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Analysis of Ultrasound-Enhanced Heating in near and far Vicinity of Cavitation Area
キャビテーション気泡発生領域近傍および遠方における
超音波加熱増強効果の解析

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1. Introduction

High intensity focused ultrasound (HIFU) is a noninvasive method for the treatment of cancer but has a problem of a long treatment time in treating a large tumor. During HIFU exposure, cavitation bubbles can be generated around the focal spot because of high intensity. The bubbles cause the scattering of the ultrasonic waves, but can be useful to make HIFU treatment more efficient because they enhance the heating effect of ultrasound through their oscillation.[1)]

In order to measure the effect of cavitation-enhanced heating, we make a temperature rise simulation model applicable to both near the cavitation area and the far vicinity of cavitation area by taking both ultrasonic absorption and scattering by cavitation microbubbles into account. The model also takes viscous heating artifact into account. The temperature rise in tissue-mimicking gel was measured and compared with the simulation model.

2. Materials and methods

2.1 Ultrasonic exposure sequence

Fig. 1 shows a schematic of the ultrasonic waveform of the exposure sequence, named "repeatedly triggered HIFU heating"[2)] used in the following experiments. In our previous study, an efficient method called "triggered HIFU heating", in which cavitation bubbles are induced to enhance the HIFU heating, was investigated.[3,4)] The waveform has two components; a very high-intensity short pulse for cavitation inception called as the "trigger pulse" and a low-intensity long burst for heating through oscillating cavitation bubbles called as the "heating waves". We also used a sequence without "trigger pulse" to measure the temperature evaluation without the enhancement by cavitation. The trigger pulse was focused at 3 mm beyond the focal point because cavitation bubble cloud tends to grow backward from its focal point.

Fig. 2 shows a schematic of the experimental setup. The array transducer (Imasonic) had outer and inner diameters of 100 and 36 mm, respectively, and a geometric focal length of 100 mm. PAA (poly acryl amide) gels containing a BSA concentration of 15 % were used as transparent tissue-mimicking targets for the ultrasonic exposure. In order to measure the temperature evaluation induced by HIFU, a sheathed thermocouple, 0.15 mm in diameter was located at a lateral distance of 2.7 mm above the focal point of the transducer to reduce the effect of viscous heating.

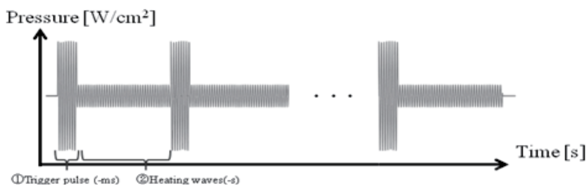

Fig.1 Repeatedly triggered HIFU heating

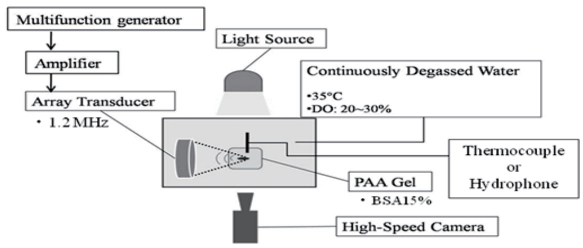

Fig. 2 Schematic of experimental setup

2.2 Simulation model

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

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

where T is the temperature rise, t is the time, ρ is the density, C_p is the specific heat capacity, k is the thermal conductivity, I is the intensity of ultrasound, W_b is the blood perfusion rate, C_b is the specific heat capacity of blood, and T_b is the blood temperature. The heating value Q, generated by ultrasonic absorption is written as

$$Q = 2AI \qquad (2)$$

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Here, nonlinear propagation and absorption were ignored. The third term on the right side of Eq. (1) is necessary to simulate in vivo temperature, but was neglected in this study because of no blood flow in the tissue-mimicking gel.

In this study, parameter A in Eq. (2) consisted of α_h, α_c, and α_v, which are the absorption coefficients of tissue-mimicking gel, cavitation-enhanced heating, and viscous heating, respectively. The volume with α_c was determined from the distribution of cavitation microbubbles observed by a high-speed camera and approximated by an ellipse with long and short axes of 9 and 3.6 mm, respectively. The viscous heat is generated by the acoustic motion of the thermocouple relative to the surrounding material, and therefore the interface between them and its vicinity is heated. Hence, α_v was assumed to exist only at the tip of the thermocouple at 2.7 mm above the focal point. (**Fig. 3**)

The scattered ultrasonic intensity field, I_s, was calculated as the incoherent sum of ultrasound scattered by microbubbles uniformly distributed in the ellipse. Then, Q is written as

$$Q = 2\alpha_h I + 2\alpha_c I + 2\alpha_v I + \alpha_s I_s \quad (3)$$

where α_s is the absorption coefficient for the scattered ultrasound.

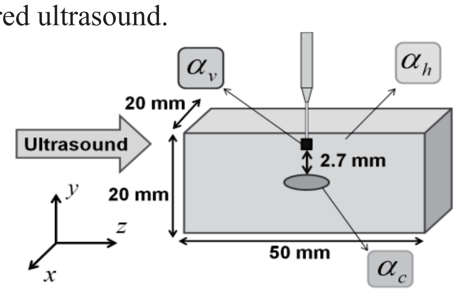


Fig. 3 model of simulation

2.3 Calculation of the absorption coefficients

In order to obtain the coefficient of ultrasonic absorption α_h, α_c, α_v, and α_s, curve fitting between the experimental and simulation results using a least-squares method was performed.

3. Results and Discussion

3.1 Temperature rise by heating waves only

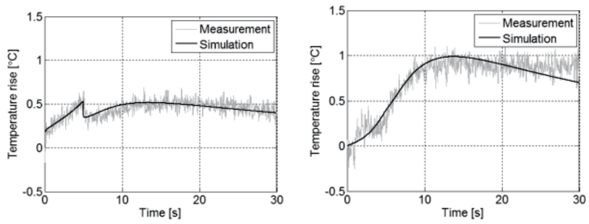
Fig. 4 (a) shows the comparison between experimental and simulation results in the case of the heating waves at 2.7 mm above the focal point. The coefficients of ultrasonic absorption of the gel, α_h, and viscous heating, α_v, were obtained as 4.34 and 0.17 Np/m, respectively.

3.2 Temperature rise using repeatedly triggered HIFU heating

Fig. 4 (b) shows the comparison between experimental and simulation results of the cavitation-enhanced heating effect also at 2.7 mm above the focal point. This was calculated by subtracting the temperature rise only by heating waves from the temperature rise by repeatedly triggered HIFU heating. The coefficients of ultrasonic absorption of the cavitation bubbles, α_c, was obtained as 2.75 Np/m.

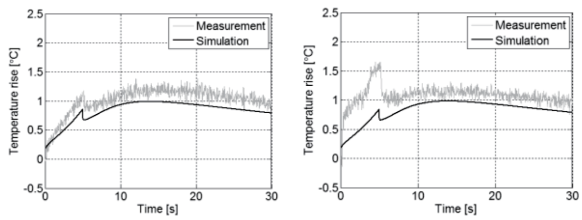
3.3 Temperature rise at far vicinity

Fig. 5 (a) and **(b)** show the comparison between experimental and simulation results by repeatedly triggered HIFU heating at 4 mm in front of and beyond, respectively, 2.7 mm above the focal point. Simulation underestimated the temperature rise at far vicinity of the focal point when the of ultrasonic absorption coefficients obtained at the nearer vicinity was used.



(a) Heating waves only (b) Effect of cavitation-enhanced heating

Fig. 4 Result of fitting



(a) In front of (b) Beyond

Fig. 5 Result of simulation

4. Conclusion

In this study, a simulation model, taking the effects of cavitation microbubbles into account, generally reproduced the experimental results. However, simulation underestimated the temperature rise at the far vicinity of the focal point. Improvement of simulation models and accurate control of cavitation bubbles in experiments will be necessary.

References

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