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Transthoracic Speckle Motion Imaging of Blood Flow in Left Ventricular Cavity with High Frame Rate Ultrasound
高フレームレート超音波計測を用いた左室内腔の経胸壁血流スペックルイメージング

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1. Introduction

Blood flow imaging in echocardiography is a very useful tool to diagnose the pumping function of the human heart. As a typical method, color Doppler flow imaging (CDI) has been widely used to obtain the information of intracardiac blood flow in clinical practice. CDI, however, does not show the direction of blood flow because only velocity component along an ultrasonic beam is measured. Recently, cardiac blood flow pattern such like vortex flow in left ventricular cavity has been studied to provide new information for diagnosis using echocardiographic particle image velocimetry (E-PIV) technique [1]. E-PIV gives the mapping of velocity vectors of blood flow which are calculated based on motions of ultrasonic echoes from contrast agent. However, E-PIV forces physical and mental burden on patients due to intravenous injection of contrast agent.

Visualization of blood flow direction without any contrast agent would be achieved by improvement of signal to noise ratios (SNRs) of echoes from blood particles. In addition, high frame rate ultrasound is required to continuously observe motions of echoes from blood particles because blood particles move at a velocity up to 1 m/s while the ultrasound beam is swept. In this work, we proposed a method for visualization of intracardiac blood flow direction with high frame rate ultrasound using enhanced echoes from blood particles and demonstrated the feasibility by performing *in vivo* experiment of one healthy male.

2. Principles

In this study, parallel receive beamforming with spherically diverging transmit beam [2] illustrated in **Fig. 1** was used for high frame rate acquisition of echo signals. In Fig. 1, r_f and θ denote the distance from a virtual point source behind the array to the center of the transducer array and the steering angle, respectively. The diverging wave was transmitted in two directions and steered at $\theta = \pm 10^{\circ}$ with a 3.75 MHz phased-array probe in the present study. The r_f was set to 100 mm.

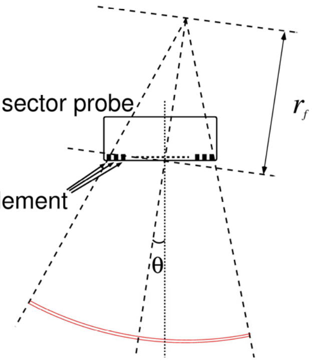

Fig. 1 Illustration of spherically diverging beam by phased-array probe.

A method in vascular ultrasound was developed for visualization of blood flow direction using motions of echoes from blood particles using high frame rate measurement [3, 4]. It is well known that the power of echo from scatterer like red blood cell is proportional to the fourth power of frequency. However, it is necessary to transmit lower frequency ultrasound wave (about from 2 to 5 MHz) in cardiac imaging than that (about from 7 to 10 MHz) in vascular imaging to avoid significant frequency dependent attenuation due to deeper location of the heart. Hence, in this study, excitation signals were coded with 5-bit Barker code to improve SNRs of echoes from blood particles. The echo signal at each element was individually decoded before receive beamforming.

Echoes from blood particles are usually contaminated those from stationary and slowly moving tissues, such like ribcage and the myocardium, caused by sidelobe, which are called clutter signal. In this study, high pass filtering was applied to beamformed RF signals in the direction of frame to enhance the echo signals from blood particles by suppressing clutter signal. The filters' impulse response was the sinc function multiplied with the Kaiser window, which is linear time-invariant. Let us define the complex

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demodulated signal at the frame number i and sampled point number n which corresponds to time $t = nT$ (T: sampling interval) as $x_i(n)$.

The undesirable noise component, which is generated from electronic devices, still remains in the high Doppler frequency range even after the clutter filter is applied. The temporal changes in phases of the echo signals from an object would be constant during a pulse duration (depth direction) and a short period (frame direction), *i.e.*, coherent. In this study, the ratio of coherent component to the total signal, which is denoted by coherence, was used as a weighting function to beamformed signal to suppress the undesirable noise as described below:

$$\hat{S}_i(n) = |x_i(n)|^2 \cdot \frac{\left|\mathrm{E}_k\left[\mathrm{E}_m\left[x^*_{i+m-1}(n+k)x_{i+m}(n+k)\right]\right]\right|^2}{\mathrm{E}_k\left[\mathrm{E}_m\left[x^*_{i+m-1}(n+k)x_{i+m}(n+k)\right]\right]\mathrm{E}_k\left[\mathrm{E}_m\left[x^*_{i+m}(n+k)x_{i+m}(n+k)\right]\right]}, \quad (1)$$

where $\mathrm{E}_k[\cdot]$ and $\mathrm{E}_m[\cdot]$ denote the averaging procedures with respect to depth and frame, respectively. In the present study, the averaging numbers of $\mathrm{E}_k[\cdot]$ and $\mathrm{E}_m[\cdot]$ were set to 8 and 6 (corresponding to about 0.4 mm and 2 ms).

3. Result

Parallel receive beamforming and spatial compounding were applied in off-line processing using individual RF echo signals received by 96 elements. The cutoff frequency of the clutter filter was set to 500 Hz. Ultrasonic RF echo signals in three chamber view of a 26-year-old healthy male were measured at a very high frame rate of 3333 Hz. **Figures 2(c)** and **2(d)** show speckle images of blood particles without and with the weighting by coherence in a frame in diastole. The magnitude was normalized by the value smaller than their maximum by 30 dB in the frame. As can be seen in Figs. 2(b) and 2(c), the noise components randomly distributed in the whole region were suppressed by the weighting by coherence. **Figures 3(a)** and **3(b)** show the B-mode images (shown by gray-scale) overlaid with speckle images of blood particle (shown by hot-scale) at frames in systole and diastole. The arrows shown in Figs. 3(a) and 3(b) denote flow vectors estimated by applying speckle tracking technique to the distributions of magnitude of echoes from blood particles. The motions of speckle-like patterns caused by blood flowing out of and into the left ventricular cavity in systole and diastole was respectively estimated as can be seen in Fig. 3(a) and 3(b).

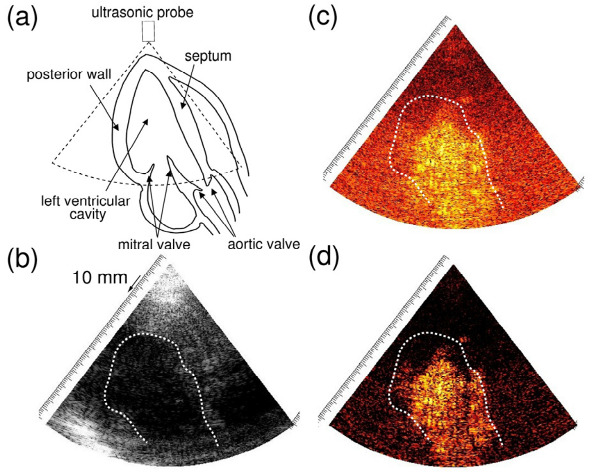

Fig. 2 (a) Illustration of measurement region in three chamber view and (b) B-mode image. Speckle images of blood particles (c) without weighting and (d) with weighting by coherence in a frame in diastole. White dashed lines denote boundary of left ventricular cavity.

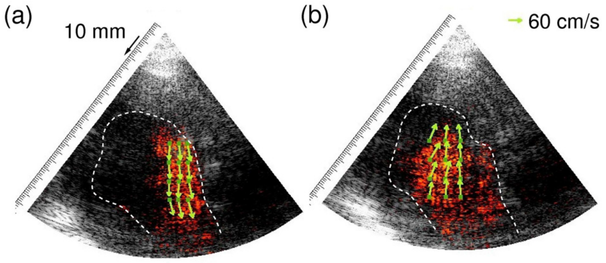

Fig. 3 B-mode image (shown by gray-scale) overlaid with speckle image of blood particles (shown by hot-scale) at frames in (a) systole and (b) diastole with flow velocity vectors estimated by speckle tracking technique. White dashed lines show roughly estimated boundary of left ventricular cavity.

4. Conclusion

In this work, through *in vivo* measurement of a 26-year-old healthy male, we demonstrated to visualize the motions of echoes from blood particles in the human heart using high frame rate ultrasound with diverging waves. Moreover, estimation of the direction of blood flowing into and out of the cavity was achieved in the *in vivo* experiment. The results showed the feasibility of high frame rate blood flow imaging of the human heart without any contrast agent by our proposed method.

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