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Estimation of thermal distribution in tissue mimicking phantom made of carrageenan gel

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1. Introduction

To secure the safety in designing the medical ultrasonic devices, the temperature elevation effect in human tissue by the ultrasonic power should be estimated[1)]. However, it is impossible to measure the temperature elevation in human tissue non-invasively, and a tissue mimicking phantom is generally used to verify the temperature elevation caused by ultrasound. In the previous works, we have introduced a tissue mimicking phantom made of agar or gelatin to visualize temperature distribution using a thermochromic material that discolors at critical temperature[2)]. The temperature elevation can be observed in real-time since the thermochromic material is reversible and its response is fast. However, there are some problems such as low transparency or low melting point in the phantom made of agar or gelatin. In this study, we propose a tissue mimicking phantom made of carrageenan, which is apt for visualizing temperature elevation owing to its high transparency and melting point[3)]. First, the tissue mimicking phantom of which acoustic properties are similar to those of human tissue is fabricated. Then, by the use of this phantom, the temperature elevation distribution is estimated quantitatively and is compared with the theoretical results calculated with Fourier transformation.

2. Theory

To calculate the temperature distribution in the phantom material, Fourier transformation is adopted in the bio-heat transfer equation. The temperature distribution $T(x,t)$ in the phantom material is governed by[4)]

$$\rho_t C_t \frac{\partial T(x,t)}{\partial t} = k_t \nabla^2 T(x,t) + Q(x,t), \qquad (1)$$

where, x is the spatial coordinates, t the time parameter, and ρ_t and C_t respectively refer to the tissue density and specific heat. k_t is the thermal conductivity. $Q(x, t)$ is the rate of the heat per unit volume of tissue produced by the source. With Fourier transformation of Eq. (1) over the space coordinates, bio-heat transfer equation can be represented by

$$A\frac{\partial T^*(v,t)}{\partial t} = -4\pi^2 v^2 B \nabla^2 T^*(v,t) + Q^*(v,t). \qquad (2)$$

If the change of Q is constant for t, and $T^*_{\mathrm{int}}(\nu)$ is the Fourier transformation of the initial temperature distribution, the solution of Eq.(2) can be obtained as following.

$$T^*(v,t) = T^*_{int}(v) exp\left(-\frac{4\pi^2 v^2 Bt}{A}\right) + \frac{Q^*(v)}{4\pi^2 v^2 B}\left\{1 - exp\left(-\frac{4\pi^2 v^2 Bt}{A}\right)\right\} \qquad (3)$$

The temperature spatial distribution $T(x, t)$ can be obtained by inverse Fourier transformation.

3. Experiment

Carrageenan is the polysaccharide that is extracted from certain genera of red seaweeds such as Chondrus, Gigartina, Eucheuma, Furcellaria, Phyllophora, etc[3)]. In this study, the tissue mimicking phantom was fabricated with 10% carrageenan powder, and the physical properties of the phantom are listed in **Table I.**

Table I Physical properties of tissue mimicking phantom.

Sound speed(m/s)	Attenuation coefficient(dB/cm/MHz)	Density(kg/m^3)
1518.27	0.4656	1039.87
Specific heat(J/kg/K)	Thermal conductivity(W/mK)	Transparency (%)
3964.28	0.5574	84

The sound speed and the attenuation coefficient in the table were measured by the transmission method, and the specific heat and thermal conductivity were measured with a Thermal conductivity analyzer (C-Therm TCi™, Technologies Ltd.). The transparency of the phantom was measured with a transparency meter (TURBISCAN LAB, Formulaction Inc.). The critical temperature of the thermochromic material which was used to observe temperature change in the phantom was 30°C, and the mean particle size was 1μm. The focused ultrasonic transducer to radiate the focused ultrasound has 57.2 mm diameter, 820 kHZ resonant frequency, and 61.5 mm focal point. A circular plane transducer with 50 mm diameter and 673 kHz resonant frequency was used for the plane ultrasound. The plane or the focused transducer was installed on a side of an acrylic box, and the tissue mimicking phantom was filled in the box. The therochromic film made of thermochromic material was inserted into the surface of the acoustic axis of the transducer. The temperature elevation caused by ultrasound from the transducer was recorded with a digital camera.

4. Result

The visualization results of temperature distribution on the plane including acoustic axis of the transducers are shown in **Fig. 1**. Figure 1(a) shows that a complicated discolored-pattern appears in the thermochromic film due to the plane ultrasound in the near-field of the circular transducer. In the case of the focused ultrasound, a high temperature area appears in the limited region

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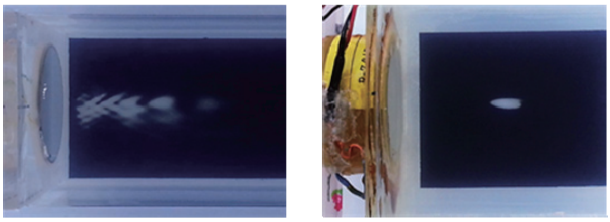


(a) (b)

Fig. 1 Visualization photograph of temperature elevation inside the phantom caused by (a) plane and (b) focused ultrasound.

near the focal point of the transducer, as shown in Fig. 1(b). In order to determine the relationship between the temperature elevation and the pixel data of the discolored area in the tissue mimicking phantom, a thermometer (GT309 Giltron, Taiwan) was set on a point on the thermochromic film and the pixel data from the image were recorded with a digital camera, as shown in **Fig. 2**. Then the temperature and the color change on the point were recorded with a thermocouple and the digital camera, respectively.

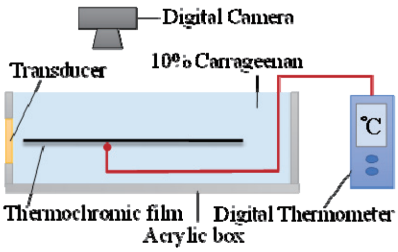
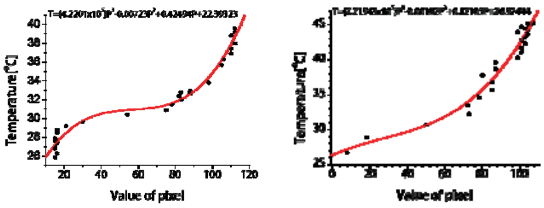


Fig. 2 Experimental set up

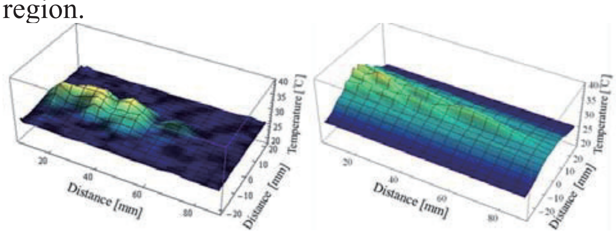
The degree of discoloring was transformed into the value of pixel data with the digital image processing, then the relationship between the pixel data P and the elevated temperature T was determined using a cubic regression function, as shown in **Fig. 3**.



(a) (b)

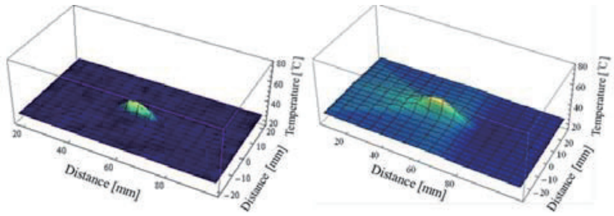
Fig. 3 Fitted temperature elevation function of pixel data value at discolored point caused by (a) plane and (b) focused ultrasound.

Applying the above relationship to the image of Fig. 1, we can obtain the temperature distribution on the surface of the acoustic axis in phantom quantitatively, as shown in **Fig. 4** and **5**. Fig. 4(a) shows the quantitative data of temperature elevation caused by the plane ultrasound, and the data were obtained by applying the relationship of Fig. 3(a) to the image of Fig. 1(a). From this result, we can see that the temperature on the surface including acoustic axis in the tissue mimicking phantom is distributed from 25°C to 30°C. The temperature distribution was calculated theoretically with inverse Fourier transformation of Eq. (3), as shown in Fig. 4(b). The result shows a complicated pattern of temperature distribution in the near-field, with temperatures ranging from 25°C to 33°C. Fig. 5 shows the temperature elevation distribution caused by the focused ultrasound. Fig. 5(a) is the measured result and Fig. 5(b) is the calculated one. These results coincide with each other. However, the regression function of Fig. 3(b) cannot fit the pixel data in low temperature. For this reason, the pattern due to small variation in the low temperature range, which appears in the calculated result, does not appear in the measured one. The agreement between the calculated and measured result is good in the area and shape in the high temperature region.



(a)Measured (b) Calculated

Fig. 4 Temperature elevation distribution caused by plane ultrasound in tissue mimicking phantom.



(a)Measured (b) Calculated

Fig. 5 Temperature elevation distribution caused by focused ultrasound in tissue mimicking phantom.

5. Summary

In this study, a temperature visualization method with a tissue mimicking phantom was proposed. For the experiment, a tissue mimicking phantom was fabricated with carrageenan gel, which has high transparency for the visualization and also, of which acoustic characteristics are similar to those of human tissue. The thermochromic film was set on the surface including the acoustic axis, and the temperature elevations caused by the plane and the focused ultrasounds was visualized noninvasively. The visualized image provided quantitative data of the temperature elevation in the phantom through an image processing method. The results showed good agreement with the calculated results by using the bio-heat transfer equation with Fourier transformation.

Acknowledgment

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