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High range resolution ultrasound imaging of a human carotid artery using frequency domain interferometry

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Abstract—**In this study, we propose a high range resolution ultrasound imaging method using frequency domain interferometry with adaptive beamforming technique. We employ multiple reference signals to compensate the variation of the vessel wall slope. The proposed method succeeded to acquire a high range resolution carotid artery image of a normal living human subject, where the method was applied to a single frame IQ data obtained by a commercial ultrasonographic device. This result verified the capability of the proposed method to improve the range resolution in ultrasonography. We believe the proposed method will largely progress medical diagnostics in vascular ultrasound.**

Keywords-Vascular ultrasound, high range resolution, frequency domain interferometry, Capon method, adaptive beamforming

I. INTRODUCTION

Cardiovascular disease is still a substantial cause of mortality. Carotid intima-media thickness (CIMT) is a sensitive measure of atherosclerosis, a surrogate marker for cardiovascular disease [1]. Since accurate measurement of CIMT requires high range resolution ultrasound imaging, the improvement of range resolution in ultrasonography (US) is desirable for early detection of cardiovascular disease.

Since the 1960's, adaptive beamforming algorithms have been proposed to improve spatial resolution in radio imaging. Capon method is one of the most common adaptive beamforming algorithms [2, 3]. The method minimizes the output power subject to the constraint that a desired signal gives a constant response. However, in US echoes from different targets are correlated with each other, causing the failure of the Capon method because the echo returned from a desired depth is canceled by echoes from other depths [4]. Therefore, Mann and Walker have employed spatial averaging technique to suppress the cross-correlation between echoes returned from different depths [5], where their work directed at the improvement of lateral resolution in US.

In a previous study, we proposed a high range resolution ultrasound imaging method based on frequency domain interferometry (FDI) with Capon method [6, 7]. This method employs several techniques to deal with broadband signals and succeeded to acquire a high range resolution image of a swine femoral artery. In this study, we modified the proposed method to acquire the high range-resolution ultrasound image of a living human carotid artery.

II. METHODS

A. FDI imaging method with the Capon method

The FDI imaging method is a technique to estimate the echo intensity from a desired depth. This method transforms the received signal returned from a region of interest (ROI) in the time domain to that in the frequency domain. The frequency components of the signal are summed after phase compensation. Since the Capon method minimizes the estimated intensity subject to a constant response at a desired depth, the estimated intensity of the FDI imaging method with the Capon method for US is expressed as the following formulae [7].

$$\text{minimize} \quad P = \mathbf{W}^{\mathrm{T}*}\mathbf{R}_{\mathrm{A}}\mathbf{W} \quad \text{subject to} \quad \mathbf{C}^{\mathrm{T}*}\mathbf{W} = 1, \quad (1)$$

$$\mathbf{C} = [\exp(\mathrm{j}k_1 r) \quad \exp(\mathrm{j}k_2 r) \quad \cdots \quad \exp(\mathrm{j}k_M r)]^{\mathrm{T}}, \quad (2)$$

where P is the estimated intensity of the FDI imaging method, $\mathbf{W}$ is a weighting vector, $\mathbf{R_A}$ is a covariance matrix of a received signal after whitening and frequency averaging, k_l is the l-th wavenumber of the frequency components utilized by the FDI imaging method, $r/2$ is the desired depth, and $[]^{\mathrm{T}}$ and $[]^{\mathrm{T}*}$ denote the transpose and the conjugate transpose, respectively. The problem expressed by equation (1) can be solved by the application of the Lagrange multiplier method. The estimated intensity of the FDI imaging method employing an appropriate weighting vector $\mathbf{W}$ is

$$P_{\mathrm{Cap}}(r) = \frac{1}{\mathbf{C}^{\mathrm{T}*}(\mathbf{R}_{\mathrm{A}} + \eta\mathbf{E})^{-1}\mathbf{C}}, \quad (3)$$

where $\eta\mathbf{E}$ is a diagonal loading matrix to obtain the inverse matrix $\mathbf{R}_{\mathrm{A}}^{-1}$ stably.

B. Reference compound applied to the FDI imaging method with the Capon method

Since US utilizes broadband signals, the target shape causes large variations in the intensity and phase of each frequency component of a received signal, resulting in a large variation in echo waveform. The FDI imaging method with the Capon method assumes that the echo waveform returned from a single target resembles that of the reference signal. When the echo waveform returned from a target is different from the reference waveform, the estimated intensity at the target depth decreases and the target image blurs. Therefore, we employed multiple reference signals, where the echo waveform of each target in a

ROI resembled at least one of the reference waveforms. We calculate the estimated intensity of a measurement plane using each reference signal separately, and then average the estimated intensities.

$$P_{\mathrm{CapRC}}(r) = \frac{1}{L}\sum_{l=1}^{L} P_{\mathrm{CapR}}(r,l), \tag{4}$$

where $P_{\mathrm{CapR}}(r,l)$ is the estimated intensity of the FDI imaging method employing a frequency component set of the l-th reference signal, and L is the number of the employed reference signals. We call this technique the reference compound. When the reference signal resembles the target echo in waveform, the estimated intensity profile using the reference signal has a sharp and large peak at the target depth. This means that the average of the estimated intensities using the multiple reference signals has the potential to depict target images stably. In addition, the appearance of false images depends on the waveform of the reference signal. This indicates that the reference compound has the same effect as the frequency compound in suppressing speckle noise [8].

Another strategy is the selection of the maximum intensity among the estimated intensities calculated using multiple reference signals.

$$P_{\mathrm{CapMI}}(r) = \max_{l} P_{\mathrm{CapR}}(r,l). \tag{5}$$

This strategy is supposed to acquire the estimated intensity profile with a sharp and large peak at the target depth; however, this strategy also selects the peaks of echo intensities that originate from speckle noise. Therefore, the strategy of selecting the maximum intensity improves range resolution at the cost of the emphasis of the speckle noise effect. Consequently, the strategy is unsuitable for the imaging of biological tissues containing multiple targets.

In ultrasound imaging of the human carotid artery in the longitudinal section, the vessel wall interfaces are supposed to be flat in the incident region of the ultrasound beam. We thus employed multiple flat interfaces with various slope angles as reference targets for vessel wall imaging in the experimental study.

C. *Experimental setup*

Experiments were conducted using a Hitachi EUB-8500 (Hitachi, Tokyo, Japan) US device with a 7.5 MHz linear array to acquire raw IQ data. The transmit focal depth was 15 mm, and the scan line interval is 0.265 mm. The sampling frequency of the quadrature detection at the acquisition of IQ data was 15 MHz, and the IQ data were converted to the RF data using the RF data oversampling technique [6, 7], where the sampling frequency of the converted RF data was 30 MHz.

$$S_{\mathrm{P}}\{(n-1/2)\Delta T\} = (-1)^n S_{\mathrm{I}}(n\Delta T), \tag{6}$$

$$S_{\mathrm{P}}(n\Delta T) = (-1)^n S_{\mathrm{Q}}(n\Delta T). \tag{7}$$

ΔT is the sampling time interval of the acquired IQ data, $S_{\mathrm{P}}(n\Delta T/2)$ is the converted RF data, and $S_{\mathrm{I}}(n\Delta T)$ and $S_{\mathrm{I}}(n\Delta T)$ are the n-th signal of the in-phase and quadrature data, respectively. We supposed that the sound velocity was 1500 m/s, and thus the range interval of the RF data was 0.025 mm. In the present study, we located a ROI at a depth of 1 to 2 cm. We employed a rectangular window function to cut out the received signal in the ROI from the whole signal, and the received signal in the ROI consisted of 400 range samples in each scan line. The –6 dB bandwidth of the echo from a single horizontal interface between the 20% gelatin and 4% agar at a depth of 15 mm was 2.6 MHz, where the gelatin layer was located forward.

The reference compound works when multiple reference signals are employed, where the echo waveform of each target in a ROI resembles at least one of the reference waveforms. To deal with the waveform variation caused by the slope angle of an artery wall interfaces, we employed six reference signals that were returned from flat interfaces between 20% gelatin and 4% agar with slope angles of 0, 2, 4, 6, 8 and 10 degrees. The center of each interface was located at a depth of 15 mm. After the depiction of separate artery images for the six reference signals, we averaged the estimated intensity of the depicted images.

We applied the proposed FDI imaging method with reference compound to the IQ data of a fixed swine femoral artery in vitro and a normal living human carotid artery in vivo. A swine femoral artery was embedded in a gelatin block after the fixation process.

III. RESULTS

A. *Imaging of a Swine Femoral Artery in vitro*

We measured the longitudinal section of a fixed femoral artery embedded in a gelatin gel using a commercial US device. Figure 1 shows the B-mode image of the fixed swine femoral artery. We applied the proposed FDI imaging method with reference compound to the IQ data of the artery obtained by the commercial US device. As shown in Fig. 2, the proposed method succeeded to depict a high range resolution image.

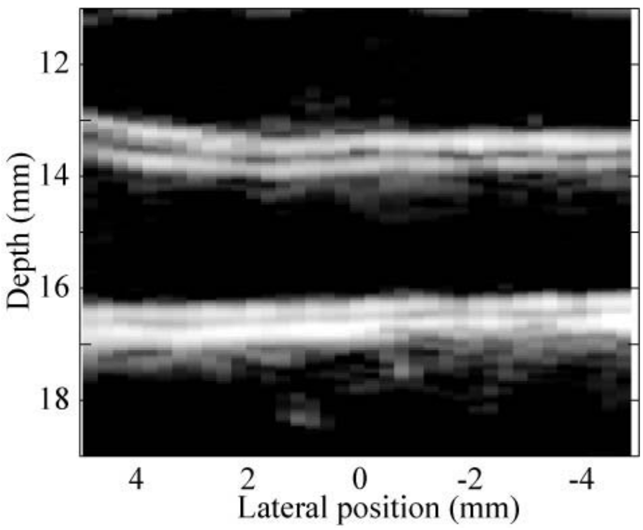

Figure 1. Ultrasound B-mode image of a fixed swine femoral artery acquired using a commercial ultrasonographic device.

Next, we evaluated the accuracy of the proposed method in depicting vessel wall interfaces. After the ultrasound measurement, we immediately cut the gelatin block with the artery in the imaging plane and photographed the cutting section magnified microscopically. Microscopic observation revealed that the interfaces at the posterior wall of the fixed swine artery depicted in the FDI image were close to the lumen-intima interface and the media-adventitia interface at the posterior wall, as shown in Fig. 3.

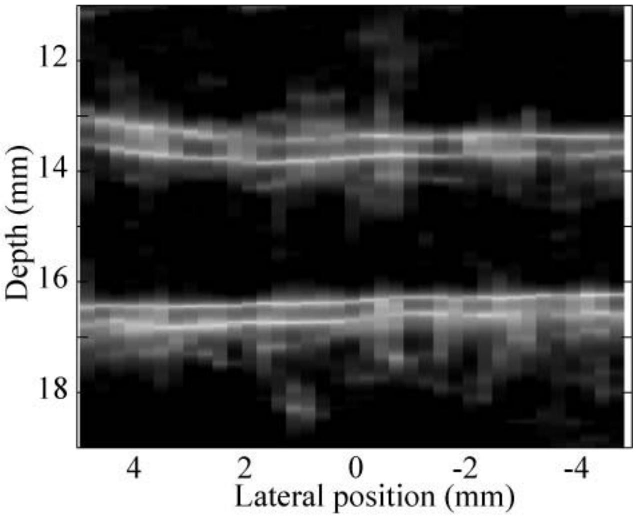

Figure 2. Image of a fixed swine femoral artery acquired using the proposed FDI imaging method with reference compound applied to a single frame IQ data obtained by a commercial ultrasonographic device.

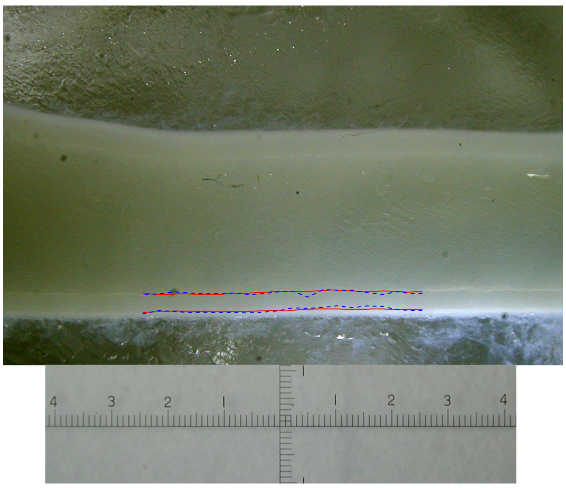

Figure 3. Interfaces depicted at the posterior wall in a FDI image projected to a corresponding microscopic image with a millimeter scale. Red lines indicate a lumen-intima interface and a media-adventitia interface traced microscopically. Blue broken lines are the interfaces depicted in the FDI image.

B. Imaging of a Living Human Carotid Artery in vivo

We applied the FDI imaging method with reference compound to a single frame of raw IQ data of a normal living human carotid artery in vivo obtained by a commercial US device. Figure 4 shows a B-mode image of a human carotid artery acquired by a commercial US device. The proposed method succeeded in depicting a carotid artery image with far higher range resolution than that of a conventional B-mode image, as shown in Fig. 5.

Since the proposed FDI imaging method constructs an image from a single frame of IQ data, after signal processing of a minute using multiple CPUs the high range resolution carotid artery images are available without a decrease in the frame rate. The calculation time for a ROI of 1 × 4 cm, i.e. 1001 range samples × 151 scan lines, was 5.8 s/frame, where we utilized a mobile PC with a single CPU (Intel Core2 Duo 2.26 GHz) and 3 GB RAM.

IV. CONCLUSIONS

We propose a high range resolution FDI imaging method with reference compound. The proposed method succeeded to depict a high range resolution image of a swine artery in vitro. A microscopic observation indicates the high potential of the proposed method in depicting vessel wall interfaces accurately. The application of the proposed method to a living human carotid artery verified that the proposed method can work in a clinical environment and it is suitable to improve the image quality in vascular ultrasound. We believe the proposed method will largely progress medical diagnostics in vascular ultrasound.

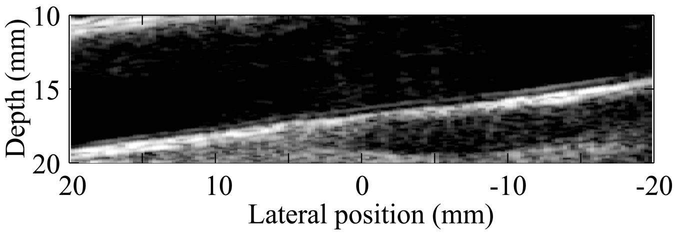

Figure 4. Ultrasound B-mode image of a living human carotid artery acquired using a commercial ultrasonographic device.

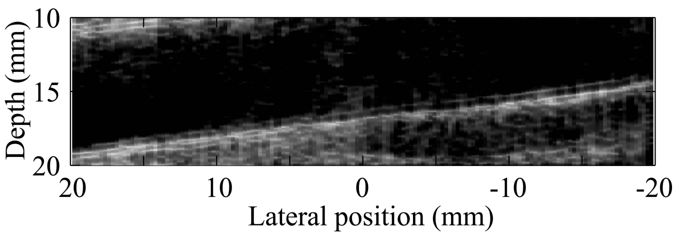

Figure 5. Image of a living human carotid artery acquired using the proposed FDI imaging method with reference compound applied to a single frame IQ data obtained by a commercial ultrasonographic device.

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