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Measurement of Two-dimensional Heart Wall Motion for Evaluation of Myocardial Contraction and Relaxation at High Temporal and Spatial Resolutions

心筋収縮弛緩特性計測を目指した心臓壁の高い時間・空間分解能を有する 2 次元変位計測

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1. Introduction

In recent years, several studies have been conducted to track speckle patterns of ultrasonic echoes from moving objects for assessment of their 2-D motion by speckle tracking methods, e.g., normalized cross-correlation, sum of absolute differences and so on[1)]. D'hooge *et al.* reported that 2-D heart wall motion can be measured by speckle tracking with a size of a ROI (correlation kernel) of 4.0×4.0 mm[2)]. However, an important parameter in the algorithm, the optimal size of an ROI, has not been thoroughly investigated. In addition, the frame rate in speckle tracking is limited to 200 Hz. However, some transitions of heart wall motion rapidly occur during a short period of about 10 ms[3)]. Therefore, the continuous observation of such transition requires a frame rate higher than 500 Hz (1 ms). In the present study, the RF data was acquired based on the parallel beam forming (PBF)[4)] so that the myocardial transition could be measured at a high temporal resolution less than 1 ms and the 2-D minute displacement of the heart wall was estimated by speckle tracking with the optimal size of an ROI.

2. Principle

2. 1 Acquisition of RF signals at high frame rate

As illustrated in Figs. (1-a) and (1-b), in conventional sector scanning, image lines are generated by focusing the ultrasound in both transmit and receive by properly selected delays of the signals applied to transducer elements, and these transmit and receive beam directions coincide. In contrast, as illustrated in Figs. (2-a) and (2-b), PBF technique allows receive beam forming in several directions for each direction of ultrasound transmission[4)]. In this study, L = 7 plane waves were transmitted in 7 different directions at angular intervals of 6 degrees to obtain one B-mode image. For each transmission, N_r = 16 receiving beams were created at angular of $\theta_\mathrm{r}/2$ = 0.375 degrees. The frame rate achieved by the parallel beam forming is obtained by $f_\mathrm{PRF}/N_\mathrm{r}$ = 1020 Hz, where f_PRF is the pulse repetition frequency.

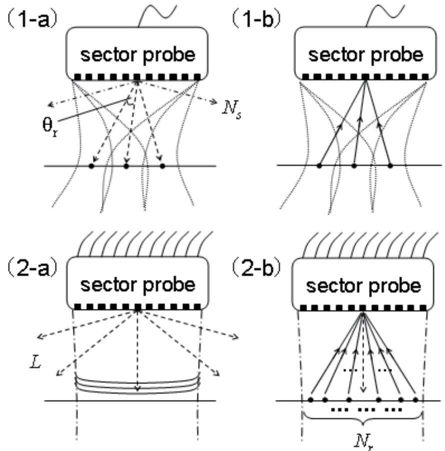

Fig. 1 (a) Transmission and (b) reception of ultrasound by conventional sector scan (1) and PBF (2).

2. 2 Estimation of instantaneous displacement by 2-D correlation function

In this study, 2-D displacement was estimated by 2-D correlation between RF echoes. The correlation coefficient $r_n(\Delta N;\, m,\, k)$ at the lateral shift m and axial shift k, is calculated from RF signal $\mathrm{rf}_n(\theta,\, d)$ at beam angle θ and depth d in the n-th frame as follows:

$$r_n(\Delta N; m, k) = \frac{1}{A} \sum_{m=-M/2}^{M/2} \sum_{k=-K/2}^{K/2} \{\mathrm{rf}_n(\theta, d) \cdot \mathrm{rf}_{n+\Delta N}(\theta + m\Delta\theta, d + k\Delta d)\}, \quad (1)$$

where $A = (\Theta+1)(D+1)\sigma_{(n;\theta,d)}\sigma_{(n+\Delta N;\theta+m\Delta\theta,d+k\Delta d)}$, and $\sigma(n;\, \theta,\, d)$ is the standard deviation of the RF signal $\mathrm{rf}_n(\theta,\, d)$ in an ROI with a size of $(\Theta \times D)$. RF signals in the ROI in the n-th frame are compared with those in the $(n+\Delta N)$-th frame. The 2-D displacement from n-th to $(n+\Delta N)$-th frames can be determined from the lags $m_0 \cdot \Delta\theta$ and $k_0 \cdot \Delta d$ which maximize the correlation function.

3. Basic Experimental Results

3. 1 Experimental System

As illustrated in Fig. 2(a), to determine the optimum size of ROI $(\Theta \times D)$, motion of a phantom was measured by basic experiments. The phantom

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was made with silicone rubber whose thickness was nearly same as that of interventricular septum (IVS). The motion velocity of the phantom was two-dimensionally controlled by an automatic XYZ stage. Both lateral and axial velocities were set at 5 mm/s. RF data were acquired using a 3.75 MHz sector-type probe of ultrasonic diagnostic equipment (Aloka SSD-6500). The sampling frequency of the RF signal was 15 MHz and the sound speed in silicone rubber was about 1000 m/s (sampling interval Δd was 33.3 μm). The frame rate and angular interval of beams were 1024 Hz and 0.375 degree, respectively.

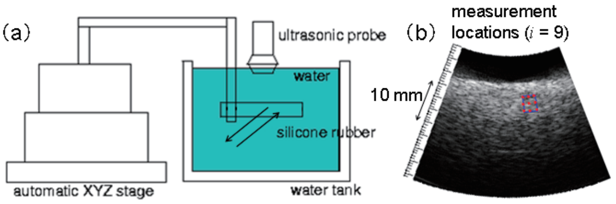

Fig. 2 (a) Schematic of system for basic experiments. (b) B-mode image and locations (red points) whose 2D displacements were estimated.

3. 2 Determination of optimal size of ROI

To determine the optimal size of an ROI ($\Theta_0 \times D_0$), 2-D displacements at ROIs with different sizes (Θ = 3.5~6.5 degree, D = 0.5~3.5 mm) were examined by means of root-mean-squared (RMS) error between estimated and actual displacements. RMS errors, $\varepsilon(t;\ \Theta,\ D)$, evaluated with a size of ROI ($\Theta \times D$) were calculated from estimated displacements, $\{x_{i;\ \Theta,\ D}(t)\}$ (i = 1, 2, ⋯, M), and actual displacement, $x_0(t)$, as follows:

$$\varepsilon(t;\Theta,D)=\sqrt{\frac{1}{NM}\sum_{i=0}^{M-1}\sum_{n=0}^{N-1}\left(x_{i;\Theta,D}(n\cdot\Delta T)-x_0(n\cdot\Delta T)\right)^2} \quad (2)$$

where M is the number of measurements of 2-D displacements. These estimated motions at nine points (M = 9) in Fig. 2(b) were obtained by 2-D tracking.

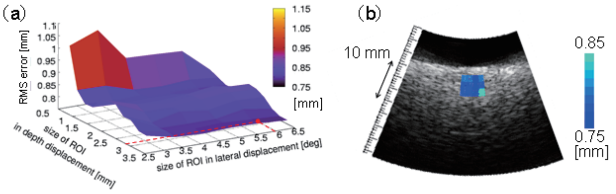

Fig. 3 (a) RMS errors between estimated and actual displacements. (b) RMS errors at ($\Theta \times D$) = (6.0 deg ×2.8 mm) superimposed on the B-mode image.

As shown in Fig. 2(a), RMS errors with the size of an ROI (Θ=3.5~6.5 degree, D=0.5~3.5 mm, the region surrounded by the red line) were small and showed the minimum at the size of the ROI ($\Theta_0 \times D_0$) = (6.0 deg×2.8 mm). **Figure 3(b)** shows that RMS error between estimated and actual displacements at every location in the region surrounded by the blue line in Fig. 2(b) with the determined optimum size of ROI ($\Theta_0 \times D_0$) = (6.0 deg×2.8 mm). These RMS errors were less than 0.85 mm.

4. *in vivo* experiment

As shown in Fig. 4(a), the motion of an arbitrary region in the IVS (M = 6) was estimated by 2-D tracking. The size of an ROI was set at the determined optimum size ($\Theta_0 \times D_0$) = (6.0 deg×2.8 mm). **Figures 4(b)** shows the two-dimensional IVS motion at each point obtained by the 2-D correlation function. The IVS moved to the apical side during cardiac systole and then, it began to return to the basal side during diastole.

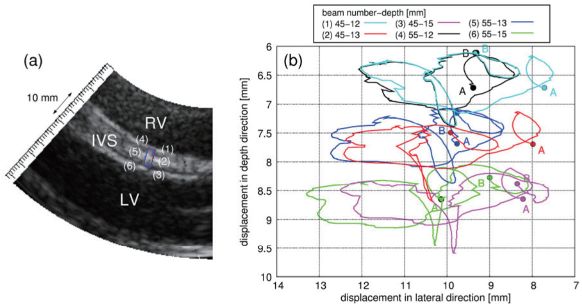

Fig. 4 (a) Cross-sectional image of heart wall in IVS. (b) Estimated 2-D displacements.

5. Conclusion

We proposed a method for a high frame rate acquisition of RF echoes based on PBF and an important parameter, size of an ROI, in 2-D tracking was determined by RMS errors of the 2-D displacements obtained with different sizes of ROIs. The determined optimal size of the ROI was (6.0 deg×2.8 mm). Regional heart wall motion was measured at high temporal and spatial resolutions. As shown in Fig. 4, *in vivo* experimental results show the possibility of this method for measurement of two-dimensional heart motion to assess the regional myocardial contraction and relaxation.

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