductivity and density of the tissue, and E is the peak value of the electric field strength. The calculated SAR are then used as heat sources for the evaluations of the temperature rise using steady-state bio-heat equation [7]:

$$\nabla \cdot (k \nabla \Delta T) - B\Delta T + \rho \cdot SAR = 0 \quad (2)$$

where k is the thermal conductivity (W/(m·°C)), the value of B is related to the blood perfusion rate (W/(m^3·°C)), and ΔT is the steady-state temperature rise. The boundary condition is:

$$k\frac{\partial \Delta T}{\partial n} + H\Delta T = 0 \quad (3)$$

where $\partial \Delta T / \partial n$ is directional derivative of ΔT normal to the body surface, H is the convection coefficient, which is set to be 20 W/(m^2·°C) for the air-eye interface, and 8 W/(m^2·°C) for the air-skin interface.

The thermal parameters of the human tissue for the temperature rise calculation are mainly adopted from IT'IS dataset [5], and are listed in Table I. The blood perfusion rate of the sclera is found to be 2.48×10^4 W/(m^3·°C) in [5], while an equivalent blood perfusion rate for compound retina/choroid/sclera tissue has been estimated to be 0.8×10^5~1.6×10^5 W/(m3·°C) [4]. In this paper, in order to investigate the effect of the thermal parameters of sclera, different blood perfusion rates are adopted as shown in Table I.

III. Results

The SAR values are first calculated using FDTD method; the temperature rise in human tissues are then calculated using finite difference method (FDM) taking the SAR as heat sources. Fig. 1 shows the temperature rise distributions inside the eye at some selected frequencies. As can be seen from Fig. 1, at higher frequencies, the hotspots of temperature rise tend to locate in the frontal part of the eyeball, due to the shallower penetration depth.

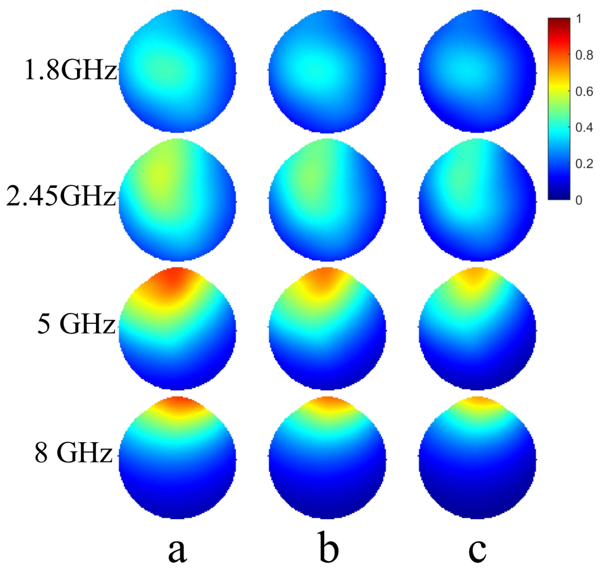

Fig. 1. Temperature rise distributions inside eyeball for different frequencies and blood perfusion rates of sclera: a: B=2.48×10^4 W/(m^3·°C), b: B=0.8×10^5 W/(m^3·°C), c: B=1.6×10^5 W/(m^3·°C).

Table II summarizes the maximum temperature rises in the lens. It can be seen that, as expected, higher blood perfusion of sclera increases the heat transfer rate between the eyeballs and surrounding tissues, and then leads to lower temperature rise in lens.

TABLE I. Thermal Parameters of Eye Tissues

Tissue	Thermal conductivity k (W/(m·°C))	Coefficient related to blood perfusion rate B (W/(m^3·°C))
Aqueous humour	0.59	0
Cornea	0.54	0
Iris	0.58	2.48×10^4
Lens	0.43	0
Sclera	0.58	A. 2.48×10^4 B. 0.8×10^5 C. 1.6×10^5
Vitreous humour	0.59	0

TABLE II. Maximum Temperautre Rise in Lens

Frequency (GHz)	Maximum Temperature Rise in Lens (°C)			
	B=2.48×10^4 W/(m^3·°C)	***B=0.8×10^5 W/(m^3·°C)***	***B=1.6×10^5 W/(m^3·°C)***	***Relative SD***
0.9	0.36	0.31	0.26	15.1%
1.8	0.38	0.33	0.29	13.5%
2.45	0.57	0.51	0.45	12.2%
3	0.64	0.58	0.51	11.3%
4	0.65	0.58	0.51	12.2%
5	0.88	0.79	0.71	10.5%
5.8	0.82	0.75	0.67	10.1%
7	0.77	0.69	0.63	9.9%
8	0.67	0.61	0.55	10.0%
9	0.62	0.56	0.50	10.5%
10	0.61	0.55	0.49	10.7%

IV. Discussions

A. Effect of resampling voxel head model

To validate the approach of resampling a low-resolution model for high resolution implementation, solutions obtained by using the same Japanese head model of 2 mm and 0.25 mm resolutions are compared. The calculated SARs are listed in Table III.

It is found that changes in the resolution would lead to differences in the peak local SARs between models of different spatial resolutions, but the averaged SARs are very close. This can be expected as the geometries of the resampled model are essentially the same as those of the original model, and resampling at a higher resolution does not alter the staircasing approximation of the physical boundaries of the original model. Similar findings have also been reported by [9], where the SARs for a 1.9 mm resolution model and the resampled model at 0.95 mm resolution have been compared.

TABLE III. COMPARISONS OF SAR VALUES FOR MODELS WITH DIFFERENT RESOLUTIONS

SAR Type	**SAR Value (W/kg)**	
	Original model Resolution - 2 mm	***Resampled model Resolution - 0.25 mm***
Eye averaged SAR	2.89 W/kg	2.93 W/kg
Cornea averaged SAR	3.92 W/kg	3.75 W/kg
Vitreous humour averaged SAR	2.90 W/kg	2.95 W/kg
Lens averaged SAR	2.14 W/kg	2.21 W/kg
Peak local SAR	25.08 W/kg	88.34 W/kg

B. *Effect of blood perfusion rate of sclera*

The effect of changing blood perfusion rate of sclera can be seen from Fig. 1 and Table II. In this study, the blood perfusion rate varies from 2.48×10^4 to 1.6×10^5 W/(m^3·°C). As shown in Fig. 1, higher blood perfusion rate of sclera leads to lower temperature rises inside the eyeballs, and the relative standard deviations (SD) of temperature rises in lens are all within 15% at about 0.9 GHz.

V. CONCLUSION

In this paper, the study of temperature rise distribution in the human eyes under plane electromagnetic wave exposure is presented from baseband to 10 GHz. The results reveal that the changes in the thermal parameter produce a maximum relative standard deviation of 15% in the temperature rise in lens.

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