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Investigation on estimation of velocity vectors for blood flow measurements

血流計測のための速度ベクトル推定に関する検討

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1. Introduction

High-frame-rate ultrasound imaging achieved an extremely high imaging frame rate of several thousand frames per second and possesses an excellent ability for visualization of blood flow dynamics. It enables detailed observation of motions of ultrasonic echoes from blood cells [1,2]. Also, quantitative estimation of flow velocity vectors is possible by applying the block-matching method to the visualized echoes from blood cells [3] or using the vector Doppler method [4]. In vector Doppler methods, velocity vectors are estimated by measuring axial velocities from multiple different directions. However, the maximum detectable velocity, which is determined by the aliasing phenomenon, is lowered by increasing the number of directions for measurements of axial velocities because the time interval of echo signals to be correlated increases. To mitigate such a significant limitation in the vector Doppler method, we introduced a specific transmit sequence, namely, the repeated transmit sequence [5], in estimation of flow velocities with plane wave imaging [6,7]. This method would be highly beneficial for detailed analysis of blood flow dynamics.

On the other hand, measurements of the arterial wall motion and deformation are also important for evaluation of vascular function. For visualization of the arterial wall, focused transmit beams are preferable because focused-beam imaging realizes less side-lobe and grating-lobe levels. Plane wave imaging suffers from more clutter signals from side and grading lobes. Although such clutters are suppressed by a clutter filter in blood flow imaging, they directly affect the measurement of the arterial wall. Consequently, focused-beam imaging is preferable for the measurement of the arterial wall. Although a time division sequence of plane-wave imaging and focused-beam imaging is one of the strategies to realize measurements of arterial wall and blood flow dynamics in one acquisition, it would be beneficial if we could realize both measurements only with focused beams. Therefore, we conducted a preliminary study on measurements of flow velocity vectors with focused transmit beams.

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2. Methods

2.1. Multi-line transmission and reception

To increase the frame rate, two focused beams were created simultaneously in one transmit event. The focal distance was set at 20 mm. The lateral distance between the two parallel transmit beams was 12 mm (60 element apart, 0.2 mm element pitch). Also, two parallel receive lines were created around each transmit beam. Each receive line was apart from the center of the transmit beam by 0.1 mm (half the element pitch), resulting a lateral interval between receive lines of 0.2 mm (receiving focal point was moved along each receive line at vertical intervals of 0.025 mm). The transmit event was repeated twice at the same aperture position to obtain a beamformed radio-frequency (RF) signal pair to be correlated for estimation of axial velocities, as in the repeated transmit sequence. Then, the transmit apertures for two parallel transmit beams were translated laterally by 0.4 mm (2 elements). By repeating such a procedure 30 times, 120 receive lines were created to compose a frame of a two-dimensional beamformed RF signal.

2.2. Estimation of velocity vectors

To estimate velocity vectors, receiving beams were created at steering angles of -20, 0, and 20 degrees for each receiving focal point. The autocorrelation method [8] was applied to the RF signals beamformed at steering angles in reception of -20, 0, and 20 degrees to obtain axial velocities. The autocorrelation kernel size was set at (lateral, axial) = (1.4 mm, 0.925 mm). From the axial velocities obtained at different steering angles in reception, velocity vectors were estimated using the vector Doppler method [4,9]. In the estimation of velocity vectors, the angles of the transmit beams were considered to be zero.

2.3. Method of simulation
In the present study, a 7.5-MHz linear array probe was simulated using Field II [10,11]. The probe was composed of 192 elements at pitches of 0.2 mm. The transmit sequence described in Section 2.1 was implemented, and echo signals received by individual elements were simulated.

Ultrasonic point scatterers were randomly distributed in a straight tube with a size of 5 mm in diameter. Those scatterers were moved along the tube axis at a maximum flow velocity of 100 mm/s. A parabolic flow was assumed, and the flow velocity at the interface between the flow and tube wall was set at zero.

3. Results
Figure 1 shows a B-mode image of the simulated phantom. The lateral and vertical velocities assigned to the scatterers are shown in Figs. 2(1-a) and 2(1-b), respectively.

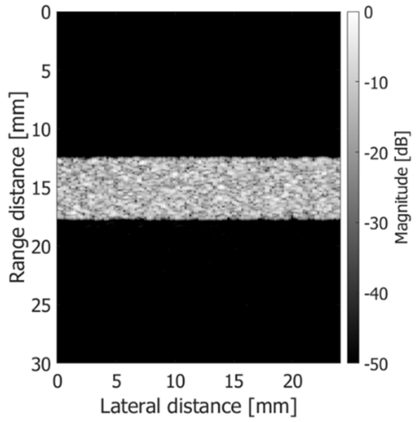

Fig. 1: B-mode image of simulation phantom.

Figures 2(2-a) and 2(2-b) show the lateral and axial velocities estimated by the proposed method, respectively. The bias error (BE) and the root mean squared error excluding the bias error (RMSEexBE) [7] were evaluated by referring to the true velocities shown in Figs. 2(1-a) and 2(1-b). The BE and RMSEexBE were 1.5% and 14.5%, respectively.

4. Conclusion
In the present study, the vector Doppler method was implemented in focused-beam imaging by generating receiving beams at different steering angles of -20, 0, and 20 degrees in parallel. The multi-line transmission and parallel receive beamforming were also used together with the repeated transmit sequence. The proposed method was validated by numerical simulation. The result shows the potential of the proposed method for measurement of flow velocity vectors with an error comparable to that obtained by plane wave imaging [7]. The proposed method also realized a frame rate of 170 Hz, which is much higher than that in the conventional color Doppler method with focused transmit beams.

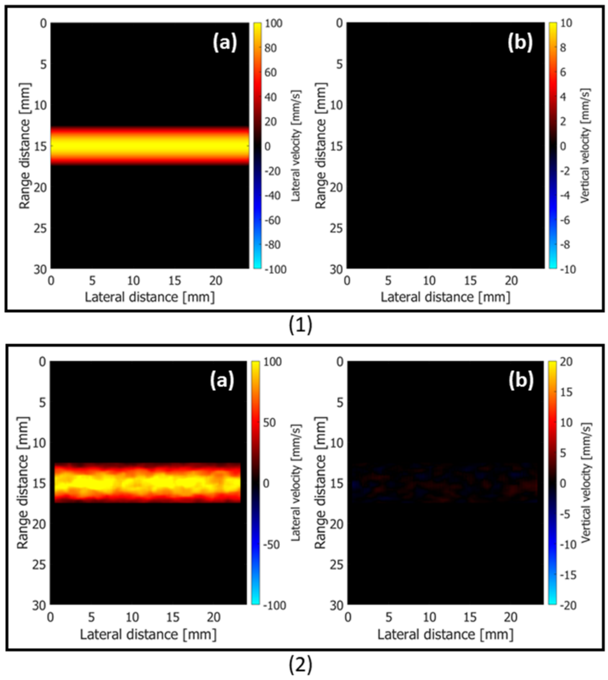

Fig. 2: True (1) and estimated (2) velocities. (a) Lateral velocity. (b) Vertical velocity.

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