An Investigation of the Heat Transport Mechanism under the Millimeter-wave Exposure Considering the Convection in the Anterior Chamber of Rabbit's Eye

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Abstract

The experiment exposing the millimeter-wave (MMWs) is performed to investigate the relation between the temperature elevation at the ocular tissue and MMW exposure. The temperature and velocity distributions in front part of the eye are simultaneously measured by using Micro-Encapsulated Thermo-chromic Liquid Crystal and Fluoroptic Thermometer. It is found that the flowing patterns of aqueous humor depend on the incident power density, and these patterns affect the heat transport mechanism.

1 Introduction

The relation between millimeter-waves (MMWs) exposure and ocular injures has been studied in the past works [1] [2]. It is thought that the thermal effect is dominant for the interaction between the MMW and the biological tissue. Most of MMW energy is absorbed within the cornea, and it becomes heat source. However, there are luck of data explaining the heat transport in the front part of ocular tissue, because the convection of aqueous humor makes the heat transport mechanism complex. Therefore, it is unclear the dependence of ocular injures on parameters of the incident MMW such as power and frequency. The purpose of this study is to investigate the dependence of the heat transport mechanism on the incident power density in the front part of the eye considering the convection of the aqueous humor under the MMW exposure.

2 Method

We performed the experiment exposing the rabbit's eye to the MMW to investigate the thermal effects. Temperature and velocity distributions are measured simultaneously [3] by using Micro-Encapsulated Thermo-chromic Liquid Crystal (MTLC) [4] in the anterior chamber. Moreover, the temperature is measured by using Fluoroptic Thermometer (Luxtron 790, Luxtron, Santa Clara, CA, USA) for tissues surrounding the anterior chamber. Figure 1 (a) and (b) show the schematic view and the configuration of the experiment, respectively. The real-time growth for convection images in the anterior chamber is captured by the CCD camera. The lens antenna is located at the position where the MMW is focussed on the surface of the cornea. MTLCs are suspended into the anterior chamber, and adjusted its density to approximately 0.07 %. This rabbit is put under anesthesia to take care of the ethical problem. The frequency of MMW source is 75.4 GHz and the incident power densities are 50 and 150 mW/cm^2.

3 Result

Figure 2 shows an example of the result of the analysis for the measurement using MTLC after 20 seconds onset from the MMW exposure at 150 mW/cm^2. Figure 2 (a) is the color image with MTLCs captured by CCD camera. Figure 2 (b) is the temperature distribution and Fig. 2 (c) is the velocity distribution. The temperature distribution is acquired by originally developed correlating method between toned color

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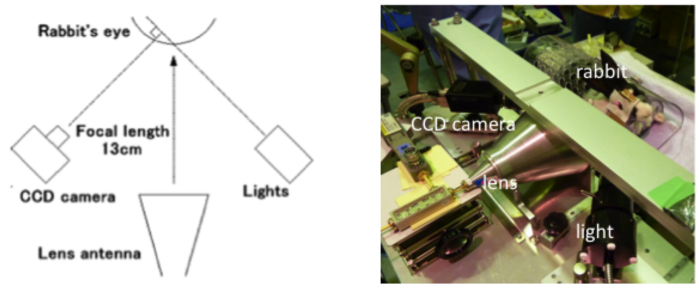
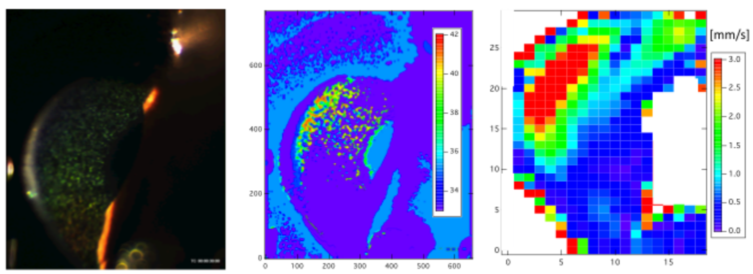


(a) (b)

Figure 1: (a)Schematic view of the experimental setup, (b)configuration of the experiment

of MTLC and temperature value [4]. The velocity distribution is acquired by 2D-PIV (Particle Imaging Velocimetry) method [5] (DIPP-FLOW, DITECT Corporation, Tokyo, Japan).



(a) (b) (c)

Figure 2: The results of the experiment after 20 seconds onset from MMW exposure at 150 mW/m^2 ; (a) temperature imaging captured by CCD camera, (b) temperature distribution, (c) velocity distribution

Figure 3 shows the flowing patterns of aqueous humor depending on the incident power density. The aqueous humor flows from the vicinity of the lens to that of the cornea in normal condition as shown in Fig. 3 (a). This homeostatic flow of aqueous humor is observed, because the temperature of the lens is higher than that of cornea. When the incident power density is 50 mW/cm^2, the flowing pattern becomes as shown in Fig. 3 (b). The flowing pattern of the aqueous humor is complex, because the temperatures are approximately same values between near the cornea and near the lens. In the case of the higher incident power density, the aqueous humor flows from the vicinity of the cornea to that of the lens as shown in Fig. 3 (c). This ordered flow is observed, because the temperature of the cornea is higher than that of lens.

Figure 4 (a) and (b) show the time growth of flow speeds under the exposure conditions of 50 and 150 mW/cm^2. In the vicinity of the cornea, they tend to be affected by the MMW power, because the energy of the MMW exposure is absorbed in the cornea. In the top of the chamber, the temperature is comparatively higher than that of other parts as shown in Fig. 2 (b). Therefore, the velocities of two points, near the cornea(1) and top of the chamber(2), are measured (See Fig. 4 (a)). The duration of exposure is 30 seconds. When the incident power density is 50 mW/cm^2, the velocities are almost same at each point. When the incident power density is 150 mW/cm^2, the velocity in the vicinity of the cornea becomes faster than that in the top of the chamber. In both incident power densities, the velocities in the top of chamber are almost same, and there are not remarkable increase of flowing speed. It is thought that the heat energy is transported by the high flowing speed in the vicinity of cornea under 150 mW/cm^2 exposure.

Figure 5 shows the time growth of the temperature elevation under each incident power density exposure. The temperatures are measured by using MTLC in the vicinity of cornea (i) and upper position of the anterior chamber (ii). Moreover, the temperatures are measured by using Fluoroptic Thermometer at the

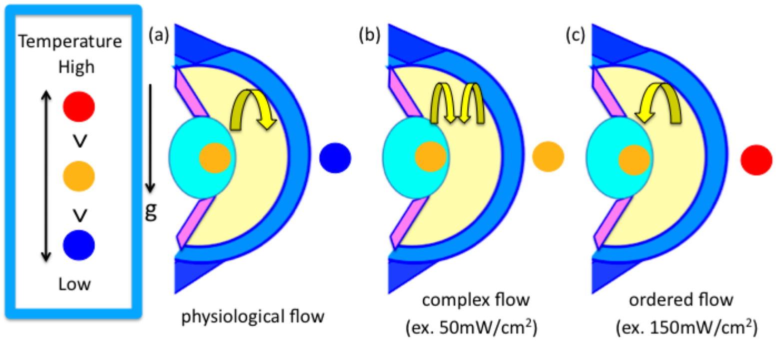


Figure 3: The flowing patterns depending on the incident power density ; (a) physiological flow, (b) complex flow (ex. 50 mW/cm^2), (c) ordered flow (ex. 150 mW/cm^2)

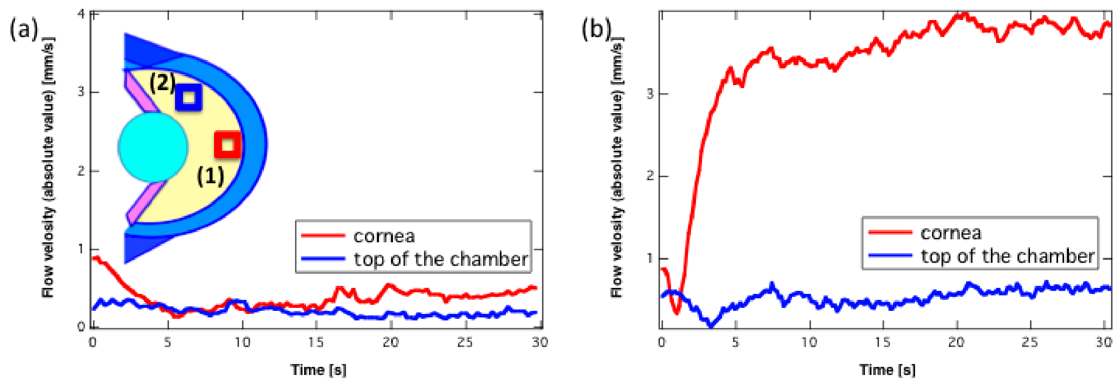


Figure 4: The time growth of velocities in the vicinity of cornea and the top of chamber ; (a) 50 mW/cm^2, (b) 150 mW/cm^2

cornea stromal layer (ⅲ) and the lens nucleus (ⅳ). Most of the MMW energy is absorbed in the cornea (ⅲ), and the flowing pattern is changed by differences of temperatures between the cornea (ⅲ) and the lens (ⅳ). Therefore, the measurement of temperatures at (ⅲ) and (ⅳ) are added. For the measurement with MTLCs, the duration of exposure is three minutes for 50 mW/cm^2 exposure, and it is two minutes for 150 mW/cm^2 exposure. The duration of exposure are three minutes for the measurement with the thermometer. There is not remarkable temperature elevation at (ⅳ) for each power density. When the incident power density is 50 mW/cm^2, MTLC is out of the color range from 0 s to 70 s. It is found that the temperatures at (ⅰ), (ⅱ) and (ⅲ) reach to the value of (ⅳ) from 70 s to 100 s. Temperatures indicate approximately same values at all observed points from 100 s to 180 s. When the incident power density is 150 mW/cm^2, the temperature at (ⅲ) becomes relatively higher than that at (ⅰ), (ⅱ) and (ⅳ). The temperature elevation in upper position of the anterior chamber (ⅱ) is faster than that in the vicinity of the cornea (ⅰ). Consequently, it is seemed that the thermal energy at the cornea is transported to the top of the chamber by ordered flow driven by MMW.

4 Discussion

We investigate the heat transport mechanism depending on the incident power density through the experiment. When the incident power density is 50 mW/cm^2, the flowing pattern becomes complex flow, because the temperatures near the cornea and the lens are approximately same . Therefore, it is assumed that the heat conduction is dominant. When the incident power density is 150 mW/cm^2, the flowing pattern becomes the ordered flow, because the temperature near the cornea is higher than that near the

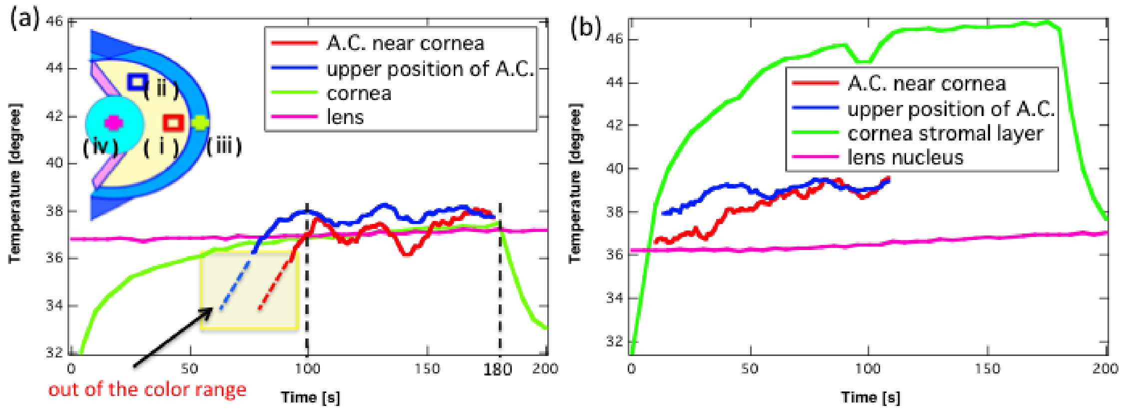


Figure 5: The time growth of temperature elevation in the rabbit's eye measured by MTLC and Fluoroptic Thermometer; (a) $50 \mathrm{mW/cm^2}$, (b) $150 \mathrm{mW/cm^2}$

lens. Therefore, it is assumed that the heat convection is dominant. It is thought that the ordered flow helps heat transport from the vicinity of cornea to the top of the anterior chamber. This mechanism of the heat transport mentioned above may decide the transient response of temperature change caused by MMW, and it is important to estimate the time constant to investigate the thermal effect. It is assumed that the time constant of the temperature elevation for 150 $\mathrm{mW/cm^2}$ become shorter than that for 50 $\mathrm{mW/cm^2}$.

5 Conclusion

We investigate the heat transport mechanism depending on the incident power density through the experiment. The temperature and velocity distributions are measured simultaneously with MTLCs and Fluoroptic Thermometer for 50 $\mathrm{mW/cm^2}$ and 150 $\mathrm{mW/cm^2}$ exposures. We found the difference of the flowing patterns depending on the incident power density. The patterns of heat transport are classified by the flowing pattern. It is supposed that the time constant of the temperature elevation depends on the incident power density.

6 References

1. SW. Rosenthal, *et al.*, "Effects of 35 and 107 GHz CW microwaves on the rabbit eye," Biological effects of electromagnetic waves, Rockville, MD: HEW Publication (FDA), pp. 110-128, 1976.

2. M. Kojima, *et al.*, "ACUTE OCULAR INJURIES CAUSED BY 60-GHz MILLIMETER-WAVE EXPOSURE," Health Physics, Vol. 97, pp. 212-218, 2009.

3. Y. Suzuki, *et al.*, "Imaging the 3D Temperature Distributions Caused by Exposure of Dielectric Phantoms to High-Frequency Electromagnetic Fields," *IEEE Transactions on Dielectrics and Electric Insulation*, Vol. 13, pp.744-750, 2006.

4. Y. Suzuki, *et al.*, "EXPERIMENTAL ANALYSIS ON THE THERMAL CONVECTION OF AQUEOUS HUMOR IN ANTERIOR CHAMBER DRIVEN BY THE MILLIMETER-WAVE EXPOSURE AT 77GHZ," The Bioelectromagnetics Society 32nd Annual Meeting, 2010.

5. The Visualization Society of Japan, "HANDBOOK OF PARTICLE IMAGE VELOCIMETRY," Morikita Publishing Co., Ltd., 2002 (in Japanese).