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2D motion velocity estimation using beamformed ultrasonic signal in Cartesian coordinate for measurement of cardiac dynamics

心臓動態計測のための直交座標系受信ビームフォーミングを用いた 2 次元移動速度推定

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1. Introduction

Ultrasonic measurement of cardiac dynamics has preferable properties, i.e., non-invasiveness, repeatability, and inexpensiveness. In recent years, some studies have been conducted to improve the accuracy in measurement of cardiac motion. As a result, reliable measurement of cardiac motion has been realized in the axial direction. However, the accuracy in the lateral direction is still worse than that in the axial direction because the frequency of the beamformed ultrasonic signals in the lateral direction is lower than that in the depth direction intrinsically. In addition, the lateral sampling interval in the conventional sector format broadens with depth faster than broadening of the point spread function (PSF) in the lateral direction. Therefore, the sampling frequency in the lateral direction might not be sufficient in a deep region.

We developed a high-frame-rate ultrasonic imaging method for observation of cardiac dynamics, such as intracardiac blood flow [1]. In high frame rate imaging using unfocused transmit beams, beamforming can be performed in an arbitrary coordinate. Using such a characteristic of high-frame-rate ultrasonic imaging, in the present study, we changed the coordinate in receive beamforming from the conventional polar coordinate to the Cartesian coordinate so that the lateral sampling interval of the beamformed ultrasonic signal becomes constant with depth. The effect of the beamforming geometry on the accuracy in motion estimation was evaluated by phantom experiments, and the feasibility under in vivo condition was shown by measurement of intracardiac blood flow.

2. Materials and Methods

Intracardiac blood that is being visualized shows complex flow pattern in the left ventricle for prompting the transportation of blood and control of the direction of blood flow. For measurement of such flow dynamics, we acquired the beamformed ultrasonic echo signals with the transmission of spherically diverging beam and parallel receive beamforming [1], which realizes a frame rate of over 6000 frames per second (fps).

In ultrasonic imaging with a phased-array probe, focal points are assigned in the polar coordinate commonly and, thus, the interval of scan lines obtained by receive beamforming increases in proportion to the distance from an ultrasonic probe. Similarly, the PSF in the lateral direction is broadened but the increasing rate is lower than that of the interval of scan lines. Therefore, the degradation of the accuracy in velocity estimation might be caused by an insufficient lateral sampling frequency because the sampling interval increases more rapidly than broadening of the PSF.

To evaluate the effect of the coordinate of receive beamforming, in the present study, we estimated the motion velocity of a phantom with the 2D displacement estimation method developed by our research group [2]. The principle of the method is briefly described as follows: The 2D frequency spectra of received ultrasound echo signals in the n-th and (n+1)-th frames respectively corresponding to before and after displacement can be modeled as follows:

$$S_n(f_x, f_z) = A_n(f_x, f_z) \cdot e^{j2\pi(f_x x + f_z z)}, \qquad (1)$$

$$S_{n+1}(f_x, f_z) = A_{n+1}(f_x, f_z) \cdot \times e^{j2\pi\{f_x(x-u_x)+f_z(z-u_z)\}}, \qquad (2)$$

where $A_n(f_x, f_z)$ is the magnitude of spectrum. The phase of spectrum in Eq. (2) includes the lateral (x) and depth (z) displacements of u_x and u_z of an object. Therefore, we can estimate the displacements u_x and u_z by applying the least-square method to the phase term of the cross spectrum calculated in the direction of frame. At the same time, we need to estimate the spatial frequencies f_x and f_z of each component of spectrum, which are obtained by calculating the cross spectra in the lateral and axial

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directions. In the case of the polar coordinate, the estimation can be performed by substituting lateral position x by angle θ.

In acquisition of echoes from a phantom, a phased-array probe at a nominal center frequency of 3 MHz was equipped on a three-axle automatic stage, which moves two-dimensionally at constant speeds. The sampling frequency and frame rate were 15.625 MHz and 6250 Hz, respectively.

3. Experimental Results

Acquired ultrasound RF echo signals were beamformed in the conventional polar coordinate and the proposed Cartesian coordinate. The accuracy in velocity estimation was evaluated both in the lateral and depth directions.

Figures 1 shows the bias errors from a true value (vertical axis) and the standard deviations (error bar) in lateral and depth velocities at different window sizes in the lateral direction. The window size in the depth direction was fixed to 14.8 mm. A Gaussian window was used to obtain spectrum.

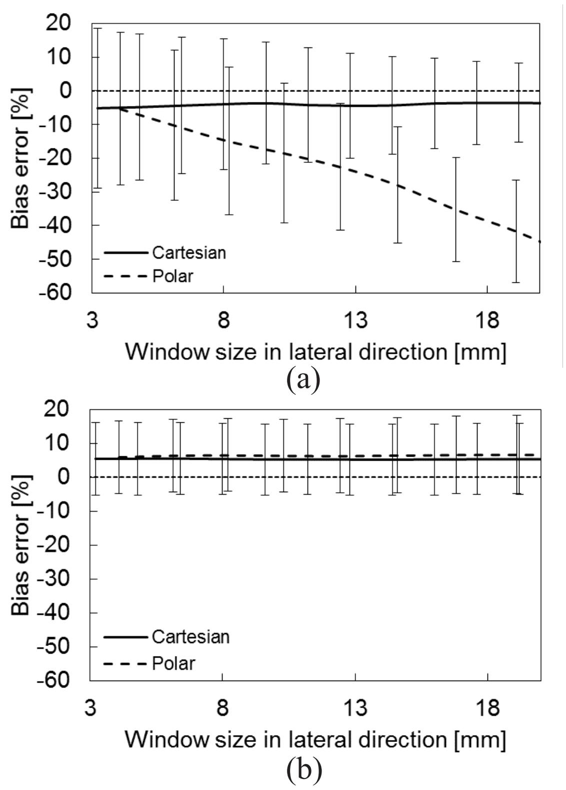

Fig. 1: Bias errors and standard deviations in (a) lateral and (b) depth velocities at different window sizes for ultrasonic RF signals beamformed in polar (dashed line) and Cartesian (solid line) coordinates.

Figure 1(a) shows the result of velocity estimation in the lateral direction. By the conventional method using the polar coordinate (dashed line), the bias errors increased significantly when the window size becomes large in the lateral direction. The standard deviation was nearly constant regardless of the window size. By the proposed method using the Cartesian coordinate (solid line), the bias error was almost constant around minus 5% regardless of the window size, and the standard deviations tended to decrease as the window size got larger. The accuracy in estimation of the lateral velocity improved by constructing the echo signals at equal intervals in the both directions in the Cartesian coordinate.

As shown in Fig. 1(b), the result of velocity estimation in the depth direction by the proposed method was very similar to that by the conventional method.

In the *in vivo* experimental result shown in Fig. 2, blood rushing toward the aorta was observed by the distribution of 2D blood velocity vectors (red arrows).

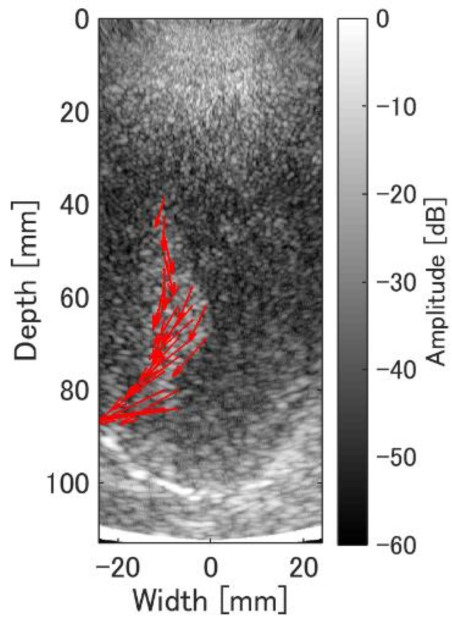

Fig. 2 Distribution of 2D blood velocity vectors in left ventricle.

4. Conclusion

The 2D motion velocity estimation using ultrasonic signals beamformed in the Cartesian coordinate was examined for the improvement of the accuracy in the lateral motion estimation. The proposed method was confirmed to realize a more accurate motion estimation by the phantom experiment.

References

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