Evaluation of Temperature Elevation in Human Ocular Tissues due to Wireless Eyewear Devices

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Abstract ─ In this paper, a numerical study is proposed to evaluate the temperature variation in the human ocular tissues during the electromagnetic radiation exposure from wireless eyewear device. The results show that the temperature in the whole eyeball increases gradually as the exposure time goes on and could reach the thermal steady state at about 30 minutes. During this process, the temperature increments in different ocular tissues are between 1.1℃ and 1.7℃. The results also show the maximal ratio of temperature increments in the initial 5 and 10 minutes to that of the whole steady state could reach to 42.9% and 69.2%, respectively. Therefore, we believe that electromagnetic radiation from wireless eyewear device might pose a threat on the health of the human eyes. People should decrease the talk time as soon as possible to protect their eyes from the possible health hazards. Finally, attention is paid to evaluate the relationship between the maximal SAR and the temperature increments. The results show the temperature increments do not increase in direct proportion to the maximal SAR, which indicates that the maximal SAR and the temperature increments should be taken into account simultaneously while evaluating the biological effect of microwave on the ocular tissues.

Index Terms ─ FDTD, ocular tissues, temperature, wireless eyewear device.

I. INTRODUCTION

With the rapid development of the mobile communication technology, increasing interest has been paid to the wireless eyewear devices (EyeTrek Insight Smart glasses, Mad Gaze X5 and so on) [1-2]. Nevertheless, continuous and longtime electromagnetic (EM) radiation from the wireless devices close to the human head might give rise to adverse physiological damage, such as headache and insomnia [3-6]. It even has been considered as the cause of cancer [7]. International organizations such as IEEE [8] and ICNIRP [9] have established the safety standards to protect human health from the EM exposures. The existing standards, however, only use the Specific Absorption Rate (SAR) which is defined as the absorption rate of EM power per unit mass to describe the extremely complex interaction between EM waves and human biological tissue. Moreover, the maximal SAR limits are not obtained by a precise quantitative process but just expert opinion which is designed to protect human body from adverse effects induced by the temperature elevation larger than the safety threshold of 1°C resulting from acute exposures. Hence, systematic quantitative research related with other parameters such as temperature, absorbed power and radiation frequency should be done [7, 10, 11]. Among them, temperature, in particular, might directly lead to physiological effects and damage. For example, brain lesions and blood chemistry change might happen when the temperature increments are between 1℃ and 5℃. Even 1℃ temperature elevation also might give rise to altered production of hormones and suppressed immune response [12]. Therefore, it is necessary to evaluate the temperature elevation due to wireless eyewear device [2].

There are many valuable researches that have evaluated the temperature rise in the human body during the EM exposure from wireless devices [13-20]. For example, Takei et al. [13] had evaluated the temperature elevation in pregnant women exposed to radiation of mobile phone. The results showed that the maximum temperature increments in fetuses were only half of those in pregnant women. Morimoto et al. [14] had studied the correlation between the peak SAR and temperature rise in the human head in the frequency range from 1 GHz to 30 GHz. Strong relationships were found between SAR and temperature rise by different algorithms. Diao et al. [15] had evaluated the influence of palpebral fissure on the variations in temperature elevation in human eyes under plane wave EM exposures. Results showed that the changes in the palpebral fissure would induce a 0.23 °C variation in the maximum temperature elevation in the human lens. Li et al. [16] had demonstrated that the elongated ocular axial length could not give rise to the significant temperature rise in human eyes. Van Rhoon et al. [17] had determined the limits of thermal dose for MR exposure by investigating the temperature elevation

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in the brain. Buccella et al. [18] had evaluated the effects of different radio frequency sources on the SAR and temperature increments in the human eyes and found the maximum temperature elevation in the lens could reach to 1.6℃. Van Leeuwen et al. [19] found the maximal temperature elevation of 0.11°C in the human brain when people use the mobile phone with 0.25 W radiated power. Wang et al. [20] had evaluated the temperature rise in the human brain exposed to the mobile phone and found the temperature increments of the peak temperature is 0.06℃ and 0.02℃ under the maximal EM radiation dose of IEEE guidelines and ICNIRP standards. So far, a few studies [2, 10, 21] have also been done to evaluate the influence of EM radiation of wireless eyewear device on the human body. They, however, mainly focus on the SAR and the absorbed power in the human head.

Based on the above reasons, this paper would mainly evaluate the temperature elevation in the human head during the EM exposure from wireless eyewear device. We would mainly focus on the human ocular tissues because they are more sensitive to EM fields [4, 22]. This is because eyes, unlike other tissues with the protection of skin, fat and so on, are directly exposed to the EM radiation. Meanwhile, eyes could not dissipate the heat timely induced by the EM thermal effects due to the lower blood flow. Thirdly, once ocular tissues are damaged, they could not return to be healthy because human ocular tissues except the cornea lack the self-renewal ability. A three-dimensional anatomical CAD human head model is established in this paper, which consists of skin, fat, brain and eyeballs including eight kinds of tissues. We designed a printed coupling element (CE) antenna to act as the wireless eyewear device. It covers 0.75-0.93 with a -6dB S11. A metallic glasses model is established to support the wireless eyewear device. The calculated results, in this paper, could provide valuable data for the establishment of related safety standards and future researches in the biological effect of microwave and human eyes.

II. SIMULATION MODELS AND MATERIALS

A. Head model

To evaluate the temperature elevation in the human ocular tissues, a three-dimensional anatomical CAD human head model, in this paper, is established. This model is shown in Fig. 1 which comprises of skin, fat, brain and eyeball. Comparing with the Visible Human Project or Magnetic Resonance Imaging model, the CAD model could provide the higher resolution to precisely characterize the eyeball with complex structure. Figure 2 shows the cross-section of eyeball which is made of eight kinds of ocular tissues.

The dielectric properties at 0.915GHz and density corresponding to variety of biological tissues for the following calculation are displayed in Table 1 [22-32]. ε_r and σ represent the relative dielectric constant and conductivity, respectively. The thermal parameters of the tissues used in this study are given in Table 2, which are obtained from those in [30, 33]. C and K represent specific heat and thermal conductivity, respectively. A is the basal metabolic rate. B is associated with blood perfusion. The new blood perfusion and metabolic rate of retina are used here. From these data, it could be found choroid has the highest blood perfusion and metabolic rate among the ocular tissues due to its high vascularization. Because of the continual photoreceptor requirement for vision, retina, as well, has the relative higher metabolic rate.

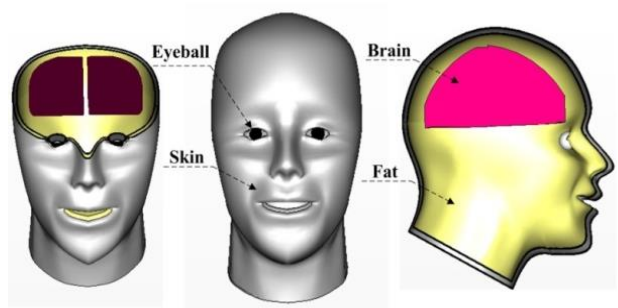

Fig. 1. Human head model.

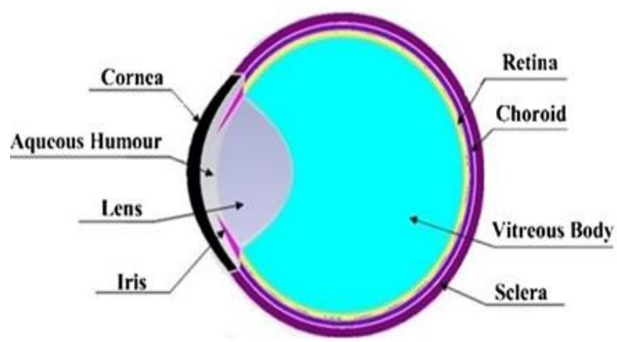

Fig. 2. Cross-section of eyeball.

Table 1. The dielectric properties and density of tissues in the human head model

Biomaterial	ε_r	σ (S/m)	ρ (kg/m^3)
Cornea	51.5	1.9	1050
Iris	55	1.18	1040
Air	1	0	0.0016
Skin	45	0.97	1100
Choroid	55	2.3	1000
Lens	44	0.8	1150
Sclera	51	1.13	1020
Aqucous Humor	74	1.97	1010
Vitreous Body	67	1.68	1030
Retina	57	1.17	1000
Fat	15	0.35	920

Table 2: Thermal properties of tissues

Biomaterial	C (J/(kg ℃))	K (W/(m ℃))	A (W/m^3)	B (W/(℃ m^3))
Cornea	4200	0.58	0	0
Iris	4178	0.58	0	0
Skin	3500	0.42	1000	9100
Choroid	3900	0.51	20000	85000
Lens	3000	0.4	0	0
Sclera	4200	0.58	0	0
Aqueous Humor	3997	0.58	0	0
Vitreous Body	4178	0.58	0	0
Retina	3700	0.56	2500	9500
Fat	2500	0.25	180	520

B. Glasses model

The wireless eyewear device is usually placed on one side of the eye by fixing on the glasses, ear and so on. Glasses is always selected as the main choice due to the reason that myopia as a typical epidemic has higher morbidity rate around the world. It is predicted that there will be 2.5 billion people with myopia by 2020 [34]. Therefore, maybe half of wireless eyewear device users would choose glasses. The glasses model, used in this paper, is shown in Fig. 3. Compared with the previous research [2] that only considers the single metallic frame, this model includes spectacle frame, spectacle lens and nose pad. The distances between two arms are 155mm. The thickness of spectacle frame is 1 mm. Polyimide (εr=3.5, σ=0.03) and Glass (εr=4.82, σ=0.0054) are selected as the materials of nose pad and spectacle lens, respectively. The spectacle frame uses the metal material rather than the plastic for the following reasons. Firstly, the metal frame has good ductility and could not lose its form with daily use comparing with the plastic frame. It is more suitable for supporting the printed circuit board (PCB) of the eyewear device. Furthermore, the former study [35] had proved the variation in conductivity posed negligible variation to the SAR in the human head, hence this paper would use the copper as the material of spectacle frame.

C. Antenna model

As is shown in Fig. 4, a printed CE antenna designed for eyewear device [1, 2] is employed in this paper. The CE is on the one side of the FR4 PCB, which is adjacent to the eyes. The ground plane is printed on the other side of the PCB. The antenna is fed by a three-elements matching network which is comprised of a shunt capacitor and two series inductors. By adjusting the matching network, the antenna could be transformed into the desired operating band. The S_{11} is displayed in Fig. 5, which covers the 0.75-0.93GHz with a -6dB S_{11}. The input power is 0.125W since a GSM terminal only transmits for one-eighth of the time.

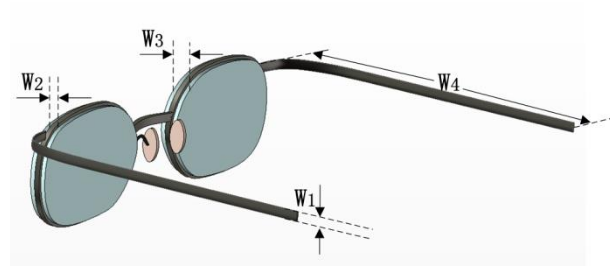

Fig. 3. Model of glasses.

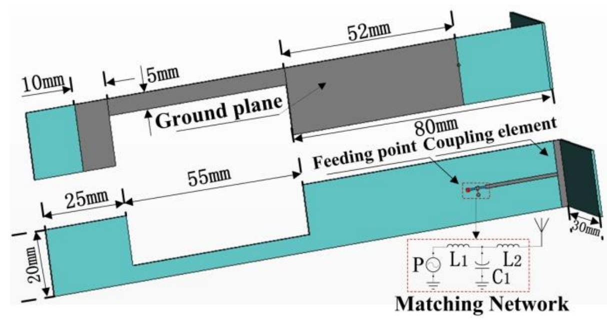

Fig. 4. Antenna model for eyewear device.

III. CALCULATION METHODS

A. EM modeling

The electromagnetic problem is calculated by solving the time-harmonic Maxwell Equations based on the FDTD method [36-38]. The computational region is divided by regular hexahedron grids. The sub-grids method is used to obtain the finer resolution by inserting the small grids into the larger one. For ease of understanding, we introduce the sub-grids method used in the two-dimensional TE propagation mode. The discretized equations are as follows:

$$H_x^{n+\frac{1}{2}}\left(i,k+\tfrac{1}{2}\right)=H_x^{n-\frac{1}{2}}\left(i,k+\tfrac{1}{2}\right)+\frac{c\Delta t}{Z_0\Delta z}\left[E_y^n(i,k+1)-E_y^n(i,k)\right], \tag{1}$$

$$H_z^{n+\frac{1}{2}}\left(i+\tfrac{1}{2},k\right)=H_z^{n-\frac{1}{2}}\left(i+\tfrac{1}{2},k\right)-\frac{c\Delta t}{Z_0\Delta z}\left[E_y^n(i+1,k)-E_y^n(i,k)\right], \tag{2}$$

$$E_y^{n+1}(i,k)=E_y^n(i,k)+\frac{Z_0c\Delta t}{\Delta z}\left[H_x^{n+\frac{1}{2}}\left(i,k+\tfrac{1}{2}\right)-H_x^{n+\frac{1}{2}}\left(i,k-\tfrac{1}{2}\right)\right]-\frac{Z_0c\Delta t}{\Delta x}\left[H_x^{n+\frac{1}{2}}\left(i+\tfrac{1}{2},k\right)-H_x^{n+\frac{1}{2}}\left(i-\tfrac{1}{2},k\right)\right], \tag{3}$$

where E and H are the electric fields strength (V/m) and magnetic fields strength (A/m). i and k refer to the Cartesian coordinates x and z, respectively. Δt is the time step. Δx and Δz are the spatial step in the x and z direction, respectively. On the basis of the sub-grids method, the fields across the interfaces between coarse grids and fine grids should be continuous. In addition, the local uniformity is vital to keep the same stability criterion. Thirdly, the grids ratio between coarse grids and fine grids should be equal to the time increment ratio.

This paper uses the 0.2mm resolution for eyeball which could represent each ocular tissue with ultra-thin millimeter-scale membrane structure separately. The resolution of 0.5mm is used for the other parts of the human head tissues. The sub-grids method helps to achieve the required computational accuracy using as little computation load as possible [39]. The uniaxial perfectly matched layer boundary with 5 cells thick is used to truncate the computational domain. The relative accuracy is 10^{-5}.

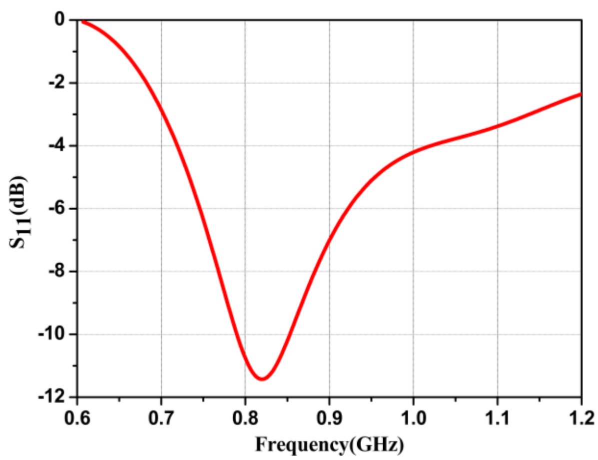

Fig. 5. S_{11} of the antenna with head model shown in Fig. 6 (L_1=9.5nH, L_2=11nH, C_1=0.95PF).

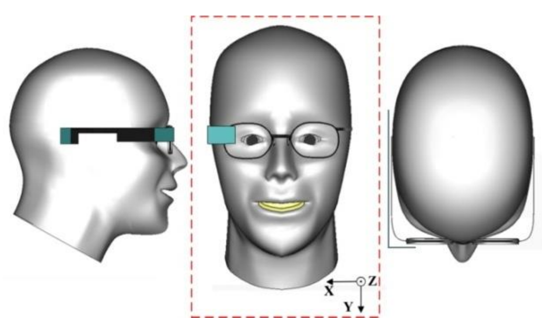

Fig. 6. Model of phone call state with glasses.

B. Thermal modeling

The temperature elevation inside the human head exposed to the EM fields from wireless eyewear device could be calculated by solving the Bioheat Equation [40]:

$$C(\vec{r})\rho(\vec{r})\frac{\partial T(\vec{r},t)}{\partial t} = \nabla\cdot\left(K(\vec{r})\nabla T(\vec{r},t)\right) + \rho(\vec{r})\cdot SAR(\vec{r}) + A(\vec{r},t) - B(\vec{r},t)\left(T(\vec{r},t) - T_b(\vec{r},t)\right). \quad (4)$$

It includes kinds of heat exchange mechanisms such as heat conduction, blood perfusion and EM heating. In Equation 4, $\rho(\vec{r})$ is the density in kg/m^3. SAR (W/kg) is obtained by:

$$\mathrm{SAR}(\vec{r}) = \frac{\sigma\left|\vec{E}(\vec{r})\right|^2}{\rho(\vec{r})}, \quad (5)$$

where $\vec{E}$ is the peak value of the electric fields strength vector. σ is the conductivity in S/m. To calculate SAR for 1 g, we add contributions of several Yee's meshes to 1 g around the cube of the maximum SAR (In this paper, all SAR refers to the SAR for 1 g.). $\vec{r}$ and t are the position vector and time, respectively. $T(\vec{r},t)$ and $T_b(\vec{r},t)$ represent the temperature of human tissues and blood, respectively. $T_b(\vec{r},t)$ is assumed to be constant of 37□ due to the reason that the EM power absorption from eyewear device is much smaller than the metabolic heat power [41].

The boundary conditions are applied on the interfaces of skin–air and cornea–air, which could be calculated by [42-43]:

$$-K(\vec{r})\frac{\partial T(\vec{r},t)}{\partial n} = -H\left(T_s(\vec{r},t) - T_e(\vec{r},t)\right), \quad (6)$$

where $T_s(\vec{r},t)$ and $T_e(\vec{r},t)$ represent the surface temperature of the biological tissues and the temperature of air. The convection coefficient of skin–air and cornea–air are assumed to be 10.5 and 20 (W/(m^2°C)) under the condition of T_e =23°C which takes into account the evaporation of tear film and perspiration, the convective and radiation exchange with the surrounding objects.

The forward Finite Difference scheme is adopted in solving the equation 4, as:

$$T(\vec{r},t)^{n+1}_{i,j,k} = \frac{K(\vec{r})}{C(\vec{r})\rho(\vec{r})\Delta^2}\Delta t\Big[T(\vec{r},t)^n_{i-1,j,k} + T(\vec{r},t)^n_{i+1,j,k} + T(\vec{r},t)^n_{i,j-1,k} + T(\vec{r},t)^n_{i,j+1,k} + T(\vec{r},t)^n_{i,j,k-1} + T(\vec{r},t)^n_{i,j,k+1}\Big] + T(\vec{r},t)^n_{i,j,k}\left\{1 - \left(\frac{N_i K(\vec{r})}{C(\vec{r})\rho(\vec{r})\Delta^2} + \frac{N_e H}{C(\vec{r})\rho(\vec{r})\Delta} + \frac{B(\vec{r},t)}{C(\vec{r})\rho(\vec{r})}\right)\right\}\Delta t + \frac{N_e H \Delta t T_e}{C(\vec{r})\rho(\vec{r})\Delta} + \frac{\Delta t}{C(\vec{r})\rho(\vec{r})}\left[\rho(\vec{r})\mathrm{SAR}(\vec{r})_{i,j,k} + \mathrm{A} + T_b\right]. \quad (7)$$

Here, the temperature node locates in the centre of the cell. Δ is the spatial step. N_i and N_e represent the number of internal and external cells adjacent to the studied cell identified by *i*, *j* and *k* according to the Finite Difference notation. To ensure the stability of the algorithm, the Equation 7 must be satisfied in the whole computational domain:

$$\Delta t \le \left(\frac{N_i K(\vec{r})}{C(\vec{r})\rho(\vec{r})\Delta^2} + \frac{N_e H}{C(\vec{r})\rho(\vec{r})\Delta} + \frac{N_e H}{C(\vec{r})\rho(\vec{r})\Delta}\right)^{-1}. \quad (8)$$

This would lead to a long computational time when considering the thermal steady-state condition. But, in contrast, it needed much less computational resources than the FDTD calculation.

The initial temperature of the biological tissues without any EM field exposure is used to solve the bioheat equation. It could be obtained by the steady-state equation [40, 44-45]:

$$\nabla(K\nabla T) + A - B(T - T_b) = 0. \quad (9)$$

The Bioheat Equation is discretized by the same rectangular grids used in the FDTD calculations [46-47]. The iteration did not stop until the relative residual of the solution was less than 10^{-7}.

IV. RESULTS AND DISCUSSIONS

We firstly evaluate the temperature variation in the ocular tissues during the EM exposure from wireless eyewear device. Fig. 7 shows the temperature distribution via two orthometric cross-sections (XY plane and YZ plane shown in Fig. 6) of eyeballs. We can see that the temperature in the whole eyeball increases gradually as the time goes on and reaches the steady state at about 30 minutes. Moreover, the closer to the cornea–air boundary the location in the eyeball is, the lower the temperature is. The temperature differences increase gradually with the increasing time. This is mainly due to the reason of heat exchange on the cornea–air boundary induced by the temperature differences.

We, as well, evaluate the temperature increments in the given time intervals (5 minutes) in the ocular tissues when people use the wireless eyewear device and show the results in the Table 3. We find the temperature increments of the maximal temperature in the ocular tissues are from 1.1℃ to 1.7℃ within 30 minutes. The results also show that the maximal ratio of temperature increments in the initial 5 and 10 minutes exposure time to that of the whole steady state could reach to 42.9% and 69.2%, respectively. Based on the above results, we believe EM exposure from wireless eyewear device may pose a threat on the health of the eyes, especially for the lens which suffer from the maximal temperature increments in the whole process to reach the steady state. Wireless eyewear device users should shorten the usage time as soon as possible to protect their eyes form the possible health hazards. The calculated results could provide valuable data for the establishment of related safety standards for wireless eyewear device.

Finally, this paper evaluates the relationship between the maximal SAR [21] and the temperature increments (in 30 minutes) in the ocular tissues during the EM exposure from wireless eyewear device. The computed results are shown in Fig. 8. We find that the temperature increments do not increase in direct proportion to the maximal SAR. On the contrary, the ocular tissues such as lens with the least value of the maximal SAR have the maximal temperature increments. This is because the temperature increments are the complex process with many factors involved. Not only does it depend on the SAR, the material properties and structure parameters of the ocular tissues, but also the heat flow among the tissues. Therefore, the maximal SAR and the temperature increments should be taken into account simultaneously while evaluating the biological effect of microwave on the ocular tissues.

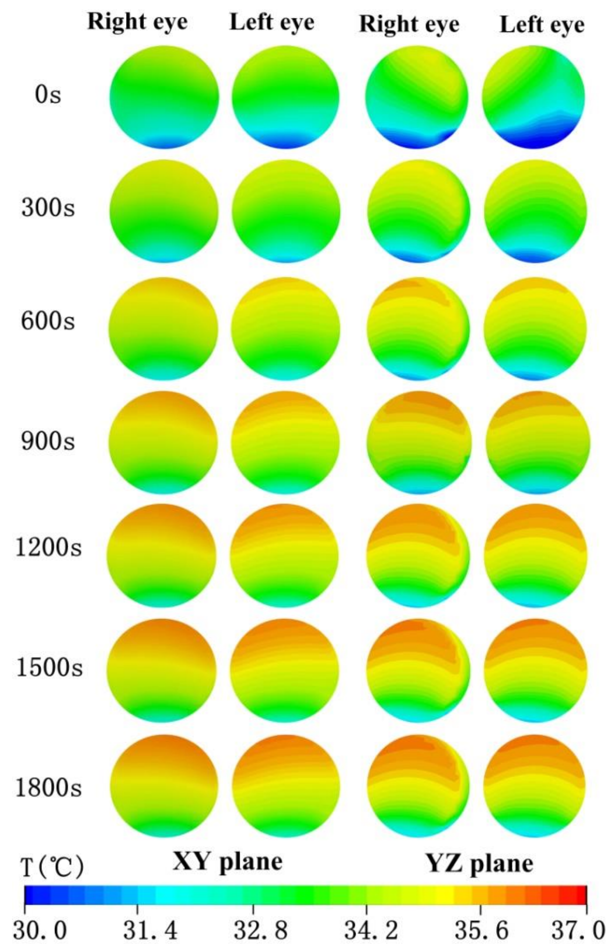

Fig. 7. Temperature distribution in the eyeballs.

Table 3. The maximal temperature Tmax (℃) at different times in the ocular tissues during the EM exposure from wireless eyewear device.

	Time (minutes)						
	0	5	10	15	20	25	30
Vitreous body	34.85	34.95	35.45	35.65	35.75	35.85	35.95
Aqueous humor	31.85	32.45	32.75	33.05	33.15	33.25	33.25
Sclera	34.85	34.95	35.45	35.65	35.85	35.85	35.95
Iris	31.55	32.05	32.45	32.65	32.75	32.75	32.85
Cornea	31.85	32.35	32.75	32.95	33.05	33.05	33.15
Lens	32.25	32.85	33.35	33.55	33.75	33.85	33.95
Choroid	34.85	35.05	35.45	35.65	35.75	35.85	35.95
Retina	34.75	34.95	35.35	35.65	35.75	35.85	35.85

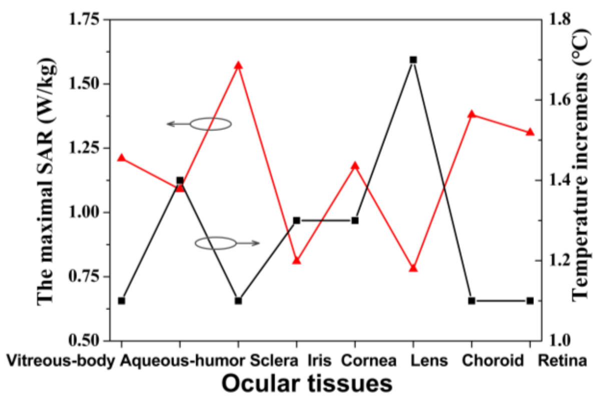

Fig. 8. The maximal SAR and the temperature increments in the ocular tissues.

V. CONCLUSION

Based on the results evaluated in this paper, we find that the temperature in the whole eyeball increases gradually and reaches the thermal steady state at about 30 minutes during the EM exposure of wireless eyewear device. The temperature increments in different ocular tissues are from 1℃ to 1.7℃. We, therefore, believe EM exposure from wireless eyewear device may pose a threat on the health of the eyes, especially for the lens which suffer from the maximal temperature increments. Meanwhile, the results also show that the maximal ratio of temperature increments in the initial 5 and 10 minutes exposure time to that of the complete thermal steady state could reach to 42.9% and 69.2%, respectively. Hence, wireless eyewear device users should shorten the usage time as soon as possible to protect their eyes from the possible health hazards. Finally, we evaluate the relationship between the maximal SAR and the temperature increments in the ocular tissues. We find that the temperature increments do not increase in direct proportion to the maximal SAR. Therefore, we believe the maximal SAR and the temperature increments should be taken into account simultaneously while evaluating the biological effect of microwave on the ocular tissues. This paper could provide valuable data for the establishment of related safety standards and future researches in the biological effect of microwave and human eyes. However, limited by the experimental condition, the experiment is not included. Therefore, conclusions presented in this paper are just indicative but not definitive.

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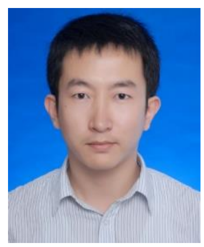

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