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Relationship between sensitivity of cavitation bubble detection and intensity of HIFU pulse inserted between imaging pulses in triplet pulse sequence

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1. Introduction

Cavitation bubbles can be used to improve the efficiency of high-intensity focused ultrasound (HIFU) treatment. To selectively image bubbles, an ultrasound imaging method called triplet pulse (3P) sequence[1)] that extracts nonlinear echo signals from bubbles has been proposed. However, the sensitivity of bubble detection by 3P method may not be sufficient under certain situations. For instance, when the stiffness of the tissue is high, the inertial bubble expansion is suppressed, and the threshold of cavitation cloud initiation is significantly increased[2)], resulting in the weak echo signals from cavitation bubbles. In the previous study by the authors, it was found that cavitation bubbles could be extracted with high sensitivity by interleaving short HIFU pulses between imaging pulses in 3P sequence. In this study, we investigated the relationship between the intensity of the inserted HIFU pulses and the sensitivity of bubble detection.

2. Materials and Methods

2.1 Triplet pulse sequence

In 3P sequence, three pulses are transmitted with phase shifts of 0° and ±120° and the three received echoes are added. In this method, the fundamental and second harmonic components of the tissue signal are canceled out when added because the phase shifts between the three received echoes from the tissue are maintained to be ±120°. On the other hand, the phase shifts between the echoes from bubbles may change from those in the three imaging pulses. Therefore, it is difficult to cancel the fundamental and second harmonic components of the signal from cavitation bubbles. Furthermore, bubbles may generate a 1.5 harmonic component due to strong nonlinearities, a feature not found in tissue. The 3P sequence utilizes these differences in scattering characteristics between tissues and bubbles to extract only the bubbles.

2.2 HIFU exposure and RF data acquisition sequence

Fig. 1 shows schematic of the experimental setup. The experiment was conducted in a tank filled with degassed water (20% dissolved oxygen saturation at room temperature) with 128-ch 2D-array transducer at the center of the side wall. Triplet pulse ultrasound imaging was performed with a sector probe attached to the center of the transducer. A chicken breast as a target tissue was set and exposed to HIFU at 1.0 MHz.The focus of the HIFU was located at a depth of 70 mm in the imaging plane. The center frequency of the transmitted waves for imaging was 2.45 MHz

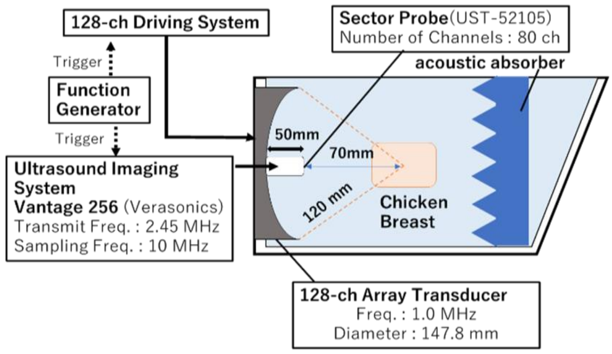

Fig. 1 Schematic of the experimental setup

Fig. 2 shows the sequence of the HIFU exposure and RF data acquisition. Trigger HIFU sequence was used, consisting of short pulses called “trigger pulses (TP)” to generate cavitation bubbles and bursts called “heating bursts (HB)” to oscillate the bubbles and heat tissue. The depth of focus of the trigger pulse and heating burst were 77 mm and 70 mm in the imaging plane, respectively. The intensities of the trigger pulse and heating burst were 67 kW/cm^2 and 0.67 kW/cm^2, respectively. Triplet pulse ultrasound imaging was performed after the heating burst when the amount of bubbles is considered to be reduced and the detection sensitivity is decreased, compared to the detection immediately after the trigger pulse[3)]. In the 3P sequence, three pulses are transmitted with phase shifts by 120° , 0°, and 240° and the received waves are added to construct 3P images. This sequence was repeated for 3 cycles.

As HIFU pulses interleaved in the 3P sequence, pulses with a duration of 3 μs at intensities of 3.1, 11.6, 23.1, 44.8 kW/cm^2 were used. The focal negative peak pressure of these pulses was -8.7, -14.6, -18.5, -22.6 MPa, respectively, when calculated with HITU simulator.

The focus of the inserted pulse was set to 70 mm in the imaging plane to match the position of cavitation bubbles generated. Then, a 2.5 MHz high-pass filter was applied to 3P RF data to remove low-frequency component generated through nonlinear propagation of imaging pulses, which are not canceled out by the addition of three echoes.

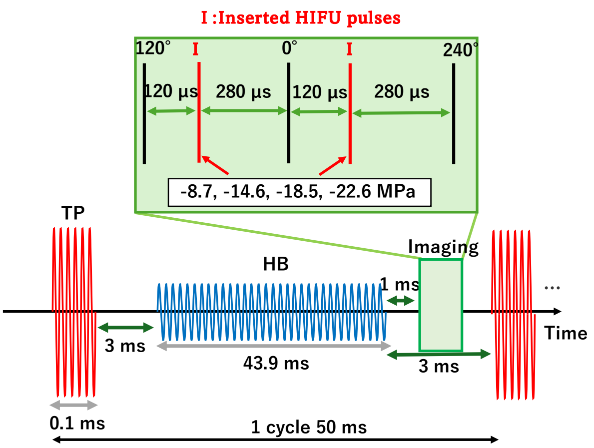

Fig. 2 HIFU and imaging sequence

3. Results and Discussion

Fig. 3(a) shows B-mode images created from 3P IQ data of the first cycle without and with inserted HIFU pulses at different intensities. Each of the data was obtained at a same place of the same sample. The highly bright area in the center of images is the cavitation bubble. (The bright area in the upper right corner of the image is a bright streak of tissue.) It was found that the higher the intensity of the inserted HIFU pulse, the brightness of bubbles increased.

Fig. 3(b) shows average contrast ratio of the bubble to the tissue in the 3P image over all cycle (N=9). The ROI of bubble region was defined as depth from 64 to 72 mm and width from -4 to -1 mm. For the tissue, the ROI was defined as the area of 50 to 80 mm depth and -15 to 15 mm width in the image of each sample, and the tissue echo intensity was calculated by averaging these areas in all samples. The contrast ratio is therefore proportional to the sensitivity of the bubble detection. Contrast ratio was increased when the focal negative pressure was lower than -14.6MPa, but no significant difference was obtained for -8.7 MPa. The higher the intensity of the inserted HIFU pulses, the higher the contrast ratio of the 3P images.

It is considered that the bubbles were imaged with higher sensitivity with the proposed method probably because the state of the bubbles (like size distribution and location of bubbles) changed between the consecutive imaging pulses, exposed to the inserted HIFU pulse. Therefore, it is thought that the higher the intensity of the inserted HIFU pulse, the greater the amount of change, and thus the more sensitive the bubble can be imaged.

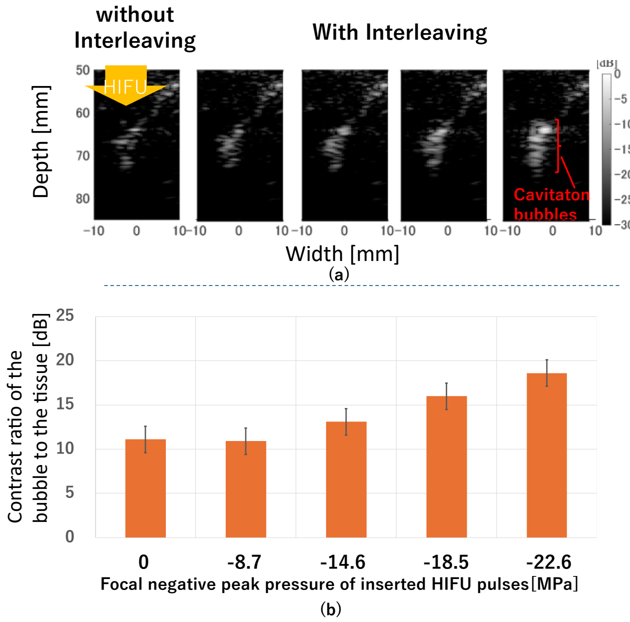

Fig. 3 (a) 3P images in the same sample tissue and (b) contrast ratio of the bubble to tissue regions in 3P images

4. Conclusion

In this study, the higher intensity of the HIFU pulses inserted between the imaging pulses of the 3P method improved the bubble contrast ratio to tissue in the 3P images. In treatment monitoring, it will be important to select the intensity of the inserted HIFU pulse in a manner that ensures sensitivity and does not affect the treatment.

References

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