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Ultrasound Imaging of Cavitation Using Triplet Pulse Sequence in Bubble-enhanced Ultrasonic Heating

気泡援用超音波加熱における 3 パルス法を用いたキャビテーションの超音波イメージング

Ikumi Shiozaki[1‡], Shin-ichiro Umemura[2], and Shin Yoshizawa[3] ([1]Grad. School of Biomed. Eng., Tohoku Univ.; [2]Grad. School of Eng., Tohoku Univ.)
潮﨑 育美 1 [1‡], 梅村 晋一郎 [1], 吉澤 晋 [2] ([1]東北大院 医工, [2]東北大院 工)

1. Introduction

High-intensity focused ultrasound (HIFU) is a noninvasive therapeutic modality for cancerous diseases. In this method, the treatment region is thermally coagulated by irradiating focused ultrasound from outside of a body. Therfore, it is required to observe the treatment by a noninvasive imaging method from outside of the body.

Acoustic cavitation bubbles are known to enhance the ultrasonic therapeutic efficiency. The pulse inversion (PI) method is a well-known technique for the selective detection of nonlinear echo scattered by bubbles. However, it is difficult to discriminate between the nonlinear echo generated by nonlinear oscillation of bubbles and that by the nonlinear propagation of ultrasound. To solve this problem, the triplet pulse sequence[1)] was employed in a previous study[2)]. The fundamental and second-harmonic components of the received echo are cancelled in the method. In this study, the contrast ratio of cavitaiton bubbles by the triplet pulse imaging is quantitatively evaluated and the behavior of the bubbles is investigated.

2. Materials and Methods

2.1 Experimental setup

Fig. 1 shows a schematic of the experimental setup. A 128-ch 2D-array transducer with both diameter and focal length of 120 mm was set at the center of a side wall of a water tank as a HIFU source. A sector probe was mounted in the central hole of the transducer for ultrasound imaging in such a way that its imaging plane should contain the focal spot of the HIFU transducer. The water was degassed (dissolved oxygen saturation at room temperature of 25%) before filling the tank. As a sample tissue, a chicken breast was set so that the HIFU focal spot was located 2.5 cm deep from its surface. The HIFU driving and ultrasound imaging systems were synchronized by a function generator. The HIFU transducer was driven at 1 MHz and the center frequency of the transmitted waves for imaging was 1.74 MHz.

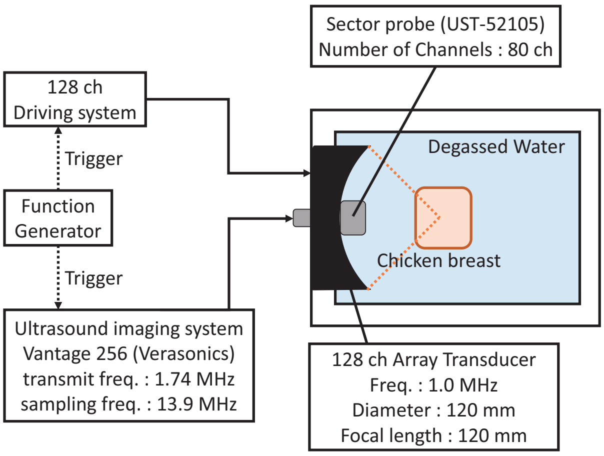

Fig. 1 Schematic of experimental setup.

2.2 HIFU exposure and RF data acquisition

Fig. 2 shows the sequence of the HIFU, exposure and RF data acquisition. The HIFU sequence consisted of short pulses called “trigger pulses” to generate cavitation bubbles and bursts called “heating bursts” to oscillate the bubbles and heat tissue for a longer duration. The intensity and duration of the trigger pulse were 32 kW/cm^2 and 0.1 ms, respectively. Those of the heating burst were 1.3 kW/cm^2 and 43.9 ms, respectively. RF signals for ultrasound imaging were acquired within the interval time between a trigger pulse and heating burst to avoid interference from HIFU. In this paper, we refer to the ultrasound imaging following the trigger pulse and heating burst as imaging-1 and imaging-2, respectively. Both consist of 4 diverging-wave transmissions with phase shifts by 120, 0, 180 and 240° and a transmission interval of 200 μs. The first wave was transmitted 1 ms after the trigger pulse and heating burst for imaging-1 and -2, respectively. A cycle of the sequence took 0.05 s, and it was repeated for 100 cycles. In the post processing, ultrasound images by the single pulse, PI, and triplet pulse sequences were obtained from the acquired RF data. The data for the transmission without a phase shift was used for constructing the single pulse images. Those with 0 and 180° shifts were used for constructing the PI images, where the

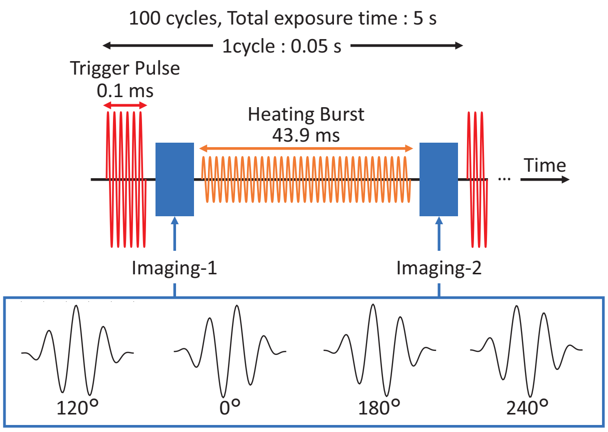

Fig. 2 Sequence of HIFU and ultrasound imaging.

fundamental should be cancelled. Those with 0, 120 and 240° were used for constructing triplet pulse images, where both the fundamental and second-harmonic should be cancelled.

3. Results and Discussion

Fig. 3 shows temporal changes of the contrast ratio in each sequence. The left and right figures show the results of imaging-1 and imaging-2, respectively. A region of interest (ROI) with about 7 mm × 5 mm (in propagation × azimuth direction) was set to contain the cavitation region. The contrast ratio was obtained by dividing an average power in ROI during the interval of HIFU exposure by that calculated from the RF data acquired before HIFU exposure as the reference. In the imaging-1, the overall contrast appears to be higher in the order of the triplet pulse, PI, and single pulse sequences. This means that the echo signals from the tissue were effectively reduced by the triplet pulse sequence. From about 1 to 2 s, the single pulse sequence shows the best contrast. The result suggests that the number of nonlinear scatters, which were supposed to be resonance bubbles, was limited and the main contribution to the contrast ratio was from bubbles with diameters larger than the resonance size. Furthermore, the effect of the multiple reflection might have increased the contrast ratio in the single pulse sequence. Thus, it is speculated that the large bubbles were dominant during the period, and bubbles with diameters close to the resonance size were newly generated at 2.3 s. The resonance bubbles might be induced by shock scattering[3] at the surfaces of the large bubbles or the fission of the large bubbles. The right figure shows the contrast ratios of imaging-2. In this figure, differences among the three sequences are not clearly observed compared with those of imaging-1. It is considered that the number of resonant bubbles decreased during the heating burst exposure due to their dissolution and coalescence.

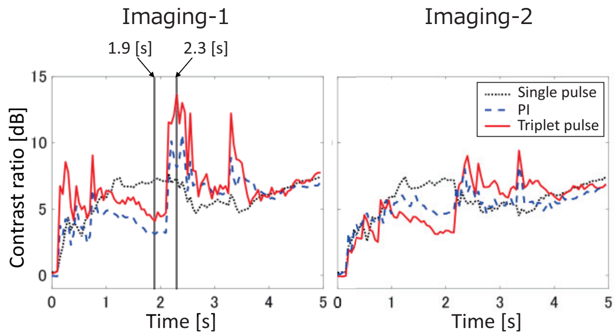

Fig. 3 Temporal change of contrast ratios. The left and right figures show the results of imaging-1 and imaging-2, respectively.

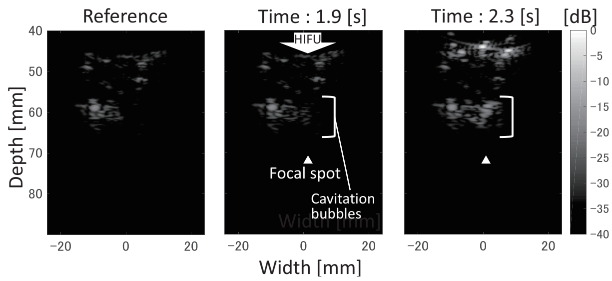

Fig. 4 B-mode images of imaging-1 by the triplet pulse sequence before the HIFU exposure, at 1.9, and 2.3 s.

Fig. 4 shows B-mode images of imaging-1 obtained by the triplet pulse sequence at 1.9 and 2.3 s when the contrast ratio changed significantly. That before the HIFU exposure is also shown for the reference. HIFU propagated from the top of the image. The focal spot of HIFU was located at a depth of 70 mm. At 1.9 s, the brightness slightly increased in the upper region of the HIFU focal spot, and at 2.3 s, the brightness in the same region obviously increased. The increase in the number of resonant bubbles in the front of the focal spot was observed by the triplet pulse sequence.

4. Conclusion

In this study, the contrast ratios of B-mode images by single pulse, PI, and triplet pulse sequences were evaluated, and the behavior of cavitation bubbles was investigated. The results suggest that imaging by the triplet pulse sequence right after the trigger pulse is most sensitive to the change of cavitation bubbles.

References
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ikumi.shiozaki.q1@dc.tooku.ac.jp