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Optimization of Window Length in Velocity Estimation in Heart Wall Using Ultrasound Phase Difference for Measurement of Local Change in Myocardial Layer Thickness

心筋層の局所的な厚み変化計測における超音波位相差を用いた速度推定法の窓長の最適化

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1. Introduction

Ultrasound-based measurements of the change in the myocardial thickness have been studied for detecting the abnormality of contractile response in acute myocardial ischemia. In our previous study, local and minute changes in the myocardial thickness were measured using the multifrequency phased-tracking method with a short discrete Fourier transform (DFT) spatial window, which allows us to estimate the local velocity in the heart wall, during a pre-ejection period [1]. With the short DFT window, however, the rapid motion of the heart wall sometimes cannot be measured accurately owing to the poor frequency resolution and the change in the waveform in the spatial window especially during ejection and rapid filling periods.

In the present study, the velocity in the heart wall was measured using the multifrequency phased-tracking method with the long and short DFT window during a cardiac cycle. Then, we discussed the optimization of the window length for the measurement of the local change in the layered myocardial thickness.

2. Methods

In the multifrequency phased-tracking method, which was described in detail in Ref. 2, the cross-spectrum between consecutive frames, $C_n(f)$, was used for the local velocity estimation in the heart wall. In the present study, ±1.5 or ±3.0 mm Hanning window was used to obtain the spectra of the received radiofrequency (RF) signals, $S_n(f)$ and $S_{n+1}(f)$. The cross-spectrum was given by,

$$C_n(f) = S_n^*(f) \cdot S_{n+1}(f). \qquad (1)$$

Assuming that the cross-spectrum phase at the nth frame, $\angle C_n(f)$, is linear, i.e. the velocities are uniform within the DFT spatial window, the velocity can be estimated from the phase gradient $\hat{a}_n$ that minimizes the root mean squared error (RMSE) $\alpha_n(a)$. The RMSE $\alpha_n(a)$ weighted by the cross-spectrum amplitude $|C_n(f)|$ is defined as

$$\alpha_n(a) = \sqrt{\frac{\sum_{f=0}^{f_s/2} |C_n(f)| \cdot |\angle C_n(f) - af|^2}{\sum_{f=0}^{f_s/2} |C_n(f)|}}, \qquad (2)$$

for the sampling frequency f_s and an arbitrary variable a. When the value of af is larger than (smaller than) π, 2π is subtracted (added) from (to) the value of af to deal with phase wrapping. The velocity $\hat{v}_\mathrm{d}(n)$ is determined as

$$\hat{v}_\mathrm{d}(n) = \frac{c_0 f_\mathrm{FR}}{4\pi} \cdot (-\hat{a}_n), \qquad (3)$$

$$\hat{a}_n = \arg\min_a \alpha_n(a). \qquad (4)$$

Here, c_0 is the speed of sound and f_FR is the frame rate in the ultrasound measurement.

In vivo measurement was applied to the posterior wall (PW) of a 20’s healthy subject in the parasternal long-axis view as shown in **Fig. 1**(a). The RF signal was obtained by the ultrasound diagnostic apparatus (F75, Aloka) with a sector probe of the 3-MHz center frequency f_c and the 20-MHz sampling frequency. The frame rate was set at 487 Hz.

3. Results and Discussion

As shown in Fig. 1(d), the estimated velocity waveforms with the ±3.0 and ±1.5 mm DFT window did not completely coincide with each other. At the time of the n_ath frame, the spike-like velocity change occurred in that with ±1.5 mm window even though the RMSE was not extremely large compared against that with ±3.0 mm window as shown in Fig. 1(e). The estimated velocity $\hat{v}_\mathrm{d}(n_\mathrm{a})$ with ±1.5 mm window was erroneous because of the continuity of the whole motion of the heart wall.

As shown in **Fig. 2**(a), the estimated displacement corresponding to $\hat{v}_\mathrm{d}(n_\mathrm{a})$ with ±3.0 mm window (blue arrow) was quite different from that with ±1.5 mm window (red arrow). However, both the estimated phase gradients passed through the phase at the peak frequency f_p where the weight $|C_n(f_\mathrm{p})|$ was maximum as shown in Figs. 2(b) and

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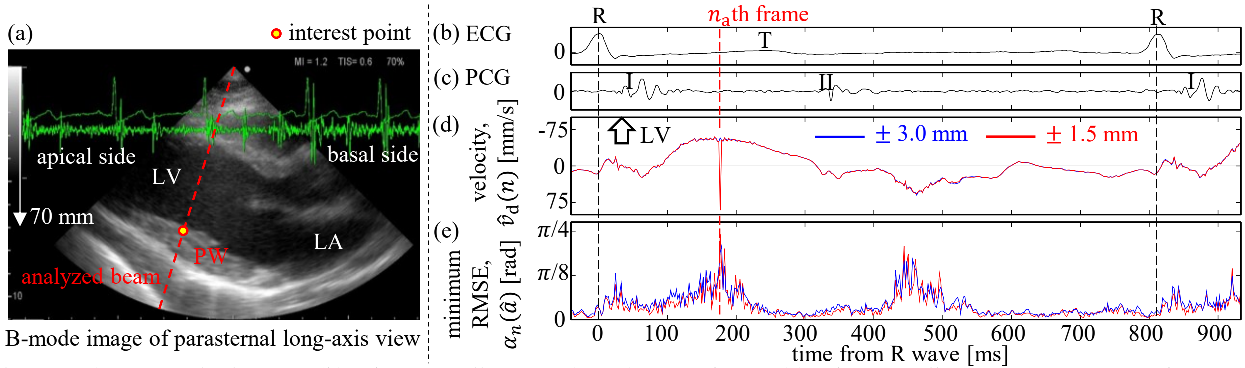

Fig. 1 (a) B-mode image, (b) electrocardiogram (ECG) waveform, (c) phonocardiogram (PCG) waveform, (d) estimated velocity waveform, and (e) minimum RMSE $\alpha_n(\hat{a})$ in a cardiac cycle. (LA=left atrium; LV=left ventricular).

2(c), and both values of RMSE had similar local minima where the interval was approximately $2\pi/f_\mathrm{p}$ as shown in Fig. 2(d). Thus, in both the ± 3.0 and ± 1.5 mm windows, these local minima were mainly determined by the phase at f_p. Because the phase gradients which pass through the origin and the phase at f_p is not uniquely determined owing to the phase wrapping, the global minimum cannot be uniquely determined by only the phase at f_p. The global minimum, which was different from each other, was determined by the multifrequency phases around f_p because the weight $|C_n(f)|$ was high. The poor frequency resolution and the change in the waveform in the short window make it difficult to measure the phase independently at each frequency component especially when the velocity (i.e., the displacement between consecutive frames) is large. Because the global minimum was determined by the multifrequency phases, that negatively affected by the poor frequency resolution within the short window did not correspond to the actual displacement which was large as shown in Fig. 2(a).

However, the local minimum with the short window which was around the global minimum with the long window might correspond to the local velocity. On the other hand, the global minimum with the long window might not coincide with the local velocity because the assumption that the velocities were uniform within the DFT spatial window might become incorrect owing to the change in thickness within the long window. This trade-off between the large and local velocity estimations should be considered to optimize the window length for the local measurement of the change in the myocardial thickness which requires the local estimation of the large velocity in the heart wall.

4. Conclusion

In the present study, the velocity in the heart wall was measured with the long and short DFT window. The window length should be optimized by considering the large velocity of the whole motion and the local velocity for the measurement of the local change in the layered myocardial thickness.

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References

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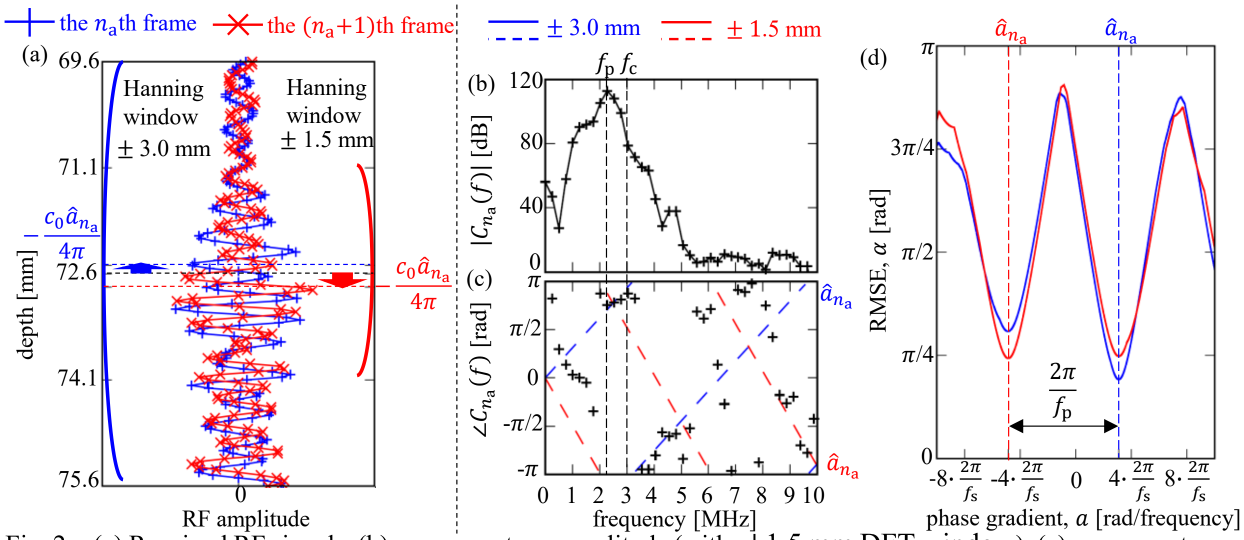

Fig. 2 (a) Received RF signals, (b) cross-spectrum amplitude (with ± 1.5 mm DFT window), (c) cross spectrum phase, and (d) RMSE at the n_ath frame.