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Improvement of contrast ratio between cavitation bubbles and tissue by frequency filtering in triplet pulse ultrasound imaging

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1. Introduction

Cavitation bubbles can be used to improve the efficiency of high-intensity focused ultrasound (HIFU) treatment.1) On the other hand, cavitation bubbles outside of the treatment region may cause side effects, thus it is important to predict and identify the region of cavitation bubbles to improve the safety and effectiveness of the treatment. Since cavitation bubbles cannot be seen with naked eyes, ultrasound imaging is generally used to visualize them. Triplet pulse method, which extracts nonlinear signals from cavitation bubbles by using three ultrasound pulses whose phases are shifted by 120 degree each, has been studied as a method to visualize bubbles.2) In this study, by using an appropriate high-pass filter, the echo signal ratio between cavitation bubbles and tissue is improved and more selective cavitation bubble imaging with triplet pulse is achieved.

2. Experimental methods

2.1. Triplet pulse method (3P)

3P is a method to image cavitation bubbles by transmitting and receiving three ultrasound imaging pulses, each with a phase shift of 120 degrees, and adding the echoes together. This imaging method utilizes the nonlinear scattering property of bubbles. In the case of signals from linear scatterers, the phase difference between before and after scattering is preserved, so that in principle, the fundamental frequency and the second harmonic components are canceled out by adding them together. On the other hand, the scattering of bubbles has very strong nonlinearity, and the phase difference before and after scattering varies depending on the state of the bubbles and ultrasound imaging pulses at the time of scattering. Thus, the signals from bubbles are less canceled by the addition in 3P. The difference results in a relative enhancement of the signal from bubbles and a high-contrast imaging of the bubbles.

2.2. Setup and ultrasound sequence

Fig. 1 shows a schematic of the experimental setup. The experiment was performed by setting chicken breast in a tank filled with degassed water. The chicken breast was degassed with 0.9% saline. HIFU was irradiated from a transducer attached to the side of the tank, and triplet pulse ultrasound imaging was performed with a sector probe attached to the center of the transducer.

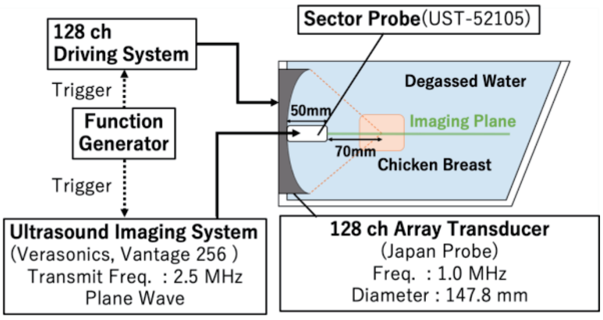

Fig. 1 Schematic of experimental setup

A high-intensity pulse was transmitted to generate cavitation bubbles and a moderate intensity burst followed to heat tissue enhanced by oscillating bubbles. HIFU exposure sequence used in the experiment consisted of a high-intensity pulse at a spatial-peak pulse-average intensity (I_{SPPA}) of 100 kW/cm^2 with a duration of 0.15 ms, a pause with a duration of 3 ms, and a moderate intensity burst at 4 kW/cm^2 with a duration of 43.9 ms, and this cycle was repeated. A set of ultrasound imaging at four phases, 120, 0, 180, and 240° was performed 1 ms after the burst wave.

2.3. Processing and analysis methods

RF data for imaging were acquired by ultrasound imaging system (Verasonics, Vantage 256) and decimated to 10 MHz without generating aliasing. IQ data were calculated after applying a high-pass filter to the acquired RF data. In this study, the amount of cancellation due to the addition of 3P method in bubble and tissue regions was compared to investigate the effect of filters. The amount of cancellation was obtained by dividing 3P image

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$(0^\circ + 120^\circ + 240/3)$ by 1P image (0°), each with the same high-pass filter applied.[3] In this process, the ROI of the cavitation bubble and the tissue regions were set at 62–68 mm depth and -3–3 mm width, and 48–54 mm depth and -3–3 mm width in B-mode images, respectively.

3. Result and discussion

Fig. 2 shows the results of frequency spectra in the cavitation bubble and the tissue regions obtained from 3P and 1P IQ data without high-pass filtering. In both the cavitation bubble and tissue regions, the 3P power is reduced from 1P power around the fundamental frequency of 2.5 MHz due to the cancellation. The amount of cancellation is about -15 and -25 dB in the bubble and tissue regions, respectively, which is a significant difference. On the other hand, it is confirmed that the 3P signal is not well canceled at around 1.5 MHz. It is considered to be due to the nonlinear propagation of the pulse wave. The envelope originating component did not change its phase by changing the initial phase of the imaging pulse and was not canceled by 3P method. As can be seen in Fig. 2, the power and the amount of cancellation vary in each frequency range, and therefore, the appropriate high-pass filter to increase the contrast between cavitation bubbles and tissue was investigated for various passband frequencies.

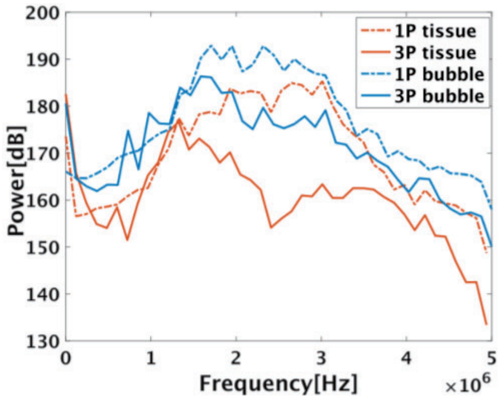

Fig. 2 IQ data spectra without high-pass filter

Fig. 3 shows ROI averages of the amount of cancellation in the bubble and tissue regions with a passband frequency from 1 to 4 MHz and difference between the cancellation in the two regions. The amount of cancellation in the tissue region increases from 1 to 2.5 MHz and then decreases. This result is reasonable comparing with the data in Fig. 2 since the ROI average of the amount of cancellation strongly depends on the peak frequency component after high-pass filtering. This is also the case for the cavitation bubble region. As for the contrast, when the passband frequency is increased to around 2.5 MH, the remaining component in 3P due to the nonlinear propagation was cut off, and the contrast was improved. When the passband frequency was raised to around 3.5 MHz, the component of the fundamental frequency band could no longer be obtained, and the contrast decreased.

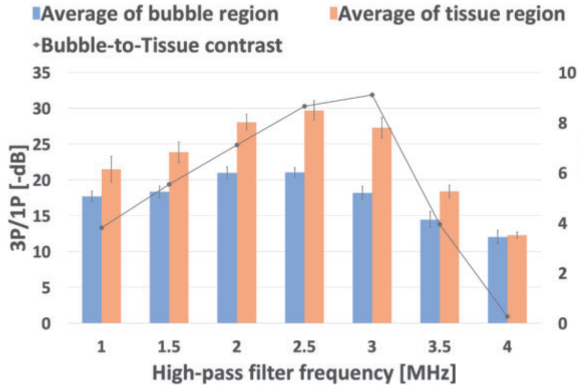

Fig. 3 Results on the effects of passband frequency on the contrast

Fig. 4 shows the ratio between 3P and 1P images with 1 and 3 MHz high-pass filters applied. At 1 MHz, the contrast between the cavitation bubble and tissue regions is poor, but at 3 MHz, the contrast is high enough to clearly distinguish between the cavitation bubble and tissue regions.

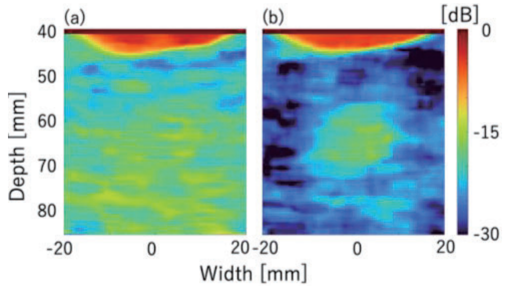

Fig. 4 3P/1P images (a) 1MHz high-pass filter (b) 3MHz high-pass filter

4. Conclusion

In this study, the contrast between cavitation bubbles and tissue was improved by applying an appropriate high-pass filter. Also, an appropriate cutoff frequency was found to be in the frequency range where the low frequency components originating from the envelope of the pulse wave due to the nonlinear propagation are removed and the fundamental frequency component that provide the contrast by 3P method is remained.

References

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