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Non-destructive 3D temperature measurement for dosimetries of the thermal dose due to high frequency electromagnetic field exposure with micro-encapsulated thermo-chromic liquid crystal

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Abstract A new method to measure the temperature distribution due to high frequency electromagnetic field (HF-EMF) power absorption is established. It is intend to develop for the specific absorption rate (SAR) measurement from the temperature elevation. A micro-encapsulated thermo-chromic liquid crystal (MTLC) is employed as the temperature probe because of its nature of high resolution and high sensitivity. In this paper, we show the non-destructive temperature visualization with MTLC for the dosimetry of *in vivo* millimeter-wave exposure experiment. It is also shown that the quantification method of the temperature distribution from the visualization image within the cross-section of rabbit eyes and transparency gel phantoms.

Keywords Thermo-chromic liquid crystal, Dosimetry, High frequency electromagnetic field, Temperature visualization

1. Introduction

Safety of radio frequency (RF) electromagnetic fields(EMF) is commonly discussed in terms of specific absorption rate (SAR) which is associated with thermal effect. One of the methods to evaluate SAR is measurement of temperature elevation due to power absorption of RF-EMF within target objects, such as biological tissues or tissue equivalent phantoms, over a short period of time following the RF exposure.

To evaluate thermal dose and heat transport mechanism for the dosimetry of RF and millimeter-wave (MMW) exposure, we propose a new non-destructive method to measure three-dimensional (3D) temperature distribution with micro-capsulated thermo-chromic liquid crystal (MTLC) [1].

In this paper, we show the principle and implementation of MTLC method. Moreover, we show applications of this method to RF exposure experiment using biological tissue equivalent phantom and *in vivo* millimeter-wave exposure experiment for ocular tissue. Examples of quantification of the temperature distribution from the visualization image with MTLC are also shown to estimate SAR distribution and to analyze heat transport dynamics within ocular tissue.

2. Principle of Temperature Measurement with MTLC

We introduce new technique to measure three dimensional temperature distributions. MTLCs, which is produced by Japan Capsular Products, are used as a temperature sensor. The diameter of MTLC is about 20 to 30 micrometers. The cholesteric liquid crystal, which has suitable nature of high resolution and high sensitivity to the changes of temperature, is encapsulated within urea resin or gelatin capsule. Wavelength of scattered light from MTLC is changes as the environmental temperature surrounding MTLCs. Therefore temperature distribution is observed by the color image.

Figure 1 shows the example of correlation of the color with the temperature. This correlation is obtained by suspending MTLC within transparency materials. Scattered light is measured with CCD camera. The wavelength of the scattered light becomes shorter with the increase of temperature. In other words, the scattered light changes in its color from red to violet with the increase of temperature.

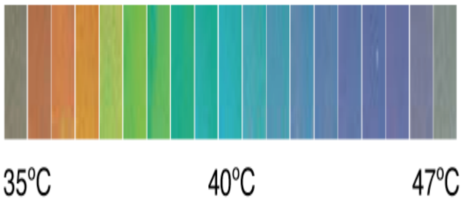


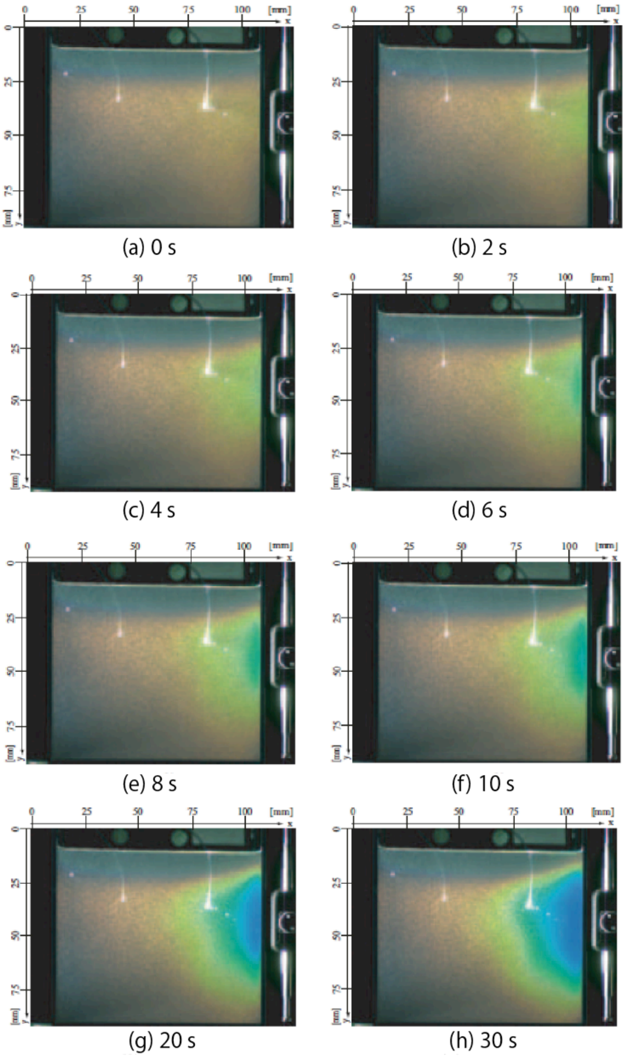
Fig.1 Example of correlation of the scattered light color with the substrate temperature.

3. Application to dosimeteries

3.1 RF Exposure for Tissue Equivalent Phantom

The substrate material for the phantom should not be convective to measure SAR. Therefore, high molecular gel constructed from “carrageenan”, which is extracted from seaweed and has high transparency, is used as the substrate of the phantom to prevent convection. The dielectric properties of the phantom are adjusted by mixing propylene glycol e and KCl (potassium chloride) [1].

We performed exposure experiment using high transparency carrageenan phantom. A dipole antenna is used to irradiate a phantom containing MTLC with RF-EMF at the frequency of 1.45 [GHz]. The applied power to the antenna is 40 [W]. The temperature distribution, which is indicated by scattering light from red to purple, on the plane lit up by the projected slit light, is obtained clearly as shown in Fig. 2. The temperature distributions on other planes are also visualized by moving the slit light location [2]. These observations imply the possibility of the 3-D visualization that is reconstructed by measured data at each plane.



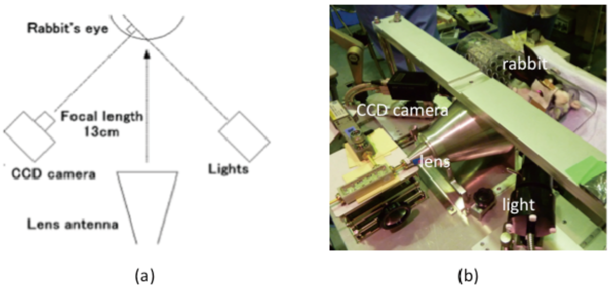
(a) 0 s (b) 2 s (c) 4 s (d) 6 s (e) 8 s (f) 10 s (g) 20 s (h) 30 s

Fig.2 Measurement results of temperature visualization obtained by a digital video camera are shown in a time sequence. (a), (b), (c), (d), (e), (f), (g) and (h) correspond to 0, 2, 4, 6, 8, 10, 20 and 30 second after starting exposure, respectively.

3.2 MMW exposure for rabbit eyes

We performed MMW exposure experiment to the rabbit eyes to investigate the thermal effects [3]. Temperature and velocity distributions are measured simultaneously by MTLC. Figure 3 (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 focused on the surface of the cornea as shown in Fig. 4. MTLCs are suspended into the anterior chamber, and adjusted its density to approximately 0.07 %. This rabbit was put under anesthesia to take care of the ethical problem. The frequency of MMW source is 75.4 [GHz] and the incident power density is 150 [mW/cm2].

Figure 4 (b) shows numerical simulation result of the electric field distribution generated by the lens antenna with the method of moments [4]. As shown in Fig. 4 (b), MMW is focused at 135 mm distance from the lens antenna, and the rabbit’s eye is placed this focal point. The SAR distribution obtained by numerical simulation with the finite difference time domain method [5] is shown in Fig. 5. It is found that the SAR distribution is highly localized in the vicinity of the outer surface of cornea. The aqueous humor within anterior chamber, surrounded by the cornea, the iris, and the lens, is heated near the inner surface of cornea, and it is supposed that thermal convection will occur in the anterior chamber. This



(a) (b)

Fig.3 (a)Schematic view of the experimental setup, (b)configuration of the experiment.

phenomenon significantly affects the patterns of temperature elevation in the ocular tissue.

The Upper row and the lower row in Fig. 6 show captured images of temperature distribution and 2D temperature value distributions obtained from captured image in a time sequence [6], respectively. Figure 6 (a), (b), and (c) indicate after 10, 20, and 30 second from the onset of the MMW exposure, respectively. Temperature value distributions are displayed with very high spatial resolution as 20 x 20 [μm]. Figure 7 shows the time development of a flowing distribution of aqueous humor obtained from captured image with 2D-PTV (Particle Tracking Velocimetry) method [7] (DIPPFLOW, DITECT Corporation, Tokyo, Japan). Indicated time below each figure denotes from the onset of the MMW exposure. Directions of the vector indicate flowing direction. Colors of the vector indicate flowing speed at each position. We can observe the change of flowing pattern driven by the MMW exposure. It is found that a vortex grows in the upper area of anterior chamber in this exposure condition.

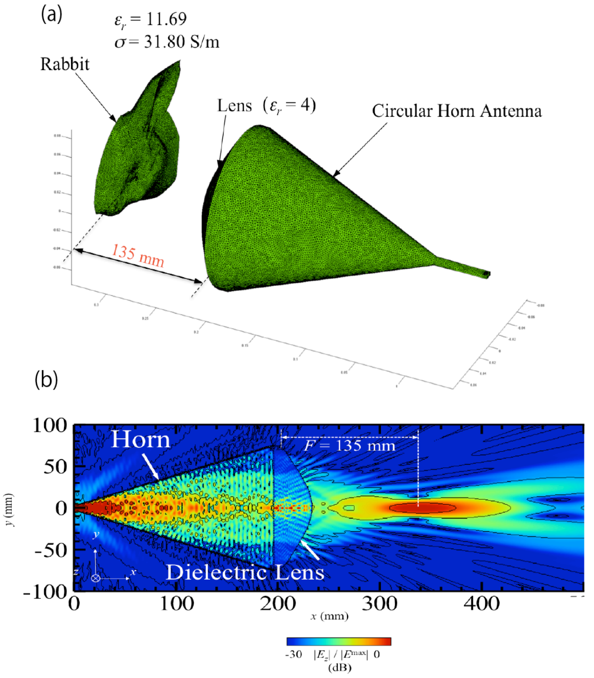


Fig.4 (a) The position of the rabbit's eye in relation to the lens antenna (b) A numerical simulation result of the electric field distribution generated by the lens antenna with moment method.

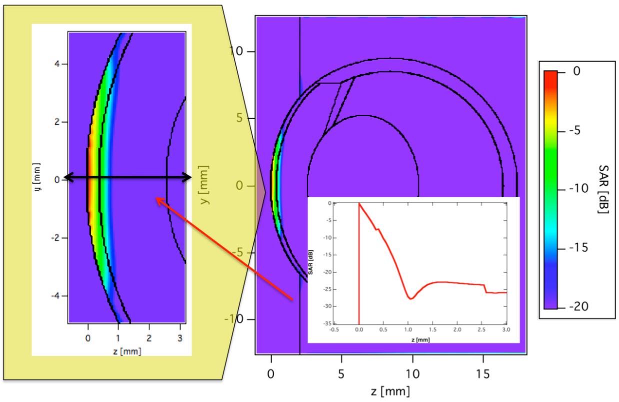
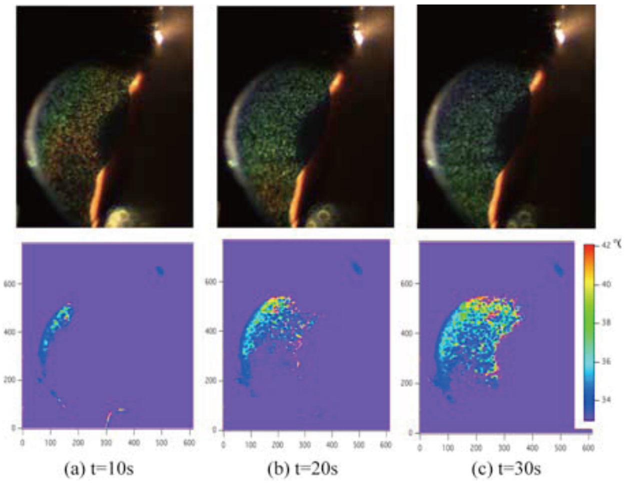


Fig.5 A SAR distribution obtained by finite difference time domain method within the rabbit's eye exposed to 75 GHz MMW under the condition shown in Fig. 4.

4. Conclusion

We have proposed a new non-destructive method for visualizing the 3-D distribution of electromagnetic power absorption by using MTLC.

The transparency phantom for this method is developed. The substrate material for the phantom is carrageenan. Values of complex permittivity for the phantom can be controlled by the concentration of propylene glycol and KCl mixed in it. The electromagnetic power absorption could be visualized by using the phantom. It suggests that this



(a) t=10s (b) t=20s (c) t=30s

Fig.6 The Upper row: 2D temperature visualization in anterior chamber, the lower row: 2D temperature value distribution in a time sequence.

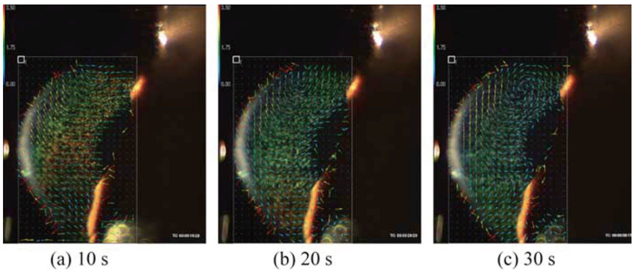

(a) 10 s (b) 20 s (c) 30 s

Fig.7 Time development of the velocity distribution of aqueous humor with 2D PTV method.

new method has capability to reconstruct the 3-D distribution of power absorption due to RF-EMF.

We performed the simultaneous measurement technique for time development of the temperature distribution and the flow velocity distribution within anterior chamber. This technique enables to analyze thermal transportation in ocular tissue under the MMW exposure, and will make clear the temperature elevation mechanism.

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