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Thermal simulation of cavitation enhanced ultrasonic heating verified with tissue mimicking gel

生体模擬ゲル中でのキャビテーション気泡を考慮した熱伝導シミュレーション

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1. Introduction

High intensity focused ultrasound (HIFU) is a noninvasive method of cancer therapy. During HIFU treatment, cavitation bubbles can be generated around the focal spot because of high intensity. They can be very useful to make the treatment more efficient because they enhance the heating effect of ultrasound.

Thermal simulation in a HIFU field is essential for treatment planning of safe thermal therapy. To utilize cavitation for clinical HIFU treatment, the thermal simulation considering the heating effect of cavitation bubbles should be performed.

The “Triggered HIFU” exposure sequence [1] was chosen to generate cavitation bubbles in prior to ultrasonic heating. It has two components, the very high-intensity short pulse (called “trigger pulse”) for cavitation inception, and the low-intensity long burst (called “heating waves”) for heating through oscillating cavitation bubbles.

The temperature rise at the focal spot was measured in two conditions-: with and without cavitation bubbles, in other words, with and without the “trigger pulse”. Cavitation inception was observed in two ways. Cavitation bubbles were detected by FFT analysis of the backscattered ultrasound signal. The volume of cavitation inception was measured by high-speed camera observation and used in the thermal simulation.

2. Experimental Methods and Simulation Model

2.1 HIFU Exposure

HIFU Phantom Material (ONDA), whose property was close to a biological tissue (e.g, specific heat 3850 J/kg-K, attenuation coefficient 0.6 dB/cm-MHz), was used as the target. Focused ultrasound was generated by a spherical PZT transducer with a resonant frequency of 1.12 MHz, a diameter of 70mm, and a focal length of 70mm was used. **Fig. 1** shows a schematic of the ultrasonic waveform. The intensity of the trigger pulse was 20 kW/cm^2, and that of heating waves was 100 W/cm^2. The duration of the trigger pulse was 100 μs, and that of heating waves was 5 s.

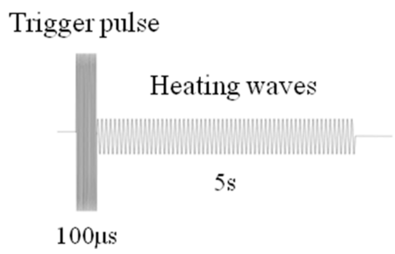

Fig.1 Schematic of ultrasonic waveform for triggered HIFU exposure.

2.2 Experimental setup

Fig. 2 shows a schematic of the experimental setup. The water in the tank was kept at 35-36 °C and continuously degassed. The backscattered signal was measured by a focused hydrophone (H10CF, Toray Engineering), and analyzed using FFT. The temperature rise was measured by a thermocouple 0.13 mm in diameter (SUS316, CHINO), whose tip was located at the focal spot. Cavitation bubbles were optically captured by a high-speed camera (Phantom v310, Nobby Tech).

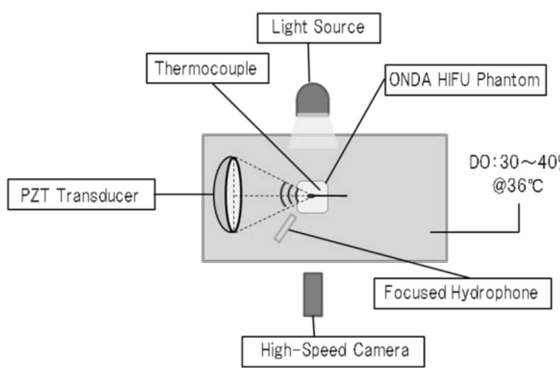

Fig.2 Schematic of experimental setup.

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2.3 Simulation model

The thermal simulation was based on a three-dimensional heat conduction equation:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_P}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{Q}{\rho C_P} \qquad (1)$$

where T is the temperature rise, and Q is the heating power applied via ultrasound in W/m^3. In this study, we approximated the second order spatial differential term as centered spatial difference. Q is equal to 2αI, where α is the ultrasonic absorption coefficient, and I is the ultrasound intensity. The absorption coefficients obtained from the experiments in two conditions (with and without cavitation) were used in the thermal simulation.

3. Results and Discussion

3.1 Experimental results

Fig. 3 shows the temperature rise, obtained from of the experiments in two conditions. These results were averaged for 5 trials. The temperature at the focal spot was 42.82 ± 0.52 °C in the condition without cavitation (the solid line), and the 47.46 ± 0.17 °C with cavitation (the dotted line). The temperature rise curve clearly shows that cavitation bubbles significantly increased the absorption coefficient. From their slopes, the absorption coefficient was calculated to be 4.37 Np/m and 68.2 Np/m in the conditions without and with cavitation, respectively, using a double exponential fitting. These values were used in the thermal simulation.

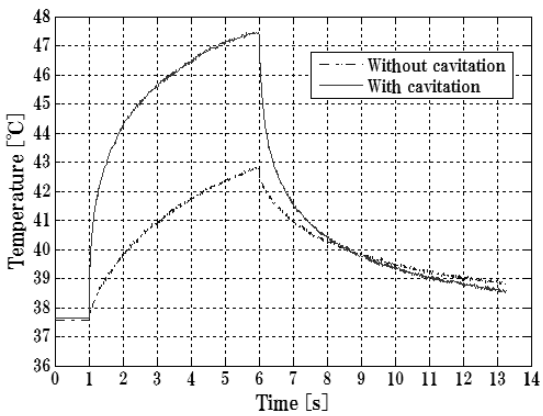

Fig.3 Experimental results of temperature at focal spot.

3.2 Simulation results

Fig.4 shows simulation results of the temperature at the focal spot in the two conditions. In the condition without cavitation, the result was very close to the experiment. In the condition with cavitation, it was also close to the experiment with a slight difference.

3.3 Discussion

The reasons for the difference between experimental and simulation results are probably the error in the estimation of the cavitation inception region and in the approximation of double exponential fitting, and the viscous heating [2]. The region of the cavitation inception was estimated by visual observation, which is difficult to be accurate. The temperature rise curves can potentially have an infinite number of time constants, to which a simple double exponential fitting may not be enough for a higher accuracy. Furthermore, the viscous heating due to the difference in particle velocity between the thermocouple and the surrounding tissue cannot be ignored in spite of the thickness of the thermocouple. These factors are future agenda.

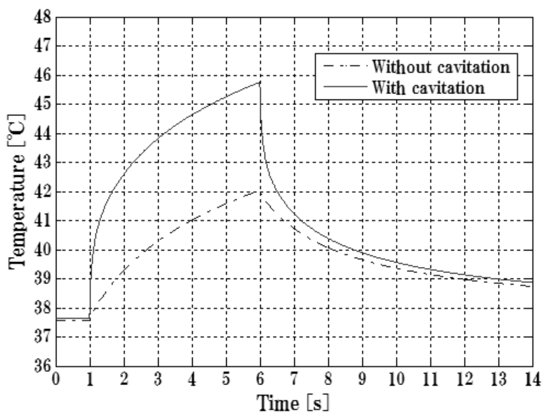

Fig.4 Simulation results of temperature at focal spot.

4. Conclusion

In this study, we have built a thermal simulation taking the heating effect of cavitation bubbles into account using their absorption coefficient obtained from the experiment.

References

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