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Experimental investigation on effect of focal scanning in ultrasound propagation direction on bubble and coagulation regions in bubble-enhanced ultrasonic heating

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1. Introduction

High-intensity focused ultrasound (HIFU) treatment is a minimally invasive cancer treatment where high-intensity ultrasound energy is focused from outside the body onto the targeted region, causing the coagulation and necrosis of the cancerous tissue due to temperature increase. HIFU treatment is time-consuming because the focal region is much smaller than the region to be treated and the cooling time is required between the HIFU shots to prevent intervening normal tissues rom excessive temperature rise. Therefore, a highly efficient ultrasonic heating method is required.

One technique to improve the heating efficiency of HIFU is to use cavitation bubbles. Cavitation bubbles are generated by highly negative pressure and the volumetric oscillation of bubbles can enhance ultrasonic heating[1)]. "Trigger HIFU sequence" has been proposed as a HIFU irradiation method to efficiently utilize the heating enhancement effect by bubbles[2)]. The sequence consists of the repetition of "trigger pulse", a high-intensity, short-duration pulse wave to generate cavitation bubbles, and "heating burst", a low-intensity, long-duration burst wave to cause sustained volumetric oscillation of the generated bubbles. To ensure the effectiveness and safety of the enhancement effect of bubbles, it is important to understand the relationship between the bubble generation region by trigger pulse and the coagulation region. In this study, the effect of the focus scanning of the trigger pulse in the ultrasonic propagation direction on the bubble and coagulations regions was experimentally investigated by high-speed camera imaging.

2. Materials and Method

2.1 Experimental setup

Fig. 1 shows the experimental setup. A 128-element array transducer with a diameter of 147.8 mm and a focal length of 120 mm was used to generate HIFU at a frequency of 1 MHz. Experiments were conducted in degassed water (dissolved oxygen saturation 20~25%). A chicken breast tissue with a thickness of 2 mm thick embedded in 0.8% low-melting-point agarose gel, shown in **Fig. 2**, was exposed to HIFU. During the HIFU exposure, high-speed images were taken at 500 fps by backlight using a pulsed laser with a pulse duration of 200 ns.

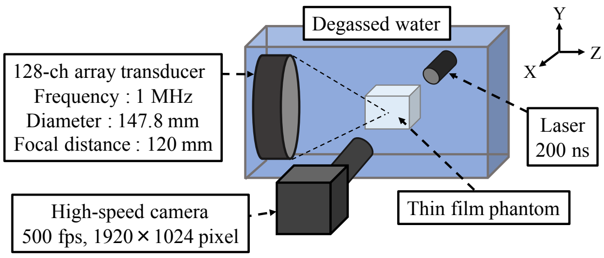


Fig. 1 Experimental setup.

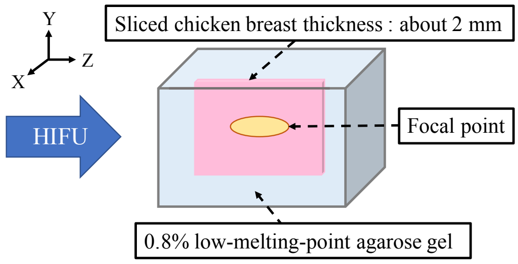


Fig. 2 Thin film phantom.

2.2 HIFU sequence and image processing

Fig. 3 shows the HIFU irradiation sequence. Trigger pulses with 0.025 ms at 96 kW/cm^2 and heating bursts with 43.9 ms at 3.5 kW/cm^2 were used in the sequence. A HIFU pause of 3.075 and 3 ms before and after the trigger pulse was provided, respectively. The sequence of 50 ms per cycle was repeated 100 times for a total of 5 s of irradiation. The trigger pulse was focused at the same position or 4 mm beyond the heating burst focus. The focal shift of 4 mm of the trigger pulse was set considering the fact that cavitation clouds are generated in front of the focus through shock scattering[3)]. As shown in **Fig. 3**, the bubble regions generated by the trigger pulse were obtained by differencing the images taken immediately before and during the trigger pulse, dividing the resulting images by every 1 s from the start of HIFU irradiation, and summing them up for each. In addition, the coagulation regions were obtained by differencing between the images taken before the HIFU irradiation and during the HIFU pause immediately before the trigger pulse.

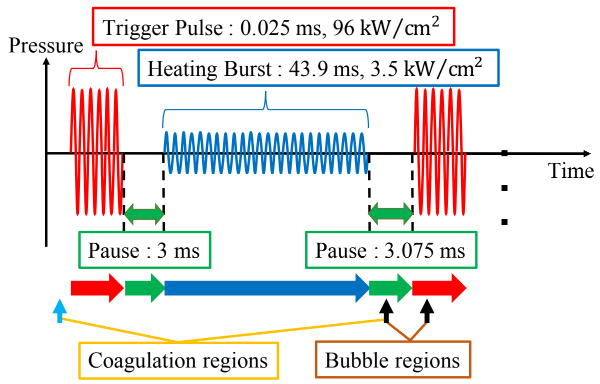
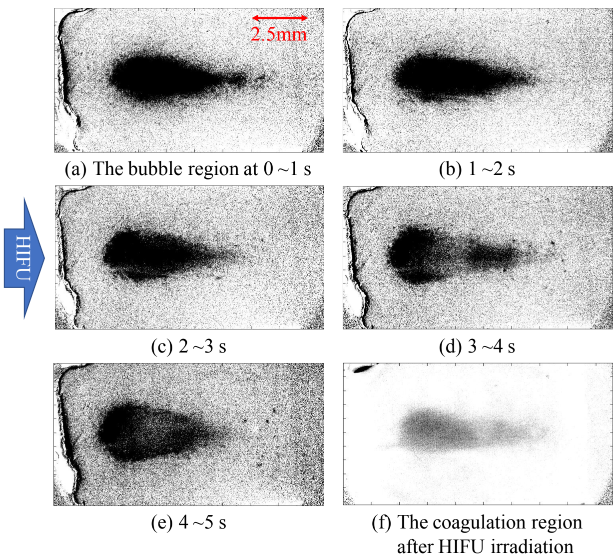


Fig. 3 HIFU irradiation sequence and timing of captured image used for image processing.

3. Result and Discussion

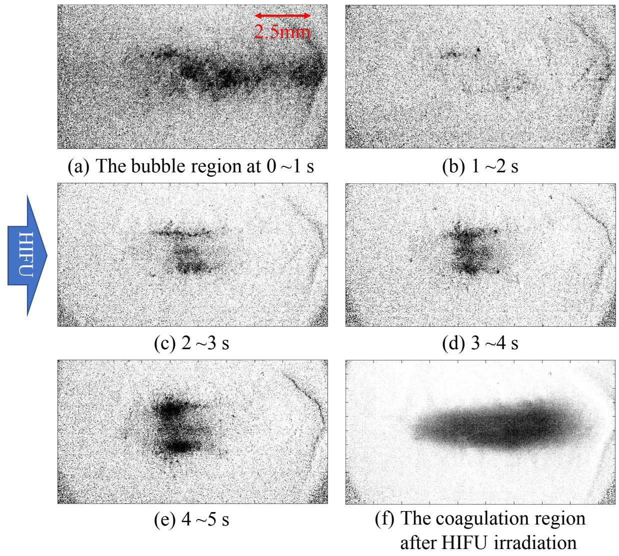
The results of the bubble regions every 1 s and the coagulation regions after HIFU irradiation are shown in **Figs. 4** and **5** without and with the focal shift of the trigger pulse, respectively. In both cases, the image center is the heating burst focal point. In **Figs. 4(a)-(e)** and **5(a)-(e)**, cavitation bubbles were generated in the entire coagulation regions, shown in **Figs. 4(f)** and **5(f)**, until 1 s after the start of irradiation, but after that time, the bubble regions moved toward the front side with the passage of time.

In addition, **Fig. 4** shows that the center positions of the bubble regions and the coagulation regions were shifted in the HIFU propagation direction from the heating burst focus by -0.5, -0.8, -1.2, -1.1, -1.4, and -0.1 mm, respectively, without the focal shift of the trigger pulse. On the other hand, **Fig. 5** shows that they were shifted by 2.0, 0.3, -0.3, -0.4, -0.5, and 0.5 mm, respectively, with the focal shift of



(a) The bubble region at 0 ~1 s (b) 1 ~2 s (c) 2 ~3 s (d) 3 ~4 s (e) 4 ~5 s (f) The coagulation region after HIFU irradiation

Fig. 4 Bubble and coagulation regions without the focal shift of the trigger pulse.



(a) The bubble region at 0 ~1 s (b) 1 ~2 s (c) 2 ~3 s (d) 3 ~4 s (e) 4 ~5 s (f) The coagulation region after HIFU irradiation

Fig. 5 Bubble and coagulation regions with the focal shift of 4 mm of the trigger pulse.

4 mm of the trigger pulse. The results show that the bubble and coagulation regions transitioned in response to the scanning focus of the trigger pulse in the direction of HIFU propagation.

The difference in the regions of cavitation and coagulation suggests that cavitation bubbles generated by the trigger pulse remained due to coalescence and temperature increase caused by HIFU irradiation. It is considered that the shift of the bubble region caused by the reflection of the trigger pulse by the remaining bubbles. It is also thought that the coagulation regions can be matched to the focal region of the heating burst by appropriately setting the amount of focal shift of the trigger pulse.

4. Conclusion

In this study, we experimentally investigated the effect of the focus scanning of the trigger pulse in the ultrasonic propagation direction on the bubble and coagulation regions. The results showed that the bubble and coagulation regions transitioned in response to the focal scan of the trigger pulse. It is thought that the effectiveness and safety in bubble-enhanced HIFU treatment can be improved by matching the coagulation regions to the focal region of the heating burst using an appropriate amount of focal shift of the trigger pulse.

References

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