Temperature elevation in the eye of anatomically-based human head models for plane-wave exposures

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Abstract:

This study investigated the temperature elevation in the eye of anatomically-based human head models for plane wave exposures. The finite-difference time-domain method is used for analyzing electromagnetic absorption and temperature elevation. The eyes in the anatomic models have average dimensions and weight. Computational results show that the ratio of maximum temperature in the lens to the eye-average SAR (named 'heating factor for the lens') is almost uniform (0.112-0.147 ^{o}C· kg/W) in the frequency region below 3 GHz. Above 3 GHz, this ratio increases gradually with the increase of the frequency, which is attributed to the penetration depth of electromagnetic wave. Particular attention is paid to the difference in the heating factor for the lens between this study and earlier works. Considering causes clarified in this study, compensated heating factors in all these studies are found to be in good agreement.

1. Introduction

In recent years, there has been increasing public concern about adverse influence of electromagnetic (EM) waves on humans. It is well known that some significant thermal damage can occur in sensitive tissue under partial-body exposure to intense EM waves. The eye is one of the most sensitive organs due to microwave heating (Elder 2003). Guy *et al* (1978) investigated the possibility of microwave-induced cataract formation using rabbit eyes. Their results showed that microwave exposure of 2 – 3 h duration produced cataracts at lenticular temperatures of 41–43 ^{o}C, corresponding to a temperature elevation of 5–7 ^{o}C. On the other hand, no cataract formation was observed in monkey eyes (Kramar *et al* 1978). The same authors attributed this inconsistency to the differences in anatomical configuration and dimensions between rabbits and monkeys. Thus, it is essential to investigate the temperature elevation in the *human* eyes due to EM waves. So far, several researchers computed the temperature elevation in eyes of anatomically-based head model due to microwave (Hirata *et al* 2000, 2002, Hirata 2005, Flyckt *et al* 2007, Wainwright 2007, Buccella *et al* 2007) and millimeter-wave (Bernardi *et al* 1998) energy.

For microwave exposure, we investigated the effect of (i) frequency (Hirata *et al* 2000, Hirata 2005), (ii) polarization (Hirata *et al* 2000, Hirata 2005), (iii) angle of incidence of the microwave (Hirata *et al* 2002), and (iv) different sources (Hirata 2005) on SAR and temperature increase in the eye. As a result, these four factors were found not to be neglected, while the ratio of maximum temperature elevation in the eye to eye-average SAR (named 'heating factor' in Wainwright 2007) was almost constant under all conditions considered in Hirata (2005). The same tendency was observed in Wainwright (2007). Another point to be stressed here is that maximum temperature elevation has a possibility of exceeding 1^{o}C at the eye average SAR of 10 W/kg, which corresponds to a basic restriction in the ICNIRP guidelines (1998) for occupational exposure. It should be noted that the ICNIRP guidelines protect humans from excess localized temperature elevation (1-2 ^{o}C) due to microwave heating. The heating factors for the lens were 0.152-0.175 $^{\circ}\mathrm{C/W\cdot kg}$ in Hirata (2005), 0.152-0.175 $^{\circ}\mathrm{C/W\cdot kg}$ in De Buccella *et al* (2007), 0.089-0.130 $^{\circ}\mathrm{C/W\cdot kg}$ for discrete vascular and bioheat model in Flyckt *et al* (2007), while the heating factor for *the whole eye* was 0.18-0.19 $^{\circ}\mathrm{C/W\cdot kg}$ in Wainwright (2007). Namely, the difference between these works is not neglected. Flyckt *et al* (2007) attributed main differences in the temperature elevation with Hirata (2005) to the difference of i) the mass of the eye and ii) the blood perfusion rate around the eye considered in previous studies. The former is because the eye diameter was about 30 mm (11.3cm^3) in Hirata (2005), while average diameter of human eye is 25-26 mm, corresponding to 7.5 g (ICRP 1975). However, no investigation has been conducted to clarify their hypothesis. The latter would be because anesthetized rabbits were used for deriving the heat transfer coefficient between the eye and the surrounding region (Lagendijk 1982). This was based on the finding by Kojima *et al* (2004) that the effect of anesthesia on temperature elevation cannot be neglected. Additional possibility of the difference in the heating factor would be morphological difference around the eye.

Thus, it is worth re-investigating the temperature elevation in eyes of reliable human head models with appropriate thermal constants. In this study, Japanese male and female models are used (Nagaoka *et al* 2004), which were developed based on the standard Japanese. Our attention here focuses on the heating factor for the lens exposed to plane wave, comparing with those in the earlier works. This measure was shown to be insensitive to different exposure scenario (Hirata 2005, Wainwright 2007), making our discussion straightforward.

2. Method and Model

2.1. Human Head Models

Japanese male and female numeric models named TARO and HANAKO were used in this study (Nagaoka *et al* 2004). The original resolution of these models is 2 mm. The models are comprised of more than 50 tissues. For the analysis of thermal elevation in the eye, we selected the head and neck part only to save computational resources. Then, we rescaled the model resolution from the original 2 mm to 1 mm with the interpolation. Manual editing was applied to maintain the anatomical accuracy around the eye. A cross-sectional view of the rescaled HANAKO is given in Fig. 1. Note that the volume of the eye in the rescaled models is 6.9 cm^3, which is somewhat smaller than the average value of 7.5 cm^3. In order to match the computational eye mass to the average value, we changed the side length of cubic cells from 1 mm to 1.03 mm. The thickness of lens (4 mm) has been edited so as to have an average value of Japanese (Karino *et al* 1983)

It is noteworthy that the thickness of some eye tissues, such as the retina, choroid, and sclera are less than the spatial resolution of numeric head models. Thus, the retina, choroid, and sclera were considered as a compound tissue in the same way as Hirata *et al* (2006b) did for the rabbit model. Their average electrical and thermal constants were used in our calculation. Similarly, the iris and ciliary body were treated as a compound tissue.

2.2. FDTD Method

The finite-difference time-domain (FDTD) method (Taflove and Hagness 2005) was used for investigating the interaction between the human head model and microwaves. We considered a plane wave with a power density of 10 W/m^2 as a source. The total-field /scattered-field formulation was applied in order to generate a incident plane wave. For the truncation of the computational region, we adopted perfectly matched layer as the absorbing boundary. The number of the layer is chosen to be 12. The separation between the head model and the boundary is 40 cells (80 mm) for reducing the computational error as much as possible. In order to incorporate the head models into the FDTD scheme, the electrical constants of tissues are required. They were determined with the aid of the 4-Cole-Cole extrapolation (Gabriel 1996).

2.3. Temperature Calculations

When the thermal problem associated with the eye was addressed in Lagendijk (1982), the following simplifications were applied. First, the blood flow in the human eye was assumed absent. Secondly, the heat exchange between the human eye and the surrounding tissues was assumed negligible. Thus, the human eye is considered as an object thermally isolated from the head. However, this assumption is not valid when the SAR is absorbed outside the eyeball (Hirata 2007), and thus whole head models were considered in the present analysis of temperature elevation due to microwave energy.

The temperature in the human body is calculated by solving the bioheat equation. The microwave energy absorbed in the human calculated by the FDTD method is used as the heat source. The bioheat equation (Pennes, 1948), which takes into account heat exchange mechanisms such as heat conduction, blood perfusion, and microwave heating, is represented by the following equation:

$$C(\boldsymbol{r})\rho(\boldsymbol{r})\frac{\partial T(\boldsymbol{r},t)}{\partial t} = \nabla\cdot(K(\boldsymbol{r})\nabla T(\boldsymbol{r},t)) + \rho(\boldsymbol{r})SAR(\boldsymbol{r}) + A(\boldsymbol{r},t) - B(\boldsymbol{r},t)(T(\boldsymbol{r},t) - T_B(t)) \quad (1)$$

where T is the temperature of the tissue, T_b the temperature of the blood, K the thermal conductivity of the tissue, C the specific heat of the tissue, A metabolic heat generation, and B the term associated with blood perfusion rate. The temperature elevation due to SAR at the ICNIRP basic restriction is at most 1 ^{o}C, and thus can only marginally activate the thermoregulatory response: the increase of local blood flow, activation of sweating mechanism, etc. In our study, these effects were neglected. The electrical and thermal constants of tissues are known to be marginally influenced by the temperature elevation of the order of 1 ^{o}C and thus assumed as constant in equation (1). The boundary condition for Eq. (1) is given by

$$-K(r)\frac{\partial T(\boldsymbol{r},t)}{\partial n} = H \cdot (T_s(\boldsymbol{r},t) - T_e(t)) \tag{2}$$

where H, Ts, and Te denote, respectively, the heat transfer coefficient, surface temperature of tissue and air temperature.

Table 1 shows the thermal parameters of main head tissues (Bernardi *et al* 1998, Hirata 2005). It should be noted that the blood perfusion rate in the retina/choroid/sclera was roughly estimated as 80,000-160,000 W/m^3 for a rabbit phantom with a resolution of 1 mm by fitting computed data with measured one (Hirata *et al* 2006b). The rationale for this variability is that the thickness of the retina and choroid depends on their position and is largest around the optic nerve head. Specifically, the thicknesses of the retina and choroid are 0.1-0.3 mm and 0.1-0.2 mm, respectively. This thin thickness suggests that these tissues cannot be taken into account straightforward even if we use state-of-art models with a sub-millimeter resolution (Buccella *et al* 2007, Flyckt *et al* 2007). On the other hand, the thermal diffusion in biological tissues is the order of a few centimeters (Hirata *et al* 2006a), and thus the eye tissues could be reasonably considered using equivalent thermal parameters. The retina/choroid/sclera is then further classified into two parts on the basis of the amount of blood flow, just as Hirata *et al* (2006b) did. The value for rabbits was applied even to humans in this study. The basal metabolism is roughly proportional to the blood perfusion rate (Gordon *et al* 1976), and the basal metabolic rate of human is three times smaller than that of rabbit (Kleiber 1975). Thus, blood perfusions for most human tissues would be lower than those in rabbits. The effect of blood perfusion rate in the compound tissue on the heating factor will be given in the next section.

We use 8 W/m$^2 \cdot {}^{o}$C and 20 W/m$^2 \cdot {}^{o}$C as the respective values of the heat transfer coefficient between the skin and the air and between the eye surface and the air (Lagendijk 1982). These values were obtained in a room temperature of 23^{o}C. Note that the latter value was in the range of 20-50 W/m$^{2}\cdot{}^{o}$C in our measurement for rabbit eyes (Hirata *et al* 2006b). This parameter influences the temperature but not so much for temperature *elevation* due to microwave energy, as shown in Hirata *et al* (2000). In this study, the room and body-core temperatures are assumed to be 23 ^{o}C and 37 ^{o}C, respectively.

3. Computational Results

Figure 2 shows the frequency dependency of eye-average SAR for exposure to vertically-polarized plane wave. The power density of the microwave is 10 W/m^{2}. The frequency region considered is from 0.6 GHz to 5 GHz, which covers the frequency region where a standing wave occurs in the eye and/or head (Hirata *et al* 2000). The lower frequency is determined so that the model truncation at the neck does not influence power absorption in the human head (Hirata *et al* 2000). The upper frequency is determined by the relationship of cell resolution to the wavelength in biological tissues considering the phase velocity error (Taflove and Hagness 2005). As is evident from this figure, the difference in the eye-average SAR is significant for different eyes. These SAR values are in fair agreement with those in our previous work (Hirata *et al* 2000), in which a Japanese head model with 2.0-mm resolution was used. It should be noted that each of the eyeballs in our models are virtually identical to one another (total four eyes), and thus this difference is caused by the difference of the eye surrounding structure. In Bernardi *et al* (2000), the importance of the nose was pointed out especially for millimeter-wave exposures.

Figure 3 shows the frequency dependency of heating factor for the lens in the four eyes. This factor is almost uniform (0.114-0.149 $^{\circ}\mathrm{C/W\cdot kg}$) in the frequency region lower than 3 GHz.

This uniformity has already been commented in Hirata (2005), Buccela (2007), and Wainwright (2007). The upper limit of 3 GHz would be determined by the penetration depth of microwaves. At 3 GHz, the penetration depth of EM waves in biological tissues is 10 mm, while the SAR averaging volume is fixed to the whole eye whose diameter is 25 mm. Thus, the eye-average SAR becomes small with the increase of the frequency, and then the factor is increasing above 3 GHz. The point to be stressed here is that the difference of 20% was observed at 1.8 GHz even for the different eyes with the same electrical and thermal parameters. This difference can be attributed to morphological difference of the head models, which would give some insight to the difference in the heating factors between different works. Note that the same tendency in the heating factor was observed for the plane wave with the horizontal polarization, and thus we do not present the results for avoiding repetition.

4. Discussion

This section compares the heating factor of the lens in this work with those in earlier studies. The heating factor for the lens in this work was 0.114-0.149 $^\circ\mathrm{C/W \cdot kg}$, while those in the earlier works were as follows: 0.152-0.175 $^\circ\mathrm{C/W \cdot kg}$ (Hirata 2005), 0.149-0.16 $^\circ\mathrm{C/W \cdot kg}$ (Buccella *et al* 2007), 0.089-0.130 $^\circ\mathrm{C/W \cdot kg}$ for discrete vascular and bioheat models (Flyckt *et al* 2007). The heating factor for the *whole eye* was 0.18-0.19 $^\circ\mathrm{C/W \cdot kg}$ (Wainwright 2007). Note that the results for the isolated eye models in Flyckt *et al* (2007) are not considered here due to its weakness that the heat evolved *outside the eyeball* can not be taken into account, resulting in underestimation of lens temperature elevation (Hirata 2007, Wainwright 2007). This underestimation can be explained using the heat diffusion length in biological tissues of a few centimeters (Hirata *et al* 2006a). As mentioned in Sec. 1, there would be several causes for the above difference in the heating factor: i) morphological differences, ii) eye mass, iii) thermal constants, and iv) computational methods, and so forth. The forth factors are not considered here, since Wainwright (2007) discussed thoroughly. He and Samaras et al (2006) revealed that the finite-difference modeling results in the underestimation of steady-state temperature. This is because of the increased surface area, attributed to stair-casing approximation. This equivalently results in increased heat transfer coefficient. As mentioned in Sec. 2, the effect of heat transfer coefficient on the temperature elevation in the lens is marginal. Thus, in the following difference, the influence of these causes on the heating factor for the lens will be discussed.

4.1 Maximum temperature elevations in the whole eye and lens

The difference of the maximum temperature elevation in the whole eye and lens are calculated in our models in order to clarify the difference in this study and Wainwright (2007). Figure 4 shows the maximum temperature elevation in the whole eye and lens of the female model for plane-wave exposure with the power density of 10 W/m^2. The maximum temperature elevation in the lens is comparable to that in the whole eye in the frequency below 1 GHz and then the difference become larger with the increase of the frequency. The difference is up to 20% around 2 GHz. This result suggests that the difference in the heating factors between the lens and the eye would not be neglected, dependent on the frequency.

4. 2 Influence of eye dimension

The average mass of eye is 7.2-7.5 g (ICRP 1975). Due to the small dimension of the eye, together with finite cell size, the masses of the eye used in earlier works were different: 11.5 g (Hirata 2005), 9.9 g (Buccella *et al* 2007), 7.2 g (Flyckt *et al* 2007), and 9.4 g (Wainwright 2007).

In order to discuss the effect of eye mass on the heating factor in the lens, we have scaled the original Japanese female head model (Nagaoka *et al* 2004) linearly by a factor of 1.1, 1.15 and 1.2. For this scaling factor, the eye mass was 8.70 g, 9.95 g and 11.2 g, respectively. We have considered the female model exposed at 2 GHz. The heating factor for the lens in the right eye was increase by 2.8 %, 5.6%, and 8.7 %, respectively, for the eye with the weight of 8.70 g, 9.95 g and 11.2 g. For the left eye, these values are 3.4 %, 7.1% and 10.4 %.

4.3 Influence of blood perfusion rate in the retina/choroid/sclera

Flyckt *et al* (2006) determined the heat transfer coefficient between the eye and body core as 300 $W/m^2 \cdot {}^oC$. For deriving this value, some assumption was applied. This heat transfer coefficient is 5 times larger than that determined in their previous study (65 $W/m^2 \cdot {}^oC$, Lagendijk 1982). One of the reasons for this difference would be the administration of anesthesia (Kojima *et al* 2004). Although no study has reported about the effect of anesthesia on blood perfusion rate in the eye as far as the authors know, typical reduction rate is smaller; 2 or less in the brain and heart and 4 in the diaphragm for rats (e.g., Seyde *et al* 1985). Taking into account the underestimation using isolated eye model by 30% (Hirata 2005, Wainwright 2007), the reduction of blood perfusion rate in choroid by Lagendijk (1982) would be 7. On the other hand, we derived this value as 110-150 $W/m^2 \cdot {}^oC$ from the comparison between measured and computed results (Hirata 2007). This value reasonably coincides with the analytic prediction by Lagendijk (1982) and Wainwright (2007).

One of the reasons for the difference in the heat transfer coefficient of our study (Hirata 2007) with Flyckt *et al* (2007) would be the thickness of the choroid in their head model. Although the thicknesses of the retina and choroid are 0.1-0.3 mm and 0.1-0.2 mm, respectively, the total thickness in their phantom seems to be the order of 1-2 mm. Additionally, the same blood perfusion rate was given in retina/choroid/sclera in Flyckt *et al* (2007).The blood perfusion rate in the choroid is the highest and that in the sclera is not so much (summarized in Hirata *et al* 2006b). From the results in the previous studies (Hirata 2005, Wainwright 2007), the effect of blood perfusion rate on the heating factor is at most 10% even when the blood perfusion rate is enhanced by a factor of 2, corresponding to the difference in this study (110-150 W/m$^2\cdot{}^o$C) and Flyckt *et al* (2007) (300 W/m$^2\cdot{}^o$C). Thus, the order of 10% or so would be the difference due to the blood perfusion rate in the choroid.

4. 4. Influence of blood perfusion rate in the skin

The other notable difference in thermal constants with the related studies is the blood perfusion rate in the skin, which was used in Flyckt *et al* (2007). The reference of this value was not listed in their study, while the similar value can be found in Douglas (1977). We have changed the blood perfusion rate in the skin from 9,100 W/m3·^{o}C (see Table 1) to 40,000 W/m3·^{o}C for comparison. We have considered the right eye of the female model exposed at 900 MHz and 2 GHz. Using this value, the heating factor for the lens was decreased by 23% and 22%, suggesting that this could be one of the main causes for the difference in the heating factor in different works.

4.5. Compensated Heating Factor for the Lens

Based on the above discussion, we introduced compensation factors for each cause to compare heating factors in different works properly. We simply considered that each cause does not affect one another for rough estimation. We chose the following condition as a reference: i) The eye mass is 7.5 g. ii) The blood perfusion rate in the choroid is 80,000-160,000 W/m$^3\cdot{}^o$C for the model with resolution of 1 mm, corresponding to the heat transfer coefficient of 110-150 W/m$^2\cdot{}^o$C. iii) The blood perfusion rate in the skin is 40,000 W/m$^3\cdot{}^o$C, which was comparable in Douglas (1977). The compensated heating in different works is listed in table 2. From this table, the compensated heating factors in this study and earlier works are in good agreement. There are still some differences between these works. The main reason for this difference would be morphological difference, which is 20% even for the Japanese male and female models. In addition, different scenarios were considered in each work.

5. Summary and Concluding Remarks

This study investigated the temperature elevation in the eyes of realistic Japanese male and female models for plane-wave exposures. The resolution of original Japanese models is rescaled from 2 mm and 1 mm. Then, the cell resolution is changed from 1 mm to 1.03 mm in order to adjust the eye mass to 7.5 cm^3, which is the average value for Japanese. Computational results showed that the ratio of maximum temperature in the lens to the eye-average SAR or the heating factor for the lens was almost uniform (0.112-0.147 $^oC\cdot kg/W$) in the frequency region below 3 GHz, suggesting that eye-average SAR is a good measure for estimating the maximum temperature elevation in the lens in this frequency region. The heating factor for the lens in the frequency region below 3 GHz was almost uniform. However, some difference in the heating factor was found between the present study and earlier works. Then, we compared the main causes for this difference as morphological differences, eye mass and thermal constants. We compensated the heating factor by introducing a compensation factor. Taking into account the compensation, all the results in the previous work and this study were in good agreement. The point to be stressed here is that the condition considered here may not be a standard condition because of lack of the physiological data. For example, the blood perfusion rate in the choroid would be somewhat larger than that used in this study, since that of rabbit was used. The blood perfusion rate is reasonably proportional to the basal metabolic rate, and that in human is smaller than the rabbit by a factor of 3 (Kreiber 1975).

Above 3 GHz, the heating factor increases gradually with the increase of the frequency. This is attributed to the decrease in the penetration depth of microwave. In the ICNIRP guidelines, one of the basic restrictions is the SAR averaged over any 10 g tissue in the frequency below 10 GHz. On the other hand, when paying attention to the temperature elevation in the lens, the upper frequency would be 3 GHz, which may coincide with the upper frequency limit where peak 10-g SAR is used as a measure in some standards/guidelines (e.g., IEEE 2005).

FIGURE AND TABLE CAPTIONS:

Table 1: Thermal constants of human head tissues

Table 2: Heating factor for the lens in different works and their compensated values.

Fig. 1: Cross-sectional view of the rescaled model based on Japanese female model named HANAKO.

Figure 2: Frequency dependency of eye-average SAR for male (TARO) and female models (HANAKO). Power density of the wave: 1.0 mW/cm^2.

Figure 3: Frequency dependency of the ratio of maximum temperature elevation in the lens to the eye-average SAR for male (TARO) and female models (HANAKO).

Figure 4: Frequency dependency of the ratio of maximum temperature elevation in the lens and whole eye.

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Table 1

tissues	K[W/m·^{o}C]	C[W·s/m·^{o}C]	B[W/m^3·^{o}C]	A[W/m^3]
Skin	0.42	3,600	9,100	1,620
Muscle	0.50	3,800	2,700	480
Fat	0.25	3,000	1,700	300
Bone	0.37	3,100	3,400	610
Cartilage	0.47	3,600	9,000	1,600
Nerve	0.46	3,400	40,000	7,100
Gray Matter	0.57	3,800	40,000	7,100
White Matter	0.50	3,500	40,000	7,100
Cerebellum	0.57	3,800	40,000	7,100
Cornea	0.52	3,600	0	0
Lens	0.40	3,000	0	0
Vitreous Humor	0.58	4,000	0	0
Anterior chamber	0.58	4,000	0	0
Iris/Ciliary	0.52	3,600	35,000	10,000
Retina/Choroid/Sclera(1)	0.58	3,800	80,000	22,000
Retina/Choroid/Sclera(2)	0.58	3,800	160,000	40,000

Table2

	original °C W kg^{-1}	i)	ii)	iii)	iv)	compensated °C W kg^{-1}
this study	0.114-0.149	0	0	0	-20%	0.091-0.12
Hirata (2005)	0.152-0.175	0	-10%	-10%	-20%	0.098-0.11
Bucella (2007)	0.149-1.60	0	-5%	0	-20%	0.11
Flyckt (2007)	0.089-0.130	0	0	+10%	0	0.098-0.14
Wainwright (2007)	0.18-0.19	-20% - 0	-5%	0	-20%	0.11-0.144

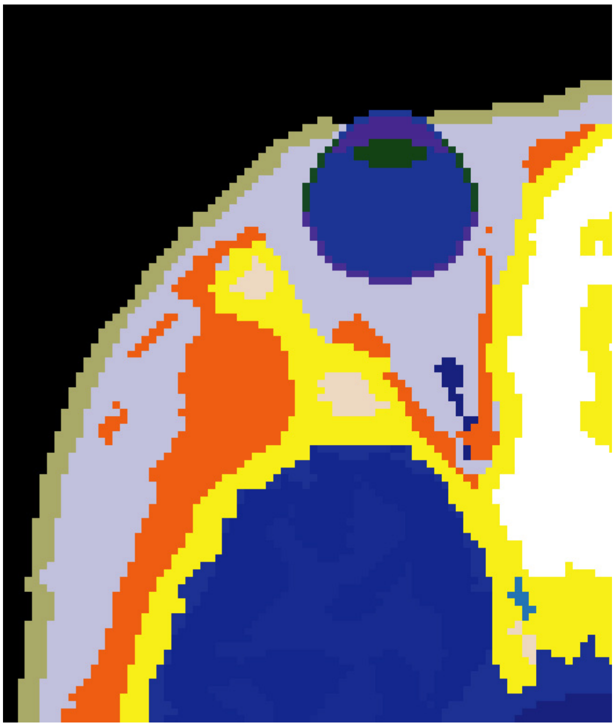


Fig. 1.

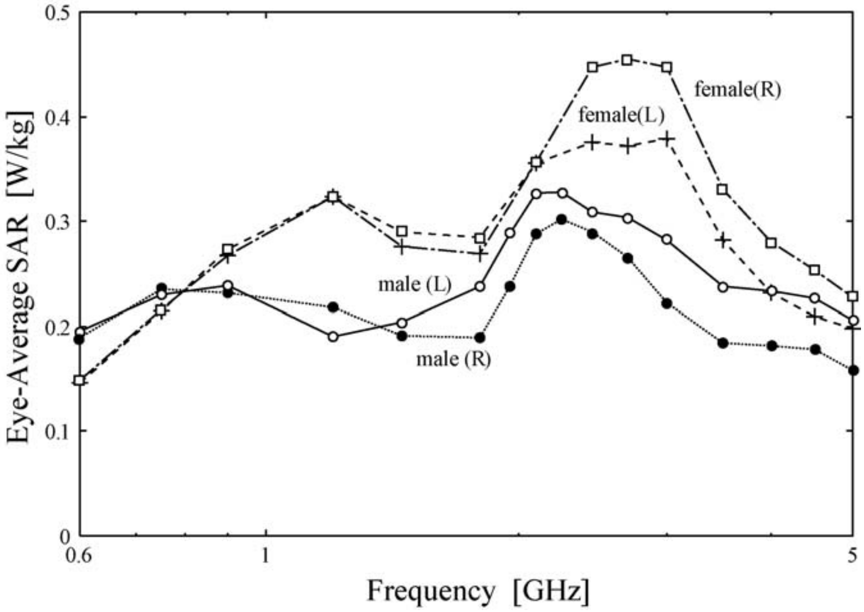

Eye-Average SAR [W/kg]
0.5
0.4
0.3
0.2
0.1
0
0.6
1
5
Frequency [GHz]
female(R)
female(L)
male (L)
male (R)

Fig. 2.

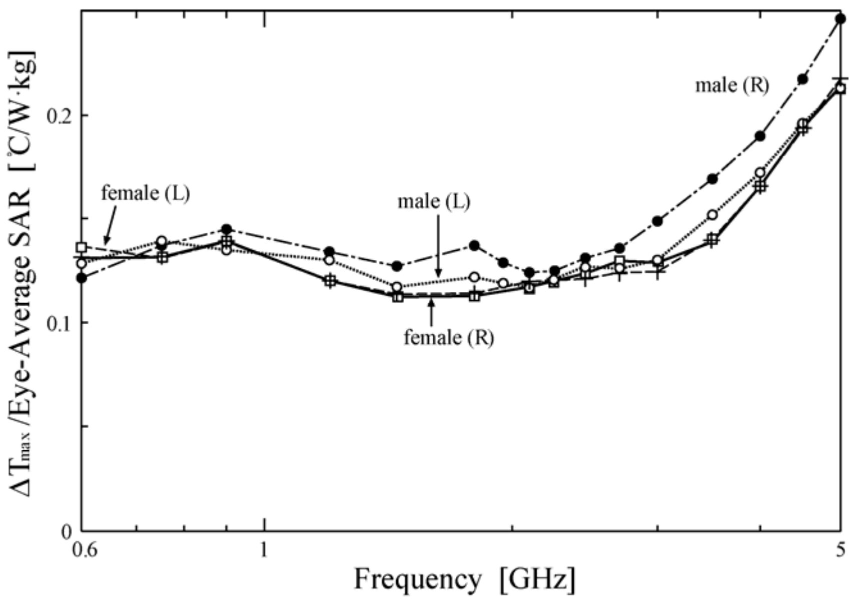
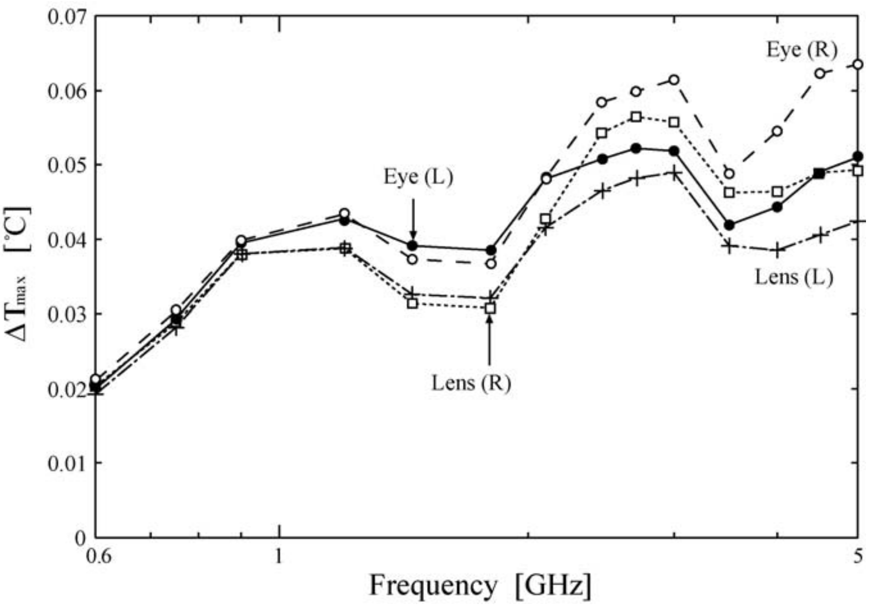

ΔTmax /Eye-Average SAR [℃/W·kg]
0.2
0.1
0
0.6
1
5
Frequency [GHz]
male (R)
female (L)
male (L)
female (R)

Fig. 3.



0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
ΔTmax [°C]
0.6
1
5
Frequency [GHz]
Eye (R)
Eye (L)
Lens (L)
Lens (R)

Fig. 4.