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Evaluation of microbubble translation and destruction by contrast enhanced plane wave ultrasound

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1. Introduction

Contrast enhanced ultrasound (CEUS) has been used as one of the methods to visualize the lymphatic system, i.e., lymph nodes and lymph vessels. Conventional contrast harmonic imaging (CHI), which uses only the information of echo intensity, cannot visualize the lymph vessels if hyperechoic tissue such as connective tissue with a high backscattering coefficient is present around them. We have proposed a contrast enhanced active Doppler imaging to improve the sensitivity in detecting microbubbles (MBs) as the contrast agent. MBs are driven by acoustic radiation force and show behaviors such as translation and collapse, resulting in a phase change in echo. The phase change can be detected by the Doppler method. In our previous studies, the focused ultrasound beam must be repeatedly transmitted several tens or hundred times per scan line to cause detectable translations of MBs. It takes an enormous amount of time to transmit, leading to a lack of real-time properties of the proposed method. Plane wave imaging resolves this problem because it can simultaneously drive MBs present over a wide area. This report investigates how translations and collapses of MBs driven by acoustic radiation force are visualized by plane wave imaging at various transmitting conditions.

2. Materials and Methods

1.1 Phantom and microbubble

A cylindrical flow channel with a diameter of 0.91 mm was formed in agar gel phantom including 5 wt% nylon particles with a diameter of 10 μm as the acoustic scatterer. Commercial ultrasound contrast agents, Sonazoid®, were used as MBs. The number and mean diameter of bubbles were 1.24 μm, 1.17×10^{10} m^{-3}.

1.2 Data acquisition and processing

A 128-elements linear array probe with a bandwidth of 4.68 – 10.52 MHz was employed for visualization. The peak frequency of the transmitted ultrasound pulse was 5.2 MHz. The probe was located 20 mm above the channel, and its lateral direction was parallel to the long axis of the channel. The plane wave was transmitted 202 times with a 4 kHz pulse repetition frequency (PRF) when the bubble suspension was kept stationary. To apply pulse inversion Doppler (PID)[1] to our method, we reverse the pulse's polarity (phase) with each pulse. The pulses were denoted as p_+ and p_- in this report. The visualization of flow channel was conducted at five conditions for negative peak sound pressure (P_{NP}) for p_+, P_{NP} = 0.10, 0.23, 0.50, 0.96 and 1.59 MPa, corresponding mechanical index (MI) were 0.04, 0.10, 0.22, 0.41 and 0.68.

The signal received by each element was digitized with quantification of 14 bit and sampling frequency of 60 MHz. The raw RF channel data were processed offline to reconstruct a 256-line image with a scanning interval of 0.15 mm by delay and sum algorism. We independently measured the point spread function (PSF) using a wire with a diameter of 50 μm. The PSFs were 0.5 mm in lateral and 0.4 mm in the depth direction at a depth of 20 mm. The number density of MBs per PSF volume was 1.67 PSF^{-1}, where PSF volume was calculated assuming that the length of PSF in the elevation direction was the diameter of the channel (0.91 mm).

1.3 Analysis of microbubble behaviors

The IQ signal in the frame (time) direction was defined as the Doppler signal, and we obtained the power spectrum of the Doppler signal by Fourier transform. The power of the echo from MBs moving away from the probe was evaluated from the integral of the power spectrum in the negative frequency region (I_N), and the mean translational velocity (v_{EV}) was evaluated from the expected value of the normalized power spectrum[2]. The destruction of MBs, resulting in the decay of the Doppler signal, might be evaluated as the index v_D calculated from the dispersion of the normalized power spectrum. We assessed the above indices separately from linear and nonlinear components by PID method[1]

3. Results and discussions

Figure 1 shows B mode images generated from first and second frame using pulse inversion

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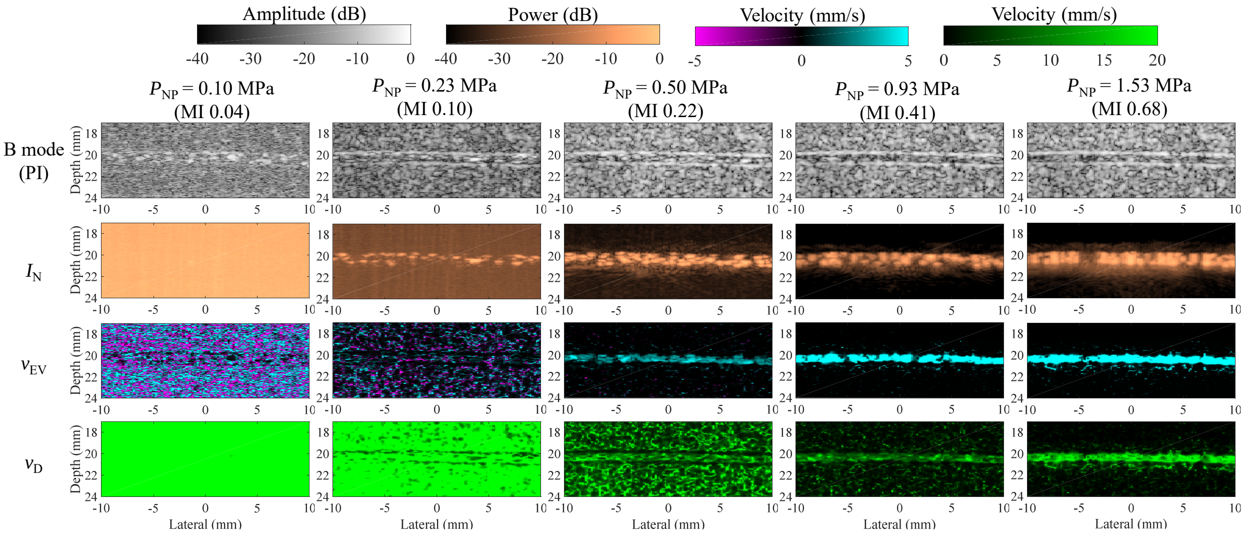

Fig. 1 Images of B mode (Pulse inversion), I_p, v_{EV} and v_D for nonlinear component at five sound pressure conditions. P_{NP} was negative peak sound pressure for p_+.

(PI) and I_N, v_{EV}, and v_D images for nonlinear components generated from PID. B mode images showed that MBs were faintly visualized, especially at P_{NP} = 0.10 MPa. In contrast, the proposed method visualized no MBs at the same condition because they did not move. As the Doppler signal included only noise, especially at the outside channel, v_{EV} was inconsistent, and v_D had a high value.

As higher sound pressure was, MBs appeared in I_N images at P_{NP} = 0.23 MPa, in v_{EV} at P_{NP} = 0.50 MPa, v_D at P_{NP} = 0.93 MPa. For I_N image, we found a lot of sharp elliptical bright spots at P_{NP} = 0.23 MPa, and they were blurry as the sound pressure increased, especially at P_{NP} = 1.53 MPa. The blur resulted from the significant translation of MBs away from the probe during the irradiation of 202 ultrasound pulses.

For v_{EV} image, the mean value in the channel seemed to increase proportional to the square of P_{NP}, and it reached over 10 mm/s at P_{NP} = 1.53 MPa for the linear component (not shown data). v_{EV} for nonlinear components tends to have a value 1.7 – 1.85 times higher than that for a linear component at P_{NP} > 0.5 MPa because the value overestimates due to the Doppler effect of the second harmonic component. Focusing on the values outside the channel, we found that its spatial variation decreased as the sound pressure increased because the clutter echo from the phantom became more significant than the noise.

For v_D image, the value in the channel was high and decreased with increasing in P_{NP} at P_{NP} < 0.23 MPa. As stated above, the noise was dominant in the Doppler signal. In contrast, the value increased at P_{NP} > 0.50 MPa and became significantly high at P_{NP} = 1.53 MPa. In this condition, we confirmed that the Doppler signal drastically decayed during several tens of ultrasound pulse irradiation, indicating that many MBs were destructed. Focusing on the outside of the channel, value decrease with sound pressure increases. The reason was the same with v_{ED}, i.e., the clutter echo from phantom became larger than the noise

4. Summary

This report showed that the application of the plane wave imaging to our proposed active Doppler method had possibility to visualize the translation and destruction of MBs, and it provided the high-contrast images compared with B mode image of pulse inversion method at higher sound pressure.

Acknowledgment

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References

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