3J4-4

Effect of split-aperture transmission methods on behavior of cavitation bubbles and temperature rise in bubble-enhanced ultrasonic heating

気泡援用超音波加熱における開口分割照射方法の気泡挙動及び温度上昇への影響

Sayaka Ito[1 †], Shin-ichiro Umemura[2], and Shin Yoshizawa[1]
([1]Grad. School of Eng., Tohoku Univ.; [2] Grad. School of Biomed. Eng., Tohoku Univ.)
伊東　沙也伽 [1 †]，梅村　晋一郎 [2]，吉澤　晋 [1]
([1] 東北大院　工，[2] 東北大院　医工)

1. Introduction

HIFU (high-intensity focused ultrasound) is a noninvasive method of cancer treatment. In a HIFU treatment, ultrasound focused on a target tissue causes a significant temperature rise mainly in the focal region, inducing the coagulation of the target tissue. This method has the problem of long treatment time for a tumor larger than the focal spot. It is important to develop a highly efficient method of ultrasonic heating for reduction of the treatment time. During HIFU exposure, cavitation bubbles can be generated by a highly negative pressure in the focal region. These bubbles can enhance the heating effect of ultrasound through their volumetric oscillation[1)].

Although a free bubble around 1 μm in diameter dissolves within in the order of 1 ms, its lifetime can be elongated by the rectified diffusion and the coalescence of bubbles during ultrasonic exposure. The trigger HIFU sequence was developed for efficient enhancement of heating by cavitation bubbles[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. For highly efficient bubble-enhanced heating, it is desirable to avoid the generation of bubbles larger than the resonance size through the coalescence of bubbles induced by Bjerknes forces. In this study, split-aperture transmission methods was applied to the heating burst to investigate the effect of temporal change in acoustic pressure field on the cavitation region and temperature rise.

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%, water temperature of 20–22℃) and the focal region was set in a tissue-mimicking 2% agarose gel. Three sheathed thermocouples 0.15 mm in diameter were located slightly away from the geometric focal point of the transducer to reduce their viscous heating. Temperature was measured 3.7 mm right above the geometric focal point and recorded every 2 ms by a data logger. The distance between the adjacent thermocouples was about 4.0 mm. During ultrasound exposure, cavitation bubbles were backlit by a pulsed laser at 640 nm with pulse duration of 20 ns and observed with a high-speed camera taken at 60 fps.

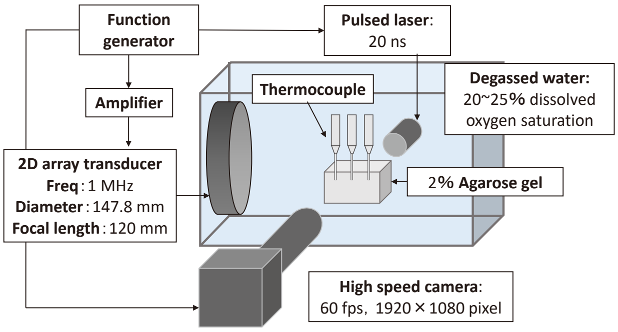

Fig.1. Experimental setup.

2.2 Ultrasonic exposure sequence

Fig.2 shows the ultrasound sequences. One cycle of the trigger HIFU sequence was 50 ms and repeated 60 times (in total 3 s). The cycle consisted of a trigger pulse for 0.025 ms, intermission for 3 ms, and a heating burst for 43.9 ms. Five exposure methods were tested; the first was a full aperture transmission method called standard, the second was the alternate transmission of two element groups consisting of four split apertures, the third was a circular split focus method, the fourth was the alternate transmission of circular split focus and standard, and the fifth was a two split focus method with rotating 90°. The trigger pulse was focused at 6 mm beyond the focal point because a cavitation bubble cloud tends to grow from the focal point to the transducer[3)]. The intensities of the trigger pulse and the heating burst were 145 kW/cm^2 and 2.8 kW/cm^2, respectively.

3. Result and Discussion

3.1 Cavitation behavior

Fig. 3 shows the high-speed images of

sayaka.ito.p3@dc.tohoku.ac.jp

cavitation bubbles generated by the five ultrasonic exposure methods. All images were photographed for 3.417 s with a resolution of 1920×1080 at a frame rate of 60 Hz.

In the images at 44 ms, the cavitation bubbles by the circular split focus method (Fig.2(c)) were widely distributed in the ultrasonic wave propagation direction and the amount was less than other methods. At the end of the exposure, it was observed that the bubbles by the standard method were pushed away from the HIFU focal region. More bubbles remain around the center of the focal region by the four split aperture method than that by the standard method.

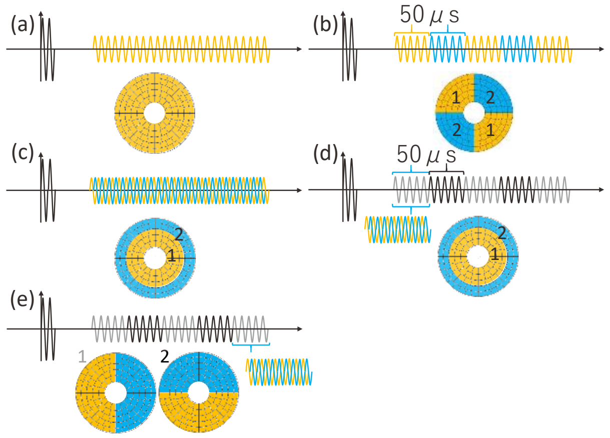

Fig.2. Schematic of ultrasonic waveform and full and split aperture.

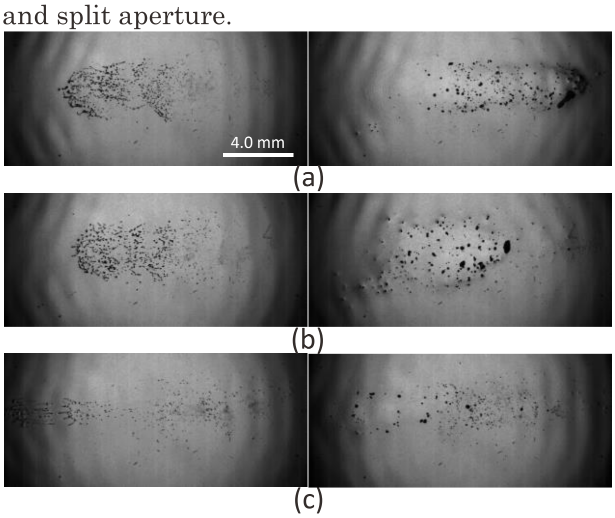

Fig.3. Images of cavitation bubbles taken by high-speed camera at 44 ms (left) and 2.99 s (right). The exposure methods were (a) standard, (b) 4 split apertures and (c) circular split focus.

3.2 Temperature rise

Fig. 4 shows the temperature rise induced by the five ultrasonic exposure methods. There was only a small difference among the temperature rise beyond the center. At the front and center, the temperature rise with four split apertures method was higher than those by the other methods and those with the standard and two split focus methods were almost the same. In the circular split focus with and without the standard methods, the temperature rises were much lower than the other methods.

It is known that cavitation bubbles tend to gather at the antinode and node of standing waves[4]. The gathered bubbles coalesce and become larger than the resonance size, so that they no longer contribute to the heating effect. The distribution of node and antinode is temporally changed by the alternate transmission methods. It is considered that the highest temperature was achieved by the four split-apertures transmission method because of the more effective temporal change of the acoustic field and the tighter focal region than the two split focus and circular focus methods.

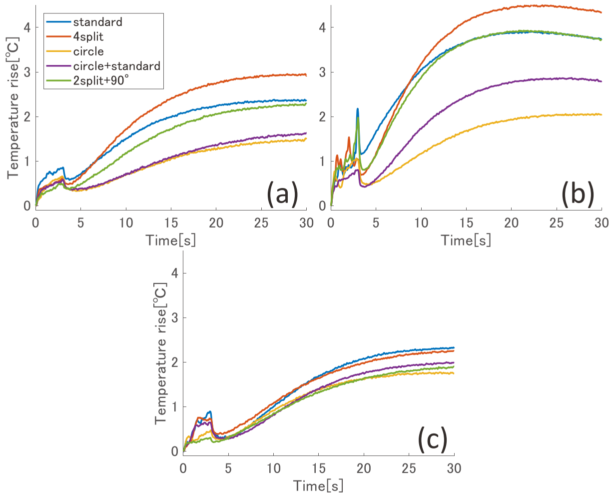

Fig.4. Temperature rise induced by sequences with five different exposure methods (n=3) measured with thermocouples (a) in front, (b) at the center and (c) beyond.

4. Conclusion

In this study, the distributions of cavitation bubbles and temperature rises were compared among five exposure methods. The result shows that the efficiency of cavitation-enhanced heating can be increased using the four split-aperture transmission method. The results of this experiment suggest that temporal changes in the position of node and antinode of the pressure field with a focal region size similar to the cavitation generation region are important for the efficient and accurate cavitation-enhanced heating in HIFU treatment.

References

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