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Analysis of acoustic absorption distribution during bubble-enhanced HIFU heating by fitting simulations to temperature measurements

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1. Introduction

High-intensity focused ultrasound (HIFU) therapy is a cancer treatment method in which ultrasound wave is focused on a target tissue to heat and coagulate it. This method has the drawback of long treatment time due to the small treatment region in one sonication and the necessity for the cooling time between consecutive HIFU exposures. To improve the heating efficiency, trigger HIFU sequence[1)] has been developed to efficiently utilize the heating enhancement effect of cavitation bubbles generated by highly negative pressure in the focal region of HIFU. This sequence consists of alternate sonication of trigger pulse (TP), which is a high-intensity, short-duration pulse wave to generate bubbles, and heating burst (HB), which is a low-intensity, long-duration burst wave to continuously oscillate the bubbles in volume. The aim of this study is to investigate the heating effect of cavitation bubbles by fitting temperature rise obtained by simulation to that measured with thermocouples.

2. Materials and Method

2.1 Experimental setup

Fig. 1 shows the experimental setup. A 128-ch array transducer with a resonance frequency of 1 MHz, a diameter of 147.8 mm, and a focal length of 120 mm was used. Experiments were performed in degassed water. A 1.0% low-melting point agarose gel containing 23 mm-thick chicken breast was used as a HIFU exposure target. Thermocouples were placed 3.7 mm above the focus and 3.2 mm in front of and behind (thermocouples A and B).

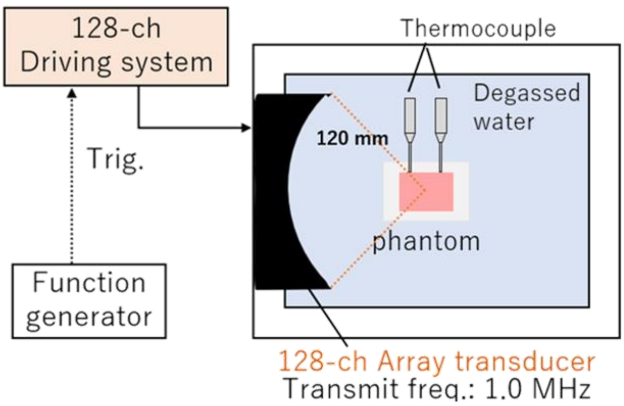

Fig.1 Schematic of experimental setup

2.2 HIFU exposure sequence

The sequence used in this study consisted of duration of 0.1 ms for TP at a total acoustic power (TAP) of 3200 W and 43.9 ms for HB at a TAP of 40.4 W, with an intermission of 3 ms before and after HB. The cycle time was 50 ms and this cycle was repeated 10 times for a total of 0.5 s of sonication. The sonication was one order of magnitude shorter than usual to avoid thermal coagulation of the tissue.

2.3 HITU simulator [2)]

HITU simulator used in this study is applicable to a layered model consisting of layers of water and chicken breast. The layer of chicken breast was set at 5 mm in front of and behind the focus and the rest were layers of water. The model equations of HITU simulator are the wide-angle KZK (WAKZK) equation and the bio heat transfer (BHT) equation. The WAKZK equation is given below.

$$\frac{\partial^2 p}{\partial t^2} - c^2\nabla^2 p + 2c\frac{\partial}{\partial t}\left[\left(\alpha(\omega) * p(\omega)\right)\right] = \frac{\beta}{\rho c^2}\frac{\partial^2 p^2}{\partial t^2} \quad (1)$$

Where p (Pa) is pressure, t (s) is time, c (m/s) is sound velocity. ∇^2 (cm^{-2}) is Laplacian in cylindrical coordinates, α (cm^{-1}) is the attenuation / dispersion function, ω (rad/s) is angular frequency, β (dimensionless) is nonlinear parameter, and ρ (kg/m^3) is mass density. This equation was used to analysis the acoustic field and heat source distribution generated by HIFU.

The heat sources obtained by the WAKZK equation was used as an input to the BHT equation which outputs the temperature distribution as a function of time. The BHT equation is given below.

$$\rho C_p \frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q \quad (2)$$

Where C_p (J/kg°C) is heat capacity, T (°C) is temperature rise above equilibrium, κ (W/m°C) is thermal conductivity.

2.4 Fitting the simulation to the measured data

First, the temperature rise without the heating effect of bubbles was calculated, denoted as T. Then, the temperature rise due to the heating effect of bubbles were calculated using the heat sources within the selected area shown in **Fig. 2**, because cavitation bubbles generated by TP are distributed near the focus. In addition, to account for the non-uniform distribution of cavitation bubbles, this area was further divided into ten parts, and temperature rise calculations were performed for each heat source, resulting in values $T_1, T_2, \ldots$ and T_{10}. Then, T, $A_1 * T_1$, $A_2 * T_2, \ldots$ and $A_{10} * T_{10}$ were summed up together. (A_i are arbitrary real number.) These value of A_i were determined by the least squares method to minimize the error between the summed-up temperature rise and the measured temperature rise.

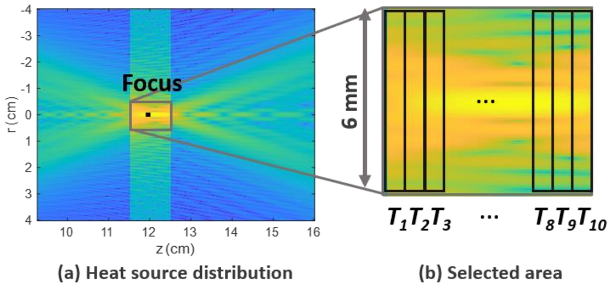

Fig.2 Heat source distribution used for simulation

3. Results and Discussion

Fig. 3(a) shows a graph of the measured temperature rise with the thermocouples A and B from the start of the HIFU exposure to 40 s. HIFU is exposed only for the time in the bold line. During the HIFU exposure, a rapid temperature rise can be seen. This is an artifact called "viscous heating[3]" due to the frictional heat generated by the velocity difference between the thermocouples and surrounding chicken breast. From this graph, it can be seen that the temperature rise at the front side (thermocouple A) is higher. This result is thought to be caused by the phenomenon called "shock scattering[4]" in which bubbles are generated back toward the front side. Cavitation bubble cloud could be generated in front of the focus due to the shock scattering and the heating effect of bubbles enhanced the temperature rise at the front side (A) stronger.

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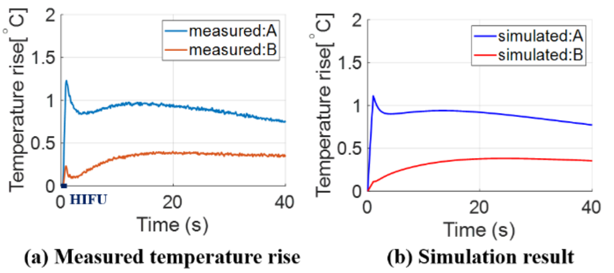

Fig.3 Measured and simulated temperature rise

Fig. 3(b) shows a graph of the summed-up temperature rise. The rapid temperature rise due to viscous heating was reproduced by setting a heat source that imitates the size of the thermocouple. The RMSE at front side (A) is 0.040°C and at back side (B) is 0.023°C. Determining the values of $A_i$by the least squares method resulted in a value of 1.5 for A_1, 6.5 for A_2, 1.5 for A_{10} and zero for the other values. The vales of A_1 and A_2 mean that the HIFU energy absorption in front of the focus is a significant contributor to the temperature rise under the present experimental conditions. The reason for the zero values for A_3 to A_9 may be that the HIFU was shielded by the bubble cloud in front of the focus generated through the shock scattering and the HIFU energy did not reach the region of A_3 to A_9 enough. The value of 1.5 for A_{10} is probably because some HIFU energy that was not absorbed or shielded by the bubbles in the front side region was absorbed in the back side region.

4 Conclusion

As a result of the analysis, it is clear that the HIFU energy absorption in front of the focus is a significant contributor to the temperature rise under the present experimental conditions. This result is considered to be caused by a phenomenon called "shock scattering" where bubbles are generated back to the front side. In the future, we will investigate under various conditions of TP and observe the spatial distribution of cavitation bubbles.

References

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