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Effect of Intermittent Duration of Ultrasound Exposure on Bubble Behavior and Temperature Rise in Bubble-Enhanced Ultrasonic Heating

気泡増強超音波加熱における超音波照射休止時間が気泡挙動及び温度上昇に与える影響

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1. Introduction

HIFU (high-intensity focused ultrasound) is a noninvasive method of cancer treatment. In a HIFU treatment, ultrasound focused at a target tissue causes a significant temperature rise in the focal region. The method has the problem of the long treatment time for a tumor larger than the focal spot. Cavitation bubbles, known to accelerate ultrasonic heating[1)], can be generated in the focal region by a highly negative pressure.

Although a bubble around 1 µm in diameter dissolves within in the order of 1 ms, its lifetime can be elongated by ultrasonic exposure through the rectified diffusion and the coalescence of bubbles. The trigger HIFU sequence was developed for the efficient use of bubble-enhanced heating[2)]. The sequence consists of an extremely high-intensity short pulse called “trigger pulse” for the generation of cavitation bubbles followed by a low- to moderate-intensity long burst called “heating burst” for the cavitation-enhanced heating. Cavitation bubbles can be monitored by ultrasound imaging during the HIFU treatment. Since the therapeutic ultrasound acoustically interferes with the ultrasound imaging, the intermission of HIFU exposure is needed. In this study, the intermission is set between the Trigger pulse and Heating burst. Then, the effect on the generation of cavitation and temperature rise is experimentally investigated using high-speed camera and thermocouples[3)]. The three different durations of intermission were tested.

2. Material and Method

2.1 Experimental Setup

Fig.1 shows the experimental setup. Ultrasound was generated at 1 MHz by a 2D array transducer (Japan Probe) with a diameter of 147.8 mm and a focal length of 120 mm. The transducer was placed in degassed water (dissolved oxygen saturation of 20-25%) and the focal region was set in a tissue-mimicking 1% agarose gel. Three sheathed thermocouples 0.15 mm in diameter were located slightly away from the geometric focal point of the transducer to reduce the effect of viscous heating. Temperature was measured 2.9 mm right above the geometric focal point as well as 4.0 mm in front of and 3.7 mm behind it. It was recorded every 2 ms by a data logger. During ultrasound exposure, cavitation behavior was backlit by a pulsed laser at 640 nm with pulse duration of 20 ns and observed with a high-speed camera.

2.2 Ultrasonic exposure sequence

Fig.2 shows the ultrasound sequences. One cycle of the trigger HIFU sequence was 50 ms and the cycle was repeated 60 times (in total 3 s). The cycle consisted of a trigger pulse for 0.1 ms, intermission time, and a heating burst. The intermission time for a heating burst for 46.9, 43.9, and 36.9 ms was 0, 3, and 10 ms, respectively. The trigger pulse was focused at 3 mm beyond the focal point because a cavitation bubble cloud tends to grow backward from its focal point[4)]. The intensity of the trigger pulse was 190 kW/cm^2. The intensities of the heating burst with intermissions of 0, 3, and 10 ms were 2.4, 2.6, and 3.1 kW/cm^2, respectively, so that all sequences should have the same total acoustic energy.

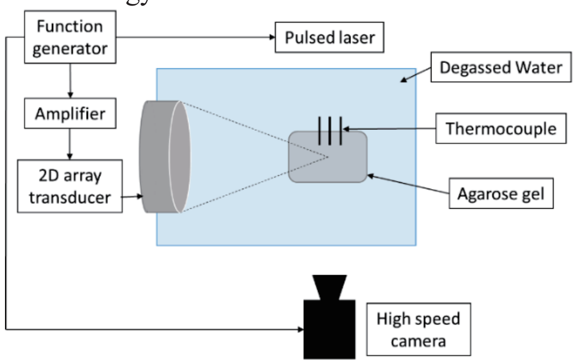

Fig.1 Experimental setup.

3. Result and Discussion

3.1 Cavitation behavior

Fig. 3 shows the high-speed images of cavitation bubbles generated by the three ultrasonic exposure sequences. All images were photographed for 3.417 s with the resolution of 1920×1080 at a frame rate of 60 Hz. The images before the HIFU exposure were subtracted to obtain clear cavitation images.

In comparison with the three images, many

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large bubbles whose resonant frequency is much lower than 1 MHz were generated by the sequence with no intermission time after the trigger pulse. It could be explained that some small bubbles generated by the trigger pulse coalesced during the heating burst exposure before they dissolved when there was no intermission after the trigger pulse.

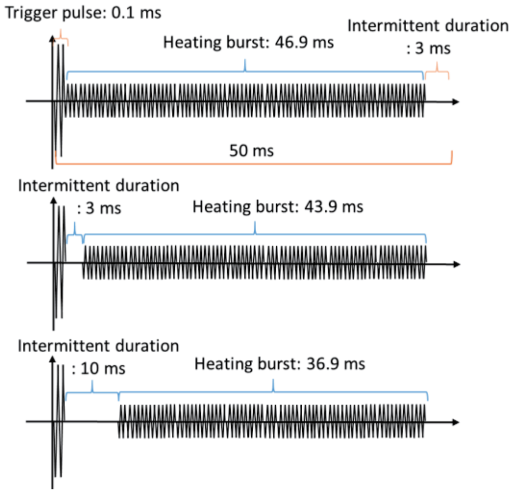
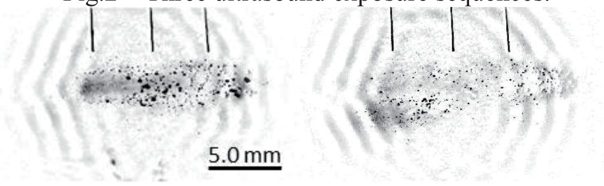


Fig.2 Three ultrasound exposure sequences.



(a) (b)

(c)

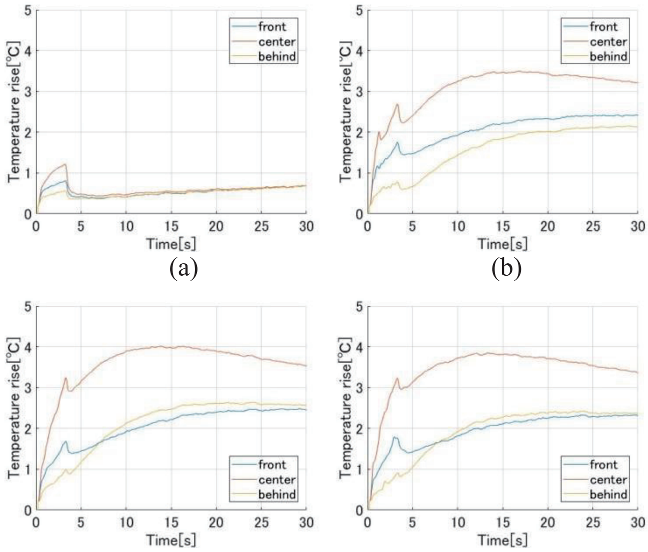
Fig.3 High-speed images of cavitation bubbles at 1.5 s after the start of heating burst exposure when the intermissions after the trigger pulse were (a) 0, (b) 3, and (c) 10 ms.

3.2 Temperature rise

Fig. 4 shows the temperature rise induced by the three ultrasonic exposure sequences and the exposure of heating burst only. The temperature rises with trigger pulses were much higher than those without trigger pulses, showing the effect of cavitation-enhanced heating. The temperature rise at the center was the largest among those at the three measurement points. With the intermission between the trigger pulse and heating burst, the temperatures at the center and behind the focal region became higher.

Exposed to the heating burst, some of bubbles induced by the trigger pulse were forced to coalesce. As a result of the active bubble coalescence, the number of large bubbles, with large acoustic scattering but small heat enhancement, in the focal region increases. This consequently increases acoustic scattering and reduces the heat generation in the focal region.

The result of temperature rises at the center and behind the focus shows that the sequence with intermittent duration has a better efficiency in a cavitation-enhanced HIFU treatment. Additionally, cavitation bubbles generated by the trigger pulse may be monitored by ultrasound imaging with higher sensitivity during the intermission just after the trigger pulse than that after the heating burst.



(a) (b)

(c) (d)

Fig.4 Temperature rise induced by the ultrasonic sequences of (a) heating burst only and (b-d) with trigger pulses. The intermission after the trigger pulse were (b) 0, (c) 3, and (d) 10 ms.

4. Conclusion

In this study, the distributions of cavitation bubbles and temperature rises were compared with and without the intermission between the trigger pulse and heating burst. The result showed that the efficiency of cavitation-enhanced heating was increased with the intermission of 3 and 10 ms between the trigger pulse and heating burst. Also, more symmetric temperature distributions along the HIFU propagation direction were obtained with the intermission, which would contribute to a better accuracy in a cavitation-enhanced HIFU treatment.

References

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