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Effect of cavitation bubble position on temperature rise in bubble-enhanced ultrasonic heating.

Taisuke Sato[1†‡], Sota Kannoto[2], and Shin Yoshizawa[1,2,3*] ([1]Grad. School of Eng., Tohoku Univ.; [2]Grad. School of Biomed. Eng., Tohoku Univ.; [3]SONIRE Therapeutics)

1. Introduction

High-intensity focused ultrasound (HIFU) therapy is a treatment method in which ultrasound wave is focused on the target tissue to heat and coagulate it. However, the treatment time is long due to the small focal region and the cooling time required between consecutive HIFU exposures. To improve the heating efficiency, a technique using cavitation bubbles has been proposed. 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 irradiation 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 generated bubbles in volume. In a HIFU treatment using bubbles, the temperature distribution depends on not only the acoustic properties of the tissue but also the distribution of the bubbles. Therefore, the objective of this study is to investigate the relationship between the bubble region and temperature increase by ultrasound imaging and thermocouple temperature measurements.

2. Materials and Method

1.1 Experimental setup

Fig. 1 shows the experimental setup. An array transducer with a resonance frequency of 1 MHz, a diameter of 147.8 mm, and a focal length of 120 mm was used for HIFU irradiation. Experiments were performed in degassed water. A 1.0% low-melting agarose gel containing 8 mm-thick chicken breast was used as a tissue mimicking phantom. Thermocouples were placed 3.7 mm above the focal spot and 3.2 mm in front of and behind the focal spot (thermocouples A and B). The region of cavitation bubbles during HIFU exposure was observed by ultrasound imaging using a triplet pulse sequence[2)] with an 80-ch sector probe placed in the center of the transducer.

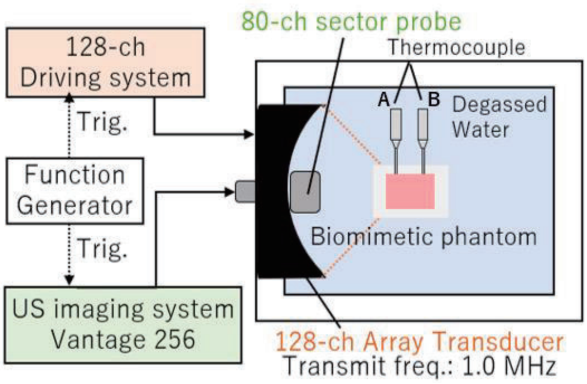

Fig. 1 Schematic of experimental setup.

1.2 Triplet Pulse Sequence

A triplet pulse sequence is a method to extract echo signals from bubbles by transmitting and receiving three pulses with a phase difference by 120 degrees each other and then adding the three received echoes. By adding the three received waves, the fundamental and second harmonic components can be canceled out because of the phase shifts. This means that the signals from a tissue, which is a linear scatterer, are cancelled out. On the other hand, the 1.5-fold harmonic components and the components with a phase difference changed from the transmission, which are contained only in the echoes from the bubbles, are not canceled out and remain. Therefore, the triplet pulse sequence can extract the components from bubbles.

1.3 HIFU exposure and RF data acquisition

Fig. 2 shows the HIFU exposure sequence used in this study. The sequence consisted of three conditions of duration of 0, 100, and 200 µs for TP at an acoustic intensity of 96 kW/cm^2 and 43.9 ms for HB at 0.6 kW/cm^2, with an intermission of 3 ms between TP and HB and about 3 ms after HB. By adjusting the intermission time after the HB, the cycle time was set to 50 ms, and this cycle was repeated 100 times for a total of 5 s of sonication.

RF signals for ultrasound imaging were acquired during the intermission after the trigger pulse to avoid interference from the HIFU. Four diverging waves were transmitted with phase shifts by 120, 0, 180 and 240° at a transmission interval of 200 µs. In the post processing, triplet pulse ultrasound images were obtained from the addition of RF data by transmitting and receiving at 120°, 0°, and 240° phase shifts.

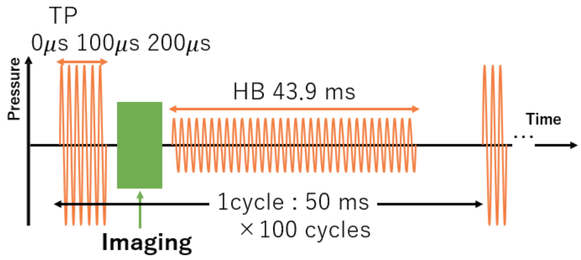

Fig. 2 HIFU exposure sequence

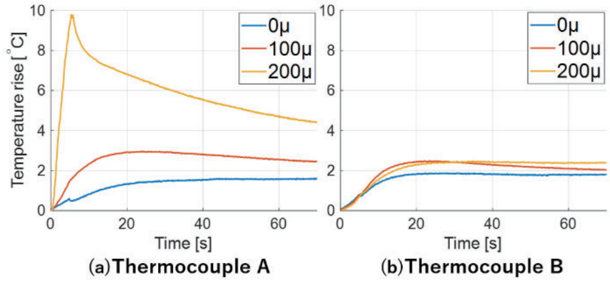

Fig. 3 Temperature rise at thermocouples

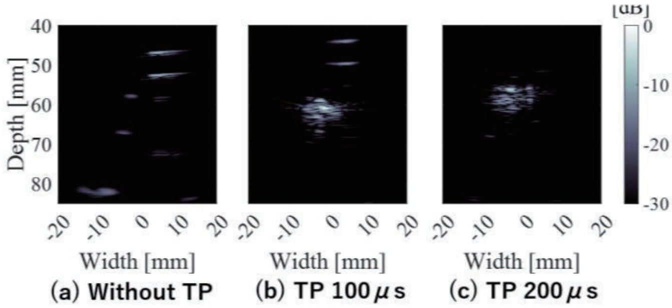

Fig 4 Bubble imaging by triplet pulse sequence

3. Results and Discussion

Fig. 3 shows a graph of the temperature rises at thermocouple A and B from the start of the HIFU exposure to 70 s. For the TP duration of 100 μs, the average of three samples is shown; and for the 0 and 200 μs conditions, the average of two samples is shown. From Fig. 3(a), it can be seen that as the TP duration time increases, at the front side (thermocouple A) temperature rise becomes higher. In particular, the temperature rise is steep for the duration of 200 μs. On the other hand, the temperature rise at the far side (B) shows little change when comparing the cases of 100 and 200 μs TP duration, although there is a slight change with and without TP. This result suggests that the amount of bubbles generated near the thermocouple B does not change much as the duration time of TP increases.

Fig. 4 shows ultrasound images obtained by the triplet pulse method when the TP duration time was set to 0, 100, and 200 μs. The images were obtained at the second cycle of 100 cycles in the sequence. The formation of bubbles cannot be confirmed without TP, while a bubble region can be seen at a depth of around 60 mm with TP. Since the focus of the transducer used in this study is located at 70 mm deep, it is seen that bubbles are generated back to the front side due to a phenomenon called shock scattering[4]. In addition, comparing the two cases with TP, the bubble region in the case with 200 μs TP duration can be confirmed to be approximately 5 mm closer toward the transducer. This is thought to be caused by the repetition of shock scattering caused by the longer duration time of TP, which resulted in the further growth of cavitation toward the transducer.

From Figs. 2 and 3, it can be seen that the temperature rise is greatly influenced by the bubble generation region. This effect is particularly clear when comparing thermocouple A and B. When the duration time of TP is changed, the temperature rise at the front side changes significantly, but there is almost no change at the back side, which is thought to be due to the growth of bubbles toward the front side. The steep temperature rise at the front side with a TP duration of 200 μs is considered to be caused by the bubbles extending toward the transducer, which increased acoustic absorption around the position of thermocouple A.

1.3 Conclusion

The measurement system used in this study provided qualitatively reasonable results that the location of bubble generation has a significant effect on the temperature rise. In the future, we plan to estimate the temperature distribution by fitting the temperature data obtained by this measurement system to those by simulation.

References

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E-mail: †taisuke.sato.r1@dc.tohoku.ac.jp
*shin.yoshizawa.e7@tohoku.ac.jp