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TECHNICAL NOTE

Expanding aliasing limit in measurement of tissue velocity using autocorrelation method

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Abstract Autocorrelation using in-phase and quadrature (IQ) signals suffers from aliasing when the velocity of rapidly moving tissue, such as the heart wall, is measured. In the present study, a simple method was proposed to expand the aliasing limit. In the proposed method, the velocity difference between two successive frames (corresponding to acceleration) of tissue was also estimated directly from IQ signals. When aliasing occurs in the velocity in the current frame, which was estimated from IQ signals, the velocity in the current frame was corrected by adding the velocity difference to the velocity in the previous frame. Using this procedure, the velocity can be estimated if the difference between velocities in the current and previous frames is less than the aliasing limit. The velocity of the posterior heart wall in the longitudinal-axis view of about 0.08 m/s could be estimated under the aliasing limit of the conventional autocorrelation method of 0.047 m/s. Myocardial velocity over the conventional aliasing limit could be measured by the proposed method.

Keywords Autocorrelation method · Aliasing · Tissue velocity · Velocity difference

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Introduction

It has already been shown that the measurement of tissue motion is of great benefit for assessment of functional imaging of tissues [1]. For this purpose, autocorrelation using in-phase and quadrature (IQ) signals [2] is widely used for the measurement of tissue velocity. This method can estimate slight tissue motion accurately using the phase shift of the IQ signal [3]. On the other hand, it suffers from aliasing when the velocity of rapidly moving tissue, such as the heart wall, is measured because the phase shift can be estimated correctly between $\pm\pi$. Also, the aliasing limit in the velocity estimation depends on the ultrasonic frequency and frame rate. In the present study, a simple method was proposed for expanding the aliasing limit by evaluating the velocity difference between consecutive frames.

Materials and methods

Method for expanding the aliasing limit

The velocity of a target $v(z; n)$ at an axial position z in the n-th frame can be estimated using the complex correlation function $r(z; n)$ of IQ signals $\{g_n(z)\}$ obtained from the received ultrasonic radio-frequency (RF) signals as follows [3]:

$$\hat{v}_1(z;n) = -\frac{c_0}{4\pi f_0 T} \cdot \angle \hat{r}(z;n), \tag{1}$$

where $\hat{v}_1(z;n)$ denotes the velocity estimated by the conventional autocorrelation method, and c_0, f_0, T, and $\angle$ are the speed of sound in the medium, ultrasonic center frequency, frame interval, and phase angle, respectively. Complex correlation function $r(z; n)$ is defined as follows:

$$\hat{r}(z;n) = \frac{\sum_{z\in W} g_n^*(z)\cdot g_{n+1}(z)}{\left|\sum_{z\in W} g_n^*(z)\cdot g_{n+1}(z)\right|}, \quad (2)$$

where W and * denote the correlation kernel and complex conjugate, respectively. The aliasing limit $v_{\max}$ of the conventional autocorrelation method corresponds to the magnitude of velocity at $\angle r\,(z;\,n) = \pi$ given by

$$v_{\max} = \frac{\pi c_0}{4\pi f_0 T}. \quad (3)$$

Figure 1a illustrates correlation functions, $r(z;\,n-1)$ and $r(z;\,n)$ (their phase values correspond to velocities in the $(n-1)$-th and n-th frames), under the presence of the aliasing effect. Even under such a condition, the change in velocity, $\Delta v(z;\,n) = v(z;\,n)-v(z;\,n-1)$ (corresponding to acceleration), from the n-th frame to $(n+1)$-th frame can be estimated as long as $|\Delta v(z;\,n)| < v_{\max}$. Figure 1b shows the range of velocity satisfying this condition. This condition would be valid in most cases because the heart wall moves continuously and, thus, the change in velocity (acceleration) would be lower than the velocity itself. Therefore, in the present study, the change in velocity was employed for the estimation of velocity.

Using the complex correlation functions $r(z;\,n-1)$ and $r(z;\,n)$ in two consecutive frames, the change in velocity $\Delta v(z;\,n)$ from the $(n-1)$-th frame to n-th frame is estimated as follows:

$$\Delta\hat{v}(z;n) = -\frac{c_0}{4\pi f_0 T}\cdot\angle\{\hat{r}^*(z;n-1)\cdot\hat{r}(z;n)\}. \quad (4)$$

Instead of Eq. (1), velocity $v\,(z;\,n)$ in the n-th frame is estimated using $\Delta\hat{v}(z;n)$ as follows:

$$\hat{v}_2(z;n) = \hat{v}(z;n-1) + \Delta\hat{v}(z;n), \quad (5)$$

where velocity $\hat{v}(z;n)$ estimated using $\Delta\hat{v}(z;n)$ is denoted by $\hat{v}_2(z;n)$.

However, accumulation of the changes in velocity $\{\Delta\hat{v}(z;n)\}$ may cause an undesirable drift in the estimated velocity. Therefore, in the present study, velocity $v(z;\,n)$ is estimated using $\hat{v}_1(z;n)$ without the aliasing effect as much as possible. To realize this strategy, velocity $v(z;\,n)$ in the n-th frame is estimated as follows:

$$\hat{v}(z;n) = \begin{cases} \hat{v}_1(z;n)\ (\text{if } |\hat{v}(z;n-1) - \hat{v}_1(z;n)| < v_{\max}), \\ \hat{v}_2(z;n)\ (\text{if } |\hat{v}(z;n-1) - \hat{v}_1(z;n)| \geq v_{\max}), \end{cases} \quad (6)$$

where $\hat{v}(z;0) = \hat{v}_1(z;0)$ and, also, the magnitude of velocity in the initial frame $v(z;\,0)$ should be under the aliasing limit $v_{\max}$ of the conventional autocorrelation method of Eq. (1). Under such conditions, the aliasing limit can be expanded if the acceleration of tissue is not extremely large ($|v(z;\,n)-v(z;\,n-1)| < v_{\max}$).

Experimental system

In the present study, a modified ultrasound diagnostic system (Aloka, SSD-6500) was used with a 3.75-MHz phased array probe. RF signals obtained by conventional transmit-receive beamforming were sampled at 15 MHz at 16-bit resolution. The number of scan lines was reduced to 9 to realize a high frame rate of 445 Hz. The RF signal along a scan line was analyzed in the M-mode format.

In vivo experimental results

In the present study, RF signals from the heart of a 26-year-old healthy male measured in vivo were analyzed. The RF signals from the posterior wall were acquired in the parasternal long-axis view. Figure 2(1-a) and (2-a) show the same M-mode images, and the tracking lines (red curves) estimated by the conventional autocorrelation method [3] and the proposed method are overlaid on the M-mode images in Fig. 2(1-a) and (2-a), respectively. Figure 2(1-b) and (2-b) show the same electrocardiogram and phonocardiogram.

Figure 2(1-c) and (2-c) show velocities on the tracking lines in Fig. 2(1-a) and (2-a) estimated by the conventional

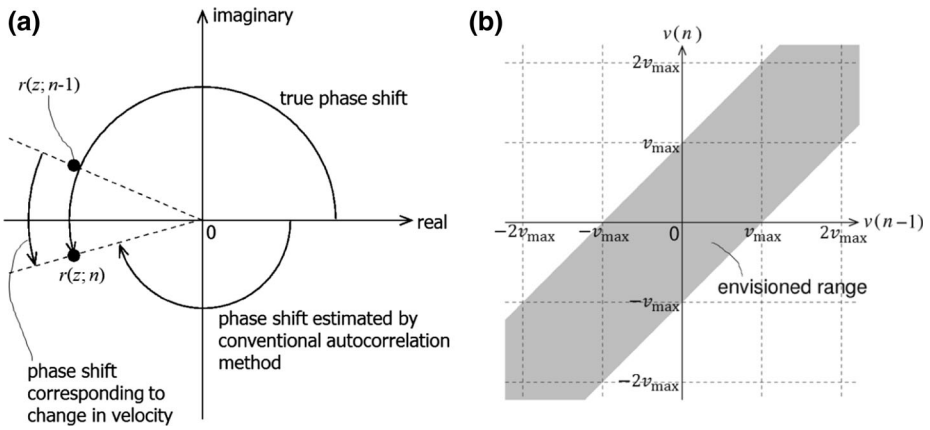

Fig. 1 **a** Illustration of the phase shift of IQ signals owing to tissue motion. **b** Illustration of the range of velocities satisfying the envisioned condition

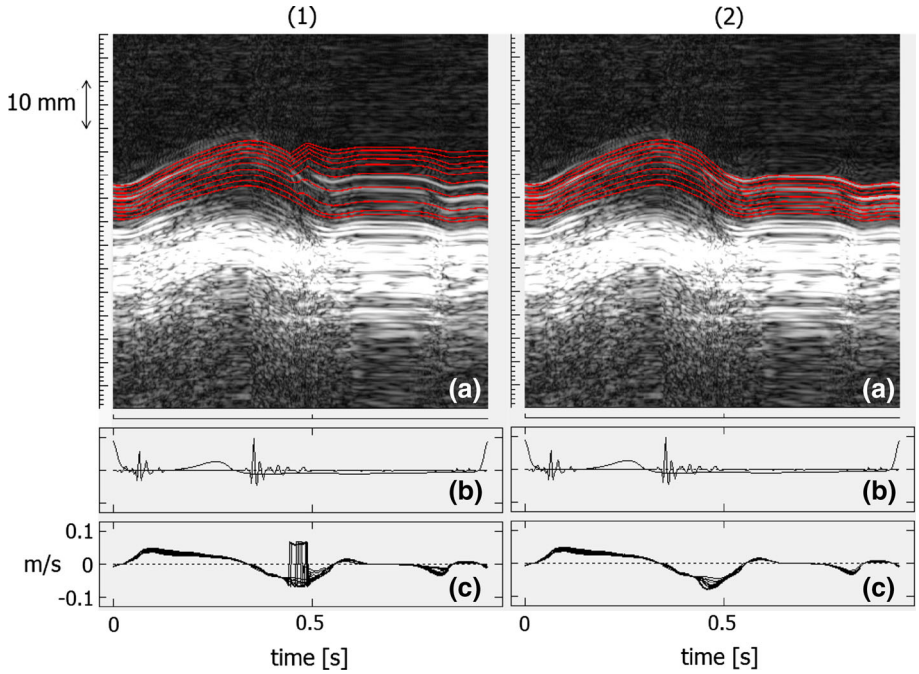

Fig. 2 In vivo experimental results from a 26-year-old healthy male obtained by the **1** conventional autocorrelation method and **2** proposed method. *(a)* M-mode image of the posterior heart wall measured in the parasternal long-axis view and tracking lines (*red curves*). *(b)* Electrocardiogram and phonocardiogram. *(c)* Estimated velocities on the *red curves* in *(a)*

autocorrelation method and the proposed method, respectively. As can be seen in Fig. 2(1-a) and (1-c), on the endocardial side of the posterior wall, aliasing is found in the velocities estimated by the conventional autocorrelation method during the rapid filling phase due to the rapid expansion of the left ventricle, and significant tracking errors are also found. In that case, the aliasing limit v_{max} of the conventional autocorrelation method was 0.047 m/s (at f_0 of 3.75 MHz). Using the proposed method, as shown in Fig. 2(2-a) and (2-c), the aliased velocity estimates and tracking errors are corrected and the velocity of about 0.08 m/s, which is over the aliasing limit of the conventional autocorrelation method, can be estimated by the proposed method.

Discussion

O'Donnell et al. [4] also tried to expand the aliasing limit by estimating and accumulating velocity difference between two nearest spatial points. However, in this case, all the spatial points in the accumulation path are influenced when a spatial point with an erroneous velocity estimate (due to various reasons such as a low signal-to-noise ratio) is included. Therefore, as discussed in their report [4], it is necessary to identify an appropriate accumulation path in a 2D data set (B-mode). However, in the case of a 1D data set (M-mode), there is only one spatial accumulation path and, thus, the proposed method is suitable because accumulation is performed in the frame direction and a spatial point with an erroneous velocity estimate does not affect other spatial points.

Conclusions

In the present study, a simple method has been proposed to expand the aliasing limit of the autocorrelation method for the estimation of tissue motion. The proposed method utilized the velocity difference between two consecutive frames, which was directly estimated using the IQ signals. By analyzing in vivo experimental data from a human heart, it was shown that the aliasing limit could be expanded using the proposed method. The proposed method would be useful for measurement of velocity of rapidly moving tissue, such as the heart wall, as shown in the present study. Also, the method is very simple and can be incorporated into any type of diagnostic system.

Conflict of interest None.

Ethical considerations This study was in accordance with the institutional committee on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008 (5). Informed consent was obtained from the subject.

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