Stabilization Technique for Real-Time High-Resolution Vascular Ultrasound Using Frequency Domain Interferometry *

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***Abstract*— We have proposed an ultrasound imaging method based on frequency domain interferometry (FDI) with an adaptive beamforming technique to depict real-time high-resolution images of human carotid artery. Our previous study has investigated the performance of the proposed imaging method under an ideal condition with a high signal-to-noise ratio (SNR). In the present study, we propose a technique that has the potential to improve accuracy in estimating echo intensity using the FDI imaging method. We investigated the performance of the proposed technique in a simulation study that two flat interfaces were located at depths of 15.0 and 15.2 mm and white noise was added. Because the –6 dB bandwidth of the signal used in this simulation study is 2.6 MHz, the conventional B-mode imaging method failed to depict the two interfaces. Both the conventional and proposed FDI imaging methods succeeded to depict the two interfaces when the SNR ranged from 15 to 30 dB. However, the average error of the estimated echo intensity at the interfaces using the conventional FDI imaging method ranged from 7.2 to 10.5 dB. In contrast, that using the FDI imaging method with the proposed technique ranged from 2.0 to 2.2 dB. The present study demonstrates the potential of the FDI imaging method in depicting robust and high-range-resolution ultrasound images of arterial wall, indicating the possibility to improve the diagnosis of atherosclerosis in early stages.**

I. INTRODUCTION

Cardiovascular disease remains a substantial cause of mortality [1]. Recent clinical issue is arterial plaque of which rupture or erosion lead to abrupt thrombosis. Urgent demand is how to establish a marker for vulnerable plaque [2]. Transcutaneous ultrasound B-mode imaging is widely used to detect plaque in carotid arteries [3]. Thus, improving the spatial resolution of the imaging would bring a major advance in identification of high-risk plaques.

*This work was partly supported by the Innovative Techno-Hub for Integrated Medical Bio-imaging Project of the Special Coordination Funds for Promoting Science and Technology, from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan and by MEXT/JSPS KAKENHI Grant Numbers 24592513 and 25870345.

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Adaptive beamforming algorithms have been proposed to improve spatial resolution without using high transmit frequencies. One common technique is the use of a Capon beamformer, which uses a set of weights calculated by minimizing the output power, subject to the constraint that a desired signal gives a constant response [4]. Several groups have used the Capon method with spatial averaging to improve the lateral resolution in US [5], [6]. In our previous study, we have proposed an ultrasound imaging method based on frequency domain interferometry (FDI) with an adaptive beamforming algorithm that has high resolution in axial direction [7]−[10]. We have reported on the necessity of employing frequency averaging to suppress coherent interference under a simple simulation study without noise. We are currently working on the effect of the bandwidths used for frequency averaging and for imaging on the performance of the FDI imaging method in the condition with noise, and propose a technique that has the potential to acquire robust depiction of arterial interfaces when there is a thin layer close to the arterial wall.

II. MATERIALS AND METHODS

The proposed technique is applied to the FDI imaging method with the Capon method, which is an adaptive beamforming algorithm. In this section, we briefly describe the FDI imaging method, and subsequently propose a technique that improves accuracy in estimating echo intensity using the FDI imaging method.

A. FDI Imaging Method Using Frequency Averaging

The FDI imaging method works under the condition where the echo at the desired depth and echoes at undesired depth have no correlation. Frequency averaging has been used to suppress the correlation between the echoes returned from different depths [7]. This technique is applied to the covariance matrix of the received signal in the frequency domain. The sub-matrices of the covariance matrix are averaged along the diagonal direction, as shown in Fig. 1. The covariance matrix after frequency averaging is given by

$$\mathbf{R}_A = \frac{1}{M}\sum_{m=1}^{M}\mathbf{R}_m, \tag{1}$$

$$R_{mij} = X_{i+m-1}X^{*}_{j+m-1}, \tag{2}$$

where R_{mij} is the (i, j) element of the m-th submatrix $\mathbf{R}_m$, X_i is the i-th frequency components of the received RF signal after whitening, M is the number of submatrices, and $[]^*$ denotes the complex conjugate.

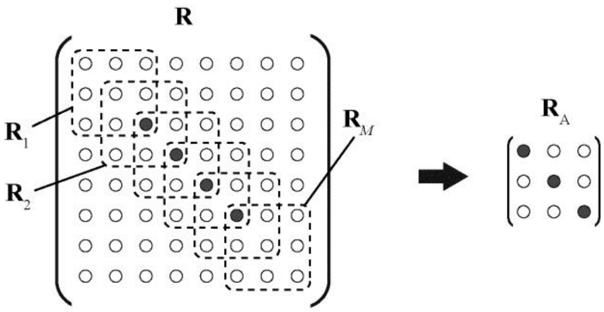

Figure 1. Schema of the frequency averaging technique. Gray diagonal elements of the covariance matrix **R** are distributed among the diagonal elements of the covariance matrix after frequency averaging $\mathbf{R}_A$.

The FDI imaging method suppresses the contribution of echoes from targets at undesired depths, subject to a constant response at the desired depth. After applying frequency averaging to the covariance matrix, this problem expressed by the following formulae:

$$\begin{aligned} &\text{minimize} \quad P(r) = \mathbf{W}^{\mathrm{T}*}\mathbf{R}_{\mathrm{A}}\mathbf{W} \\ &\quad \text{subject to} \quad \mathbf{C}^{\mathrm{T}*}\mathbf{W} = 1, \end{aligned} \tag{3}$$

$$\mathbf{C} = \left[\exp(\mathrm{j}k_1 r) \quad \exp(\mathrm{j}k_2 r) \quad \cdots \quad \exp(\mathrm{j}k_N r)\right]^{\mathrm{T}}, \tag{4}$$

Where $r/2$ is the desired depth, $P(r)$ is the output intensity at the desired depth, **W** is a weighting vector, k_n is the n-th wave number of frequency components of a received signal, N is the size of the correlation matrix $\mathbf{R}_A$, and $[]^T$ denotes the transpose [10].

The estimated intensity of the FDI imaging method employing an appropriate weighting vector is given by

$$P_{\mathrm{Cap}}(r) = \frac{1}{\mathbf{C}^{\mathrm{T}*}(\mathbf{R}_{\mathrm{A}} + \eta\mathbf{E})^{-1}\mathbf{C}}, \tag{5}$$

where $\eta\mathbf{E}$ is a diagonal loading matrix used to avoid the instability in calculating the inverse matrix $\mathbf{R}_A^{-1}$ [7].

B. Stabilization Technique for the Improvement in Estimating Echo Intensity

When the bandwidth for frequency averaging is wider than that for imaging, i.e. the size of the sub-matrix L is smaller than the number of submatrices M, the output intensity of the FDI imaging method is rewritten as

$$\begin{aligned} P(r) &= \frac{1}{M}\sum_{m=1}^{M}\mathbf{W}^{\mathrm{T}*}\mathbf{R}_m\mathbf{W} = \frac{1}{M}\sum_{m=1}^{M}\left|\sum_{l=1}^{L} X^*_{l+m-1}W_l\right|^2 \\ &= \frac{1}{M}\sum_{m=1}^{M}\left|\sum_{l=1}^{L} X^*_{l+m-1}W_l \exp\{\,\mathrm{j}(m-1)\Delta kr\}\right|^2 \\ &\geq \frac{1}{M}\left|\sum_{m=1}^{M}\sum_{l=1}^{L} X^*_{i'}W_l \exp\{\,\mathrm{j}(i'-l)\Delta kr\}\right|^2 \\ &= \frac{1}{M}\left|\sum_{l=1}^{L} X^*_{\mathrm{B}l}W_l + \sum_{i'=L}^{M} X^*_{i'} \exp\,\mathrm{j}k_{i'}r\right|^2, \end{aligned} \tag{6}$$

$$\begin{aligned} X^*_{\mathrm{B}l} &= \sum_{i'=l}^{L-1} X^*_{i'} \exp\{\,\mathrm{j}(i'-l)\Delta kr\} \\ &\quad + \sum_{i'=M+1}^{M+l-1} X^*_{i'} \exp\{\,\mathrm{j}(i'-l)\Delta kr\}, \end{aligned} \tag{7}$$

where Δk is the wavenumber of the sampling frequency interval and $i' = l + m - 1$.

When we use a wider bandwidth for frequency averaging than that for imaging, the Capon beamformer with frequency averaging is similar to the combination of a simple phase-compensation beamformer for central frequency components and a Capon beamformer for peripheral frequency components. Under this condition, the intensity estimated by the FDI with the Capon method with frequency averaging would be larger than the summation of the intensities among the central frequency components from $L\Delta k$ to $M\Delta k$, i.e. the summation of the intensities of gray diagonal elements shown in Fig. 1. Therefore, the estimated intensity of the FDI imaging method is supposed to satisfy the following formulae:

$$I_{\mathrm{E}} \geq F_{\mathrm{S}} I_{\mathrm{True}}, \tag{8}$$

$$F_{\mathrm{S}} = (B_{\mathrm{A}} - B_{\mathrm{I}})/B_{\mathrm{A}}, \tag{9}$$

where B_A and B_I are the bandwidth used for frequency averaging and for imaging, respectively. We call F_S the stabilization factor. The employment of a sufficiently large value of F_S should suppress the underestimation of the echo intensity using the FDI imaging method with the Capon method at the cost of a little range resolution. When $F_S = 1/3$, the estimated intensity is supposed to be larger than –4.77 dB relative to the true echo intensity.

III. RESULTS

In the simulation study, we investigate the performance of the proposed technique when there were two horizontal interfaces in a ROI, where the waveform returned from each interface was the same as that of the reference signal. When

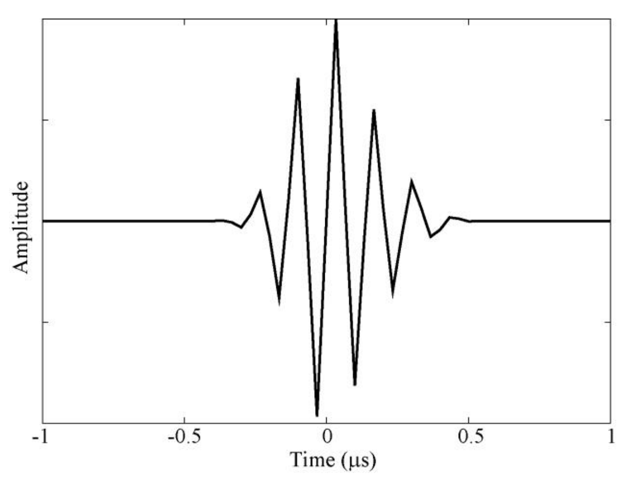

Figure 2. Echo waveform of a horizontal interface between 20% gelatin and 4% agar, where 10 echoes of different scan lines were coherently averaged to suppress noise.

the received signal includes no noise, the echo returned from two interfaces is given by

$$s(I_T, t) = s_R(t) + s_R(t - 2I_T / c), \tag{10}$$

where I_T is the target interval, $s_R(t)$ is the reference signal and c is the sound velocity. Fig. 2 shows the waveform used for the reference signal. The reference signal was the echo from the interface between the 20% gelatin and the 4% agar at a depth of 15 mm acquired by a Hitachi EUB-8500 (Hitachi Medical Co. Ltd., Tokyo, Japan) US device with a 7.5 MHz linear array, where 10 echoes of different scan lines were averaged. Before the averaging process, the center of each echo was adjusted to $t = 0$ to average coherently. The −6 dB bandwidth of the reference echo was 2.6 MHz. To investigate the effects of noise in the proposed method, we added white noise to the constructed received signal given by equation (10). The signal intensity was the average echo intensity in the –3 dB temporal width of a reference signal, and the noise intensity was the average echo intensity of the received signal in a 2 cm range that includes no echo signal.

Fig.3 shows the intensity at the target depth estimated by the conventional FDI imaging method under the condition of no noise, where there are two horizontal interfaces in the ROI and the true echo intensity at each target depth is adjusted to 0 dB. The imaging method used the band from 5.3 to 9.3 MHz, and the bandwidths for frequency averaging B_A were 3, 2, and 1 MHz. This result indicates that the employment of a wide bandwidth for frequency averaging improves the accuracy in estimating echo intensity under an ideal condition without noise.

Fig. 4 shows the intensity estimated using a conventional B-mode imaging method, the conventional FDI imaging method and the FDI imaging method with the proposed technique that employed a wider bandwidth for frequency averaging compared with that for imaging. The SNR ranged from 0 to 30 dB, there were two horizontal interfaces in a ROI and the target interval was 0.2 mm. The conventional FDI imaging method allocates a half of the whole bandwidth for frequency averaging [7]. The FDI imaging method using the proposed technique employed the setting of (B_A, B_I) = (3 MHz, 2 MHz). Because the –6 dB bandwidth of the signal used in this simulation study is 2.6 MHz, the conventional B-mode imaging method has range resolution of about 0.3 mm and it failed to depict the two interfaces. The conventional FDI imaging method has higher range resolution than the B-mode imaging method under the condition where its SNR was higher than 20 dB. This result is consistent with our previous work [7]. Under the condition of low SNR less than 15 dB, in some cases the conventional FDI imaging succeeded to depict two interfaces. However, the estimated intensity at the interface position decreased severely, and the estimated depth of the interface varied. These two defects might have caused that some false images appeared in the conventional FDI images at the SNR of less than 10 dB. In contrast, the FDI imaging with the proposed technique succeeded to depict the interfaces reliably at the cost of little deterioration in range

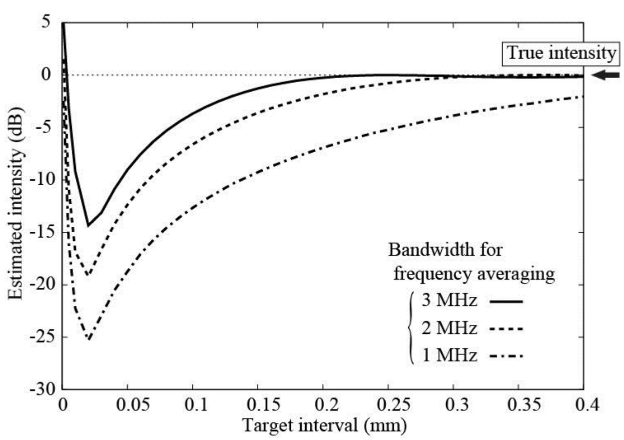

Figure 3. Estimated intensity at the target depth using the conventional FDI imaging method under the condition without noise, where two target interfaces are located in a ROI and the true echo intensity at the target depth is adjusted to 0 dB. The imaging method uses the band of the received data from 5.3 to 9.3 MHz, and the bandwidths for frequency averaging are 3, 2, and 1 MHz.

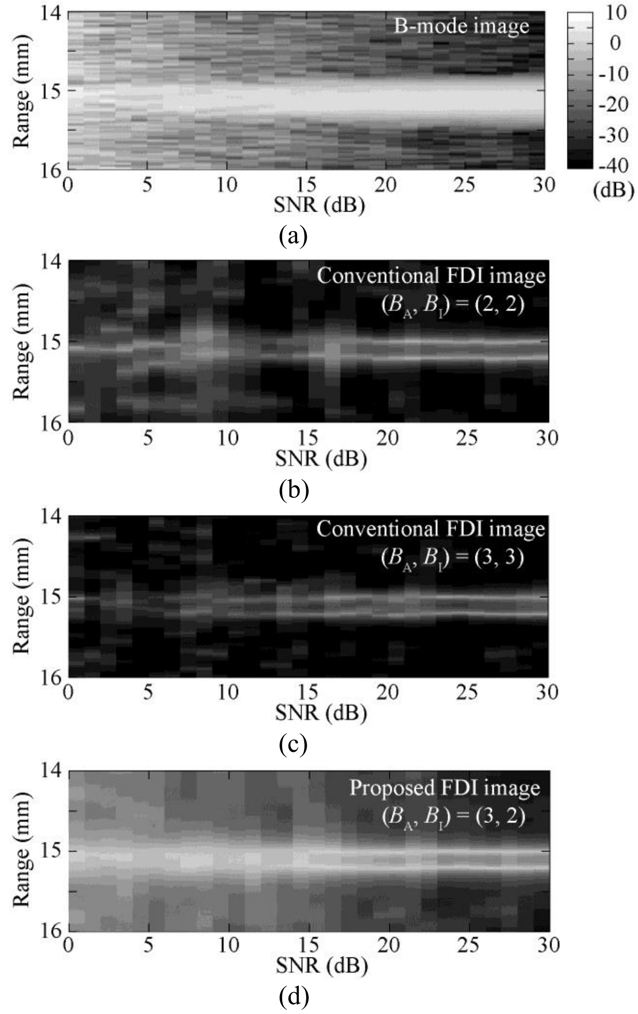

Figure 4. Estimated intensity as a function of the SNR from 0 to 30 dB when there are two interfaces at depths of 15.0 and 15.2 mm. The intensity profiles are estimated by (a) a conventional B-mode imaging method, (b) and (c) the conventional FDI imaging method, and (d) the FDI imaging method with the proposed technique. The bandwidth for frequency averaging (B_A) and that for imaging (B_I) are respectively (b) 2 and 2 MHz, (c) 3 and 3 MHz, and (d) 3 and 2 MHz, respectively.

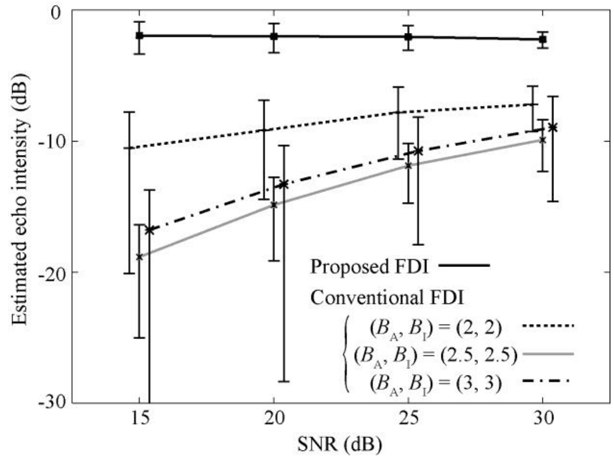

Figure 5. Estimated echo intensity of target interfaces calculated using the conventional FDI imaging method and the FDI imaging method with the proposed technique, where there are two target interfaces at depths of 15.0 and 15.2 mm and the true echo intensity is 0 dB. The FDI imaging method with the proposed method allocates bandwidths of 3 and 2 MHz for frequency averaging and imaging, respectively. The conventional FDI imaging method allocates half bandwidths for frequency averaging from total bandwidths of 4, 5 and 6 MHz. Each error bar denotes the standard deviation, where 10 simulation data with random white noise are used.

resolution. This result indicates the efficiency of the proposed setting that the bandwidth for frequency averaging is wider than that for imaging.

The above-mentioned defects of the conventional FDI imaging method cause uncertainty in selecting peak values as the estimated intensity at the interfaces. When SNR ranged from 15 to 30 dB, two peaks appeared clearly in both the conventional and proposed FDI imaging methods. We thus calculated the estimated echo intensity at the interfaces by averaging two peak values in each scan line under the condition that SNR ranged from 15 to 30 dB. Because the true echo intensity was 0 dB, we call the underestimation of the echo intensity at the interfaces as the estimation error. Fig. 5 shows the estimated echo intensity of the target interfaces calculated using the conventional FDI imaging method and using the FDI imaging method with the proposed technique. Using 3 MHz bandwidth for frequency averaging suppresses coherent interferences sufficiently when the target interval is 0.2 mm; however, using a wide bandwidth means using low SNR frequency components that makes the conventional FDI imaging method unreliable. Because the Capon method minimizes the output power, the conventional FDI imaging method underestimates the echo intensity with the average error ranged from 7.2 to 10.5 dB, and its unreliable performance results in large variations in estimated echo intensity. This should be one of the reasons why the conventional FDI imaging method has low continuity in the lateral direction [7]. In contrast, the FDI imaging method with the proposed setting succeeded in estimating the echo intensity with average estimation error ranged from 2.0 to 2.2 dB and with small variation. Under the condition of the FDI imaging method with the proposed technique, the stabilization factor F_S is equal to 1/3. In all cases, the normalized echo intensity estimated by the FDI imaging method with FAS is larger than –4.77 dB. This result is consistent with the results of the theoretical investigation shown in section II B. These results indicate that the proposed technique has high potential not only in estimating the echo intensity but also in improving continuity in the lateral direction.

IV. Conclusion

We proposed a high-range-resolution FDI imaging method employing a technique that improves robustness of the FDI imaging method in estimating echo intensity. We investigated the performance of the proposed technique in a simulation study under the condition. In a simulation study where the SNR ranged from 15 to 30 dB, the average error of the estimated echo intensity using the conventional FDI imaging method ranged from 7.2 to 10.5 dB. In contrast, that using the FDI imaging method with the proposed technique ranged from 2.0 to 2.2 dB. The present study demonstrates the potential of the FDI imaging method in depicting robust and high-range-resolution ultrasound image, indicating the possibility to improve the diagnosis of atherosclerosis in early stages.

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