Identification of Heart Wall Using Frequency Spectrum of Ultrasonic RF Echo.
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ABSTRACT

Purpose: The heart wall in an ultrasonic image cannot be distinguished from the ventricular lumen using only the amplitude of the RF echo because the amplitude inside the heart wall is as low as that in the lumen. In this study, frequency spectra of echoes from the heart wall and lumen were analyzed in order to differentiate the frequency characteristics between them.

Principle: After applying the Fourier transform to ultrasonic RF echoes from the interventricular septum, right ventricle, and left ventricle, the changes in their frequency spectra in multiple frames were investigated. Using the phased tracking method, the object motion was tracked so that the analyzing window follows the object displacement.

Results: The coherence among frames of the echo signal from the heart wall was high. On the other hand, in the lumen, the coherence of the echo signal from the lumen was low because the ultrasonic scatterers (blood cells) are slipped off from the focal area of ultrasound by blood flow. The difference between spectra of echoes from the heart wall and lumen would be effective in identification of the heart wall.

INTRODUCTION

In recent years, the number of patients suffering from cardiovascular diseases such as cardiac infraction has increased. For diagnosis of these diseases, cardiac catheterization, X-ray, CT, ultrasound, and so on are employed. Among these methods, ultrasound is superior to the others in terms of noninvasive and real-time diagnosis.

For diagnosis of cardiac diseases with ultrasonic diagnostic equipment, a tomographic view such as a B-mode image and M-mode image is employed to observe the large motion of the heart and the ultrasonic Doppler method is applied to estimate the blood flow in the lumen. In these methods, however, observable shape and movement of the heart wall are limited to those in visible by naked eyes. Moreover, the area of heart wall is not able to be distinguished from cardiac lumen objectively by only echogenicity because the echogenicity, which corresponds to the envelope of the RF signal, at the inside of heart wall is as low as at lumen. Due to these circumstances, the region of the heart wall is subjectively distinguished from the lumen based on the premise of knowledge about the heart structure.

Although the envelope of the RF signal dose not provide enough information of ultrasonic reflectors/scatterers, it has been shown that the RF signal, especially frequency characteristics of the RF echoes, depends on the properties of the ultrasonic reflectors/scatterers [1,2,3,4,5]. Therefore, the frequency characteristics of the amplitude and phase of the RF
echo provide more information about the reflector/scatterer property in comparison with the echogenicity in the tomographic view. In this study, complex frequency spectra of echoes from the heart wall and lumen were analyzed in order to find the difference in frequency characteristics between both regions.

ANALYSIS METHOD

As illustrated in Fig. 1(a), the interventricular septum (IVS), and right ventricle (RV), and left ventricle (LV) were scanned by the ultrasonic beam, which scans sparsely to realize a high temporal resolution. At first, RF data \( y_{n=x}(t) \) along four beams were acquired using a 3.75 MHz sector-type probe of ultrasonic diagnostic equipment (ALOKA SSD-6500), where subscript \( n \) and \( x \) show frame (time) and depth, respectively. The sampling frequency of the RF signal was 15 MHz and the frame rate in the measurement was 704 Hz. Secondly, RF signal along each beam at \( n_0 \) (time \( t_0 \)), which was the central frame in the analyzing period, was analyzed by sliding the window (Hanning window) along each RF line by 51.3 \( \mu \)m (1 sampled point). In this analysis, four length (410 \( \mu \)m: 8 sampled points, 821 \( \mu \)m: 16 points, and 3.28 mm: 64 points) of windows were employed. When 8-, 16-, and 32-point windows were used, 56, 48, and 32 zero points were added respectively in order to obtain the same apparent frequency resolution of estimated spectra. Subsequently, the fast Fourier transform (FFT) was applied to each windowed and zero-added RF data. Then, the complex frequency spectrum \( Y_{n=x}(f) \) was obtained.

Next, the time changes of the spectra were analyzed by applying the above procedure to multiple frames. The position of the window was made to follow the motion of the object using the phased tracking method [6] in order to analyze the same object in every frame, and the spectrum \( Y_{n,x}(f) \) in every frame were obtained. Using the phased tracking method, the motion of a point of interest is traced without constraint of sampling interval along the depth direction, and the displacement of the point between two adjacent frames is calculated in analog value. However, the window position should be assigned in discrete value depending on the sampling interval. This difference \( \Delta x_{n,x} \) between the estimated position of the point of interest and the discrete position of the window leads to undesirable phase shift \( \Delta \theta_{n,x}(f) \) between the estimated spectra, \( Y_{n,x}(f) \) and \( Y_{n+1,x}(f) \). Phase difference \( \Delta \theta_{n,x}(f) \) is shown as follows:

\[
\Delta \theta_{t,x}(f) = -\frac{4\pi f}{c_0} \Delta x_{n,x},
\]

where \( c_0 \) shows acoustic velocity of 1,540 m/s. Consequently, \( \Delta \theta_{n,x}(f) \) can be compensated as follows:

\[
\hat{Y}_{n,x}(f) = Y_{n,x}(f)e^{j\Delta \theta_{n,x}(f)},
\]

where \( \hat{Y}_{n,x}(f) \) is the corrected complex frequency spectrum.

Using frequency spectrum \( \hat{Y}_{n,x}(f) \) in each frame, the power of the time (frame)-averaged frequency spectra were obtained. In addition, the magnitude-squared coherence function \( |\gamma_x(f)|^2 \) is evaluated as follows:

\[
|\gamma_x(f)|^2 = \frac{E_n \left[ \hat{Y}_{2n,x}(f) \hat{Y}_{2n-1,x}(f) \right]^2}{E_n \left[ \hat{Y}_{2n,x}(f) \right]^2 E_n \left[ \hat{Y}_{2n-1,x}(f) \right]^2},
\]
Fig. 1. (a) Pattern diagram of tomographic view of the human heart. (b) B-mode image in the long-axis view of the human heart. Blue arrows show ultrasonic beams and red trapezoid shows acquisition area of RF signals.

Fig. 2. (a) Tracking locus on the M-mode image of the heart along beam 1. (b) Electrocardiogram (ECG). (c) Phonocardiogram (PCG). (d) Acquired RF signal at $t_0$.

where $E_n[\cdot]$ means time averaging. This magnitude-squared coherence function shows that the power of the complex correlation between spectra in two adjacent frames at each depth. This function enables us to evaluate the time changes of complex spectra of reflected/scattered echo from the heart wall and lumen quantitatively.

**IN VIVO EXPERIMENTAL RESULTS**

RF data were acquired from the heart of a healthy 23-year-old male, and the analysis described in the previous section was applied.

Figure 1(b) shows an acquired B-mode image. The RF data were obtained from the beams shown by blue arrows within acquisition area shown by the red trapezoid in Fig. 1(b).

Figure 2(a) shows an M-mode image along beam 1. Time $t_0$ is set as the central time
Fig. 3. (a) Power spectra $|\hat{Y}_{n,x}(f)|^2$ of RF signal along beam 1 and power of time-averaged complex spectrum, (b) magnitude-squared coherence function $|\gamma_x(f)|^2$ between spectra in two adjacent frames along beam 1, acquired from window whose width was (1) 410 µm (8 points), (2) 821 µm (16 points), (3) 1.64 mm (32 points), and (4) 3.28 mm (64 points).
Fig. 4. (a) Original B-mode image before color-coding. (b) Images of magnitude-squared coherence function $|\gamma_x(f)|^2$ at each frequency. The regions that the window crosses the boundary between RV and IVS and between IVS and LV are not color-coded.

function is high. On the other hand, in the lumen, the coherence function is low because the ultrasonic scatterers (blood cells) are slipped off from the focal area of ultrasonic beam by blood flow. These differences between spectra of the heart wall and lumen would be effective in identification of the heart wall. Although the coherence function of the area near the anterior wall in the RV is as high as that in the heart wall region, this is due to the multiple reflection by the tissue outside of the heart.

For the identification at a high spatial resolution, the window length should be narrow, but a narrow time window leads to the worsening of the resolution of the frequency spectrum. When zero points are added to the time sequence to which the FFT is pre-applied, the frequency resolution is apparently improved, but the actual frequency resolution is not improved. Actually, spectra shown in Fig. 3(1a) and 3(2a) are only smoothed and thus seem to lack much information. However, the difference in the coherence function obtained by a narrow window between the heart wall and lumen is similar to that obtained
by a wide window. The coherence function in the high frequency range obtained by a narrow window is useful to differentiate the heart wall from lumen.

Figure 4(a) shows B-mode image obtained by sparse scan. Figure 4(b) shows color-coded images of the magnitude-squared coherence functions at 5 different frequencies and at 4 window width. In these figures, differences between the coherence functions of heart wall and lumen in beams 1 and 2 are shown more clearly than that on beam 3 and 4. This is because beams 1 and 2 are almost perpendicular to the IVS but beams 3 and 4 are not. However, the difference between the heart wall and lumen is clearly shown in all beams especially at 5.6 MHz when the window length and at 4.7 MHz when the window length is 0.82 mm.

DISCUSSION

The proposed method using the magnitude-squared coherence function exploits the variance in spectra in two adjacent frames (1.42 ms). The time \( t_0 \) shown in Fig. 2(b) was chosen so as to be the central time in the analyzing period. This period corresponds to the late phase of rapid filling and early phase of reduced filling in a cardiac cycle, when the movement of heart wall is comparatively slow and blood flow is fast. This is the suitable condition for the region identification with magnitude-squared coherence function \( |\gamma_x(f)|^2 \). That is because the number and width of the myocardium within the window would not change so much in the heart wall region, and blood cells would be slipped off from the focal area of the ultrasonic beam during a few frames. Blood flow velocity in the LV was about 0.7 m/s, which was measured by the ultrasonic Doppler method, and the beam width was 1.45 mm (width of half maximum of the amplitude of echo from a fine wire). Then, blood cells pass over the focal area of the ultrasonic beam by about 2 ms (1.5 frame). It is supposed that this rapid movement of the scatterers decreases the coherence of the echo signal from the cardiac lumen.

CONCLUSIONS

Based on the time change of frequency spectra of the RF signals from the heart, the difference between the heart wall and lumen were shown. The magnitude-squared coherence function of the RF signal windowed by a narrow window showed the good differentiation between heart wall and lumen. These results show the possibility of region identification of the heart wall using the frequency spectra of ultrasonic RF echoes.

REFERENCE