32nd Annual International Conference of the IEEE EMBS
Buenos Aires, Argentina, August 31 - September 4, 2010

High Range Resolution Medical Acoustic Vascular Imaging with Frequency Domain Interferometry

Hirofumi Taki, *Member, IEEE*, Kousuke Taki, Takuya Sakamoto, *Member, IEEE*, Makoto Yamakawa, *Member, IEEE*, Tsuyoshi Shiina, *Member, IEEE*, Toru Sato, *Member, IEEE*

Abstract—**For high range resolution acoustic vascular imaging we apply frequency domain interferometry and Capon method to a few frames of in-phase and quadrature (IQ) data acquired by a commercial ultrasonographic device. To suit the adaptive beamforming algorithm to medical acoustic imaging we employ three techniques; frequency averaging, whitening, and pseudo-double RF data conversion. The proposed method detected two couples of boundaries 0.26 and 0.19 mm apart using a single frame and two frames of IQ data, respectively, where each couple of boundaries is indistinguishable from a single boundary utilizing B-mode images. Further this algorithm could depict a swine femoral artery with higher range resolution than conventional B-mode imaging. These results indicate the potential of the proposed method for the range resolution improvement in ultrasonography, originating the progress in detection of vessel stenosis.**

I. Introduction

EARLY and accurate detection of artery stenosis is important for early diagnosis and treatment of lifestyle diseases. Since ultrasonography (US) is the primary imaging modality for the investigation of artery stenosis, the improvement of range resolution of US is strongly desired.

The frequency domain Interferometry (FDI) imaging methods using two frequencies have been proposed for the improvement of range resolution [1]. The methods are commonly applied in radar signal processing; however, because only two frequencies are used, the results of them are ambiguous and they are unsuitable to the environment with multiple targets [2]. For further improvement of range resolution in radar signal processing an FDI imaging method using multiple frequencies was proposed [3]. This method employed adaptive beamforming algorithms to improve range resolution using multiple frequencies of narrow-band signals. Therefore blind application of this method to medical acoustic imaging is unlikely to be successful.

Manuscript received March 26, 2010. This work was supported in part 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.

H. Taki, T. Sakamoto, and T. Sato are with the Graduate School of Informatics, Department of Communications and Computer Engineering, Kyoto University, Kyoto, Japan (e-mail: hirofumi.taki@mb6.seikyou.ne.jp).

K. Taki is with the Department of Anatomy, Shiga University of Medical Science, Shiga, Japan.

M. Yamakawa is with the Advanced Biomedical Engineering Research Unit, Kyoto University, Kyoto, Japan.

T. Shiina is with the Graduate School of Medicine, Kyoto University, Kyoto, Japan.

Since the 1960's adaptive beamforming algorithms have been developed to achieve high spatial resolution and suppress undesired signal's contribution. One of the most common approaches calculates a set of weights by minimizing the output power subject to the constraint that a desired signal gives a constant response [4]. In medical acoustic imaging a desired signal and interferences are strongly correlated. Shan and Kailath thus introduced spatial averaging technique to suppress coherent interferences [5]. Mann and Walker confirmed the improvement of spatial resolution using a modified Capon method experimentally [6]. However, these studies are directed to improve lateral resolution of medical acoustic imaging. Viola *et al*. [7] presented a method for medical acoustic imaging to improve spatial resolution introducing an assumption that targets are modeled as points. Although the Viola's method is effective, it needs enormous computational cost, causing its application extremely difficult in clinical environment.

We have presented a high range resolution method based on frequency domain interferometry with an adaptive beamforming algorithm [8]. In this paper we present a high range resolution method suitable to medical acoustic imaging employing three techniques; frequency averaging, whitening, and pseudo-double RF data conversion. We explain the method, present experimental results utilizing a commercial US device, and offer conclusion.

II. Methods

The presented method is based on FDI with Capon method, an adaptive beamforming algorithm. For the improvement of range resolution in medical acoustic imaging we apply the method to each individual scan line of in-phase and quadrature (IQ) data. In this section we describe FDI briefly, and then explain three techniques employed to suit the method to medical acoustic imaging.

A. Data Processing Method Based on FDI

The phase of each frequency component of a received signal depends on the ranges of targets. FDI is a technique to estimate target range and its scattering cross-section using the phases and intensities of the frequency components. The estimated intensity based on FDI at a range in a scan line is

$$P = yy^* = \mathbf{W}^{\mathrm{T}*}\mathbf{R}\mathbf{W}, \quad (1)$$

$$y = \mathbf{X}^{\mathrm{T}}\mathbf{W}^*, \quad (2)$$

$$\mathbf{R} = \mathbf{X}\mathbf{X}^{\mathrm{T}*}, \quad (3)$$

$$\mathbf{X} = [X_1 \quad X_2 \quad \cdots \quad X_N]^{\mathrm{T}}, \tag{4}$$

$$\mathbf{W} = [W_1 \quad W_2 \quad \cdots \quad W_N]^{\mathrm{T}}, \tag{5}$$

where $\mathbf{X}$ is a set of frequency components of a received signal after a common delay and sum process, $\mathbf{W}$ is a weighting function, N is the number of frequency component samples used for imaging, $[]^*$, $[]^{\mathrm{T}}$, and $[]^{\mathrm{T}*}$ denote the complex conjugate, the transpose, and the conjugate transpose, respectively.

B. Pseudo-Double RF Data Conversion

Medical acoustic imagers utilize quadrature detectors to acquire IQ data. The detection is equivalent to the multiplication processes between a received signal and two sinusoidal waves, where the phase difference of the two sinusoidal waves is 90 degrees and their center frequency is equal to transmit center frequency. Fig. 1 shows the two echoes of IQ data returned from a boundary between 20% gelatin and 4% agar. Since the waveform of a received signal after quadrature detection depends on the phase difference between the received signal and sinusoidal waves, blind applications of FDI to a received signal of IQ data is unlikely to be successful.

We introduce the assumption that signals of IQ data are detected at the occasion when the amplitudes of the sinusoidal waves are maximums.

$$S_{\mathrm{I}}(n) \cong S(n\Delta T)\cos(\omega_{\mathrm{s}} n\Delta T) = (-1)^n S(n\Delta T), \tag{6}$$

$$\begin{aligned} S_{\mathrm{Q}}(n) &\cong S\{(n+1/2)\Delta T\}\sin\{\omega_{\mathrm{s}}(n+1/2)\Delta T\} \\ &= (-1)^n S\{(n+1/2)\Delta T\}, \end{aligned} \tag{7}$$

where $S_{\mathrm{I}}(n)$ and $S_{\mathrm{Q}}(n)$ are respectively the n-th signal of in-phase and quadrature data, $S(t)$ is a received signal with a common delay and sum process in the time domain before quadrature detection, ω_{s} is the angular velocity at the center frequency of a transmit wave, ΔT is the sampling interval of quadrature detection. In this study we propose pseudo-double RF data conversion for the reconstruction of received signals from signals of IQ data.

$$S_{\mathrm{P}}(2n-1) = (-1)^n S_{\mathrm{I}}(n), \tag{8}$$

$$S_{\mathrm{P}}(2n) = (-1)^n S_{\mathrm{Q}}(n), \tag{9}$$

$$\Delta T_{\mathrm{P}} = \Delta T / 2, \tag{10}$$

where $S_{\mathrm{P}}(n)$ is the n-th pseudo-double RF data, ΔT_{P} is the sampling interval of the pseudo-double RF data. Fig. 2 shows the waveforms of the echoes returned from the boundary in two scan lines after pseudo-double RF data conversion. The result shows that signals of IQ data are converted to those of RF data resemble to received signals.

C. Whitening Frequency Components

Since Capon method was designed for the cases using narrow-band signals it assumes that the frequency components of a signal returned from a target have the same intensity. For the application to medical acoustic imaging using broad-band signals we employ whitening technique. This technique corrects the intensity of all frequency

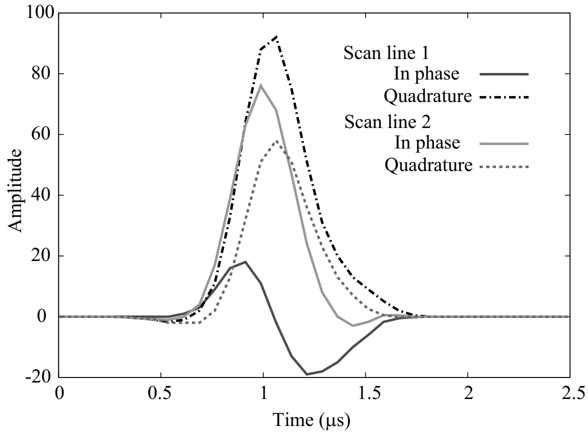

Fig. 1. IQ data of the echoes from a boundary between gelatin and agar in two scan lines.

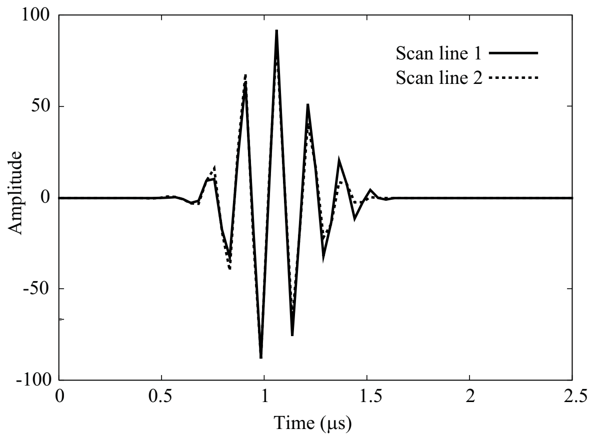

Fig. 2. Pseudo-double RF data converted from the two IQ data of the echoes from the boundary.

components uniformly using a reference signal returned from a single boundary.

$$X_{\mathrm{W}k} = X_{\mathrm{P}k} X_{\mathrm{R}k}^{*} / (|X_{\mathrm{R}k}|^2 + \eta) \tag{11}$$

where η is a constant term for stabilization, $X_{\mathrm{W}k}$, $X_{\mathrm{P}k}$ and $X_{\mathrm{R}k}$ are k-th frequency components of a signal of pseudo-double RF data after whitening, that before whitening, a reference signal of a pseudo-double RF data without whitening, respectively.

D. Capon Method with Frequency Averaging

FDI applications do not work when the signals received from different targets are correlated. In atmospheric radar signal processing temporal averaging are applied to the correlation matrix $\mathbf{R}$ to suppress the correlation between echoes from different targets [9]. Whereas common medical acoustic imaging techniques use broad-band signals with high center frequencies, resulting in their environment nonstationary and difficulty applying temporal averaging to $\mathbf{R}$. We thus employ frequency averaging technique to decorrelate signals from different targets.

$$\mathbf{R}_{\mathrm{A}} = \frac{1}{M}\sum_{m=1}^{M}\mathbf{R}_m, \tag{12}$$

$$R_{mij} = X_{W(i+m-1)} X_{W(j+m-1)}^{*} \quad (13)$$

where $\mathbf{R}_A$ is a correlation matrix of a received signal after frequency averaging, R_{mij} is the (i, j) element of a m-th sub-matrix $\mathbf{R}_m$ extracted from a correlation matrix of signals of pseudo-double RF data converted from a received signal of IQ data after whitening. This technique requires that the sampling frequency interval is constant.

The Capon method minimizes the contribution of signals from undesired ranges subject to a constant response at a desired range.

$$\min \quad \mathbf{W}'^{T*} \mathbf{R}_A \mathbf{W} \quad \text{subject to} \quad \mathbf{C}^{T*}\mathbf{W}' = 1, \quad (14)$$

$$\mathbf{W}' = [W_1 \quad W_2 \quad \cdots \quad W_{N-M+1}]^T, \quad (15)$$

$$\mathbf{C} = [\exp(jk_1 r) \quad \cdots \quad \exp\{jk_{(N-M+1)} r\}]^T, \quad (16)$$

where r is a desired range, k_n is n-th wave number of frequency components of a received signal. Using Lagrange multiplier methods the solution to (14), (15) and (16) is given by

$$P_{Cap}(r) = \frac{1}{\mathbf{C}^{T*}(\mathbf{R}_A + \eta'\mathbf{E})^{-1}\mathbf{C}}, \quad (17)$$

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

E. Experimental Setup

US was performed with a Hitachi EUB-8500 (Hitachi, Tokyo, Japan) US device with 7.5 MHz linear array probe, which has the function to export raw IQ data. For the investigation of the range resolution using the proposed method we prepared two 20% gelatin blocks, where each block has an agar membrane at 1 cm depth. We first prepared 4% agar membranes 0.4 and 0.3 mm thick, and then embedded them into the gelatin blocks after airing. The airing process compressed the thicknesses of the two membranes to about 0.27 and 0.2 mm, respectively. To examine the potential of the proposed method for clinical applications we further applied the method to a fresh swine femoral artery, as shown in Fig. 3. We utilized the echo from a boundary between 20% gelatin and 4% agar as a reference signal.

In this study we utilized frequency components from 5 to 9 MHz, where the frequency interval is 30 kHz. The sampling frequency of IQ data is 15 MHz, the number of sampled frequency components N = 134, and the number of sub-matrix M = 67.

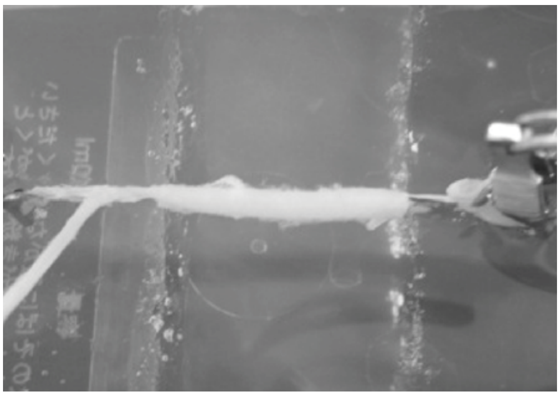

Fig. 3. Fresh swine femoral artery utilized in this study.

III. Results

Fig. 4 shows a B-mode image of a gelatin block with an agar membrane about 0.27 mm thick. For the conventional B-mode imaging it is difficult to detect the couple of boundaries between the agar membrane and gelatin. Fig. 5 shows the estimated intensities of the proposed method in a scan line of a frame and that using a conventional method. The estimated intensity of a conventional method is calculated from a scan line of IQ data. Whereas the conventional method shows only the indication that two boundaries might exist, the proposed method detects both the boundaries clearly.

Fig. 6 shows the estimated intensities of the proposed method and the conventional method, where an agar membrane about 0.2 mm thick was embedded at 1 cm depth. Here we integrated a scan line of IQ data coherently to improve signal-to-noise ratio (SNR) of the data. In this case the conventional method shows no indication that two

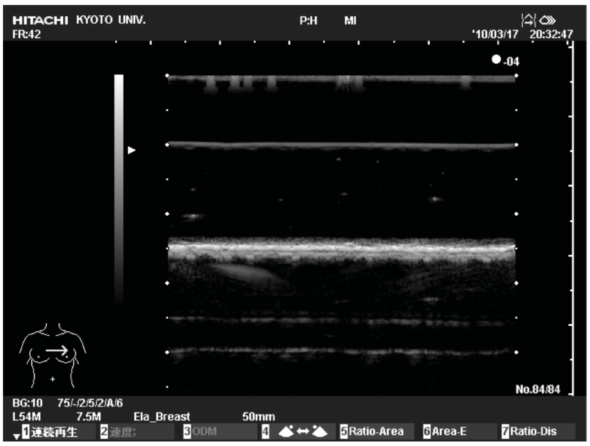

Fig. 4. B-mode image of a gelatin block with an agar membrane about 0.27 mm thick at 1 cm depth.

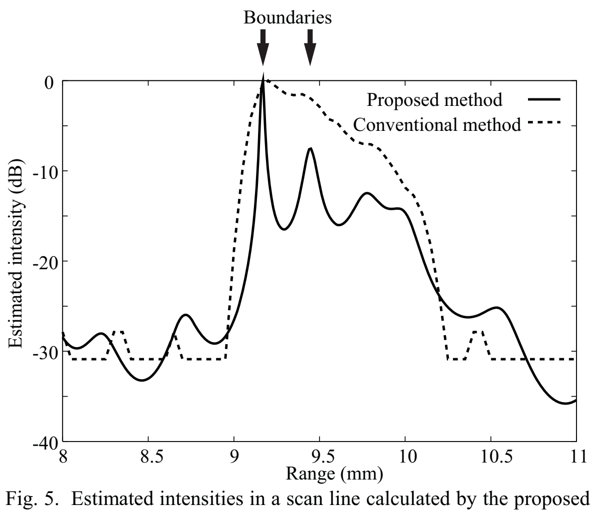

Fig. 5. Estimated intensities in a scan line calculated by the proposed method and a conventional method. An agar membrane about 0.27 mm thick was located at 1 cm depth. Arrows indicate the boundary ranges.

boundaries exist, as shown in Fig. 6. The proposed method failed to detect the two boundaries from a scan line of IQ data without coherent integration; however, after coherent integration both the boundaries are detected by the proposed method. In addition as the number of coherent integration increases, the range resolution of the proposed method improves.

The average intervals between two couples of boundaries calculated from the proposed method are 0.26 and 0.19 mm, respectively. The ratio of the estimated intervals is equal to that of the thicknesses of two agar membrane before airing. This implies the accuracy of the proposed method for the target range estimation.

Fig. 7 shows a B-mode image of a fresh swine femoral artery calculated from a frame of IQ data. The estimated intensity calculated from the same frame of IQ data using the proposed method is shown in Fig. 8. The image depicted by the proposed method has much higher range resolution than that of a B-mode image. This result indicates that the proposed method is robust and suited to medical acoustic imaging, having the potential for the clinical application to vascular imaging with high range resolution. Future work is to evaluate the efficiency of the proposed method for the estimation of vessel wall thickness.

IV. Conclusion

In this paper we propose a high range resolution imaging method suitable for medical acoustic imaging employing three techniques; frequency averaging, whitening, and pseudo-double RF data conversion. The proposed method detected two couples of boundaries 0.26 and 0.19 mm apart using a single frame and two frames of IQ data, respectively, where a conventional method failed to distinguish each couple of boundaries from a single boundary.

We further applied the proposed method to a fresh femoral artery, and verified the potential of the method for the clinical application to vascular imaging with high range resolution.

References

[1] E. Kudeki, and G.R. Stitt, "Frequency domain Interferometry: a high-resolution radar technique for studies at atmospheric turbulence," Geophysical Research Letters, vol. 14, pp.198-201, 1987

[2] H. Luce, M. Crochet, C. Hanuise, M. Yamamoto, and S. Fukao, "On the interpretationof the layered structures detected by MST radars in dual frequency domain Interferometry (FDI) mode," Radio Science, vol. 34, pp. 1077-1083, 1999.

[3] H. Luce, M. Yamamoto, S. Fukao, D. Helal, and M. Crochet, "A frequency domain radar interferometric imaging (FII) technique based on high-resolution methods," Journal of Atmospheric and Solar-Terrestrial Physics, vol. 63, pp. 21-234, 2001.

[4] J. Capon, "High resolution frequency-wavenumber spectrum analysis," *Proc. IEEE*, vol. 57, no. 8, pp. 1408-1418, 1969.

[5] T.-J. Shan and T. Kailath, "Adaptive beamforming for coherent signals and interference," *IEEE Trans. Acoust., Speech, Signal process.*, vol. ASSP-33, no. 3, pp. 527-536, 1985.

[6] J. A. Mann and W. F. Walker, "A constrained adaptive beamformer for medical ultrasound: initial results," *Proc. IEEE Ultrason. Symp.*, pp. 1807-1810, 2002.

[7] F. Viola, M. A. Ellis, and W. F. Walker, "Time-domain optimized near-field estimator ultrasound imaging: initial development and results," *IEEE Trans. Med. Imag.*, vol. 27, No. 1, pp. 99-110, 2008.

[8] H. Taki, T. Kimura, T. Sakamoto, and T. Sato, "High resolution medical acoustic vascular imaging using frequency domain interferometry," *Proc. IASTED Visualization, Imaging, and Image Processing*, 652, 2009.

[9] K. Takao and N. Kikuma, "An adaptive array utilizing an adaptive spatial averaging technique for multipath environments," *IEEE Trans. Antennas Propagat.*, AP-35, pp. 1389-1396, 1987.

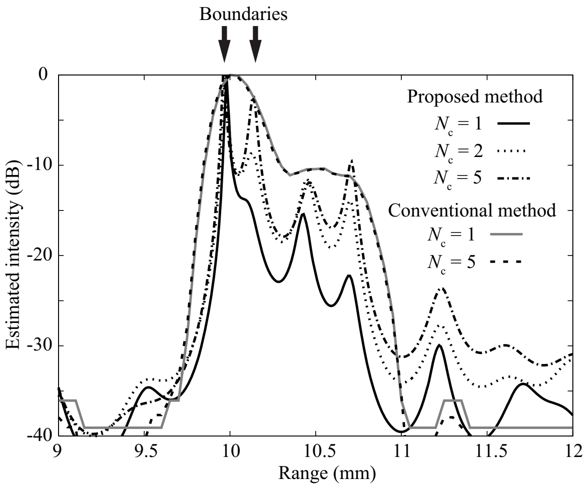

Fig. 6. Estimated intensities in a scan line calculated by the proposed method and a conventional method. An agar membrane about 0.2 mm thick was located at 1 cm depth. N_c denotes the number of coherent integration for the improvement of signal to noise ratio of IQ data. Arrows indicate the boundary ranges.

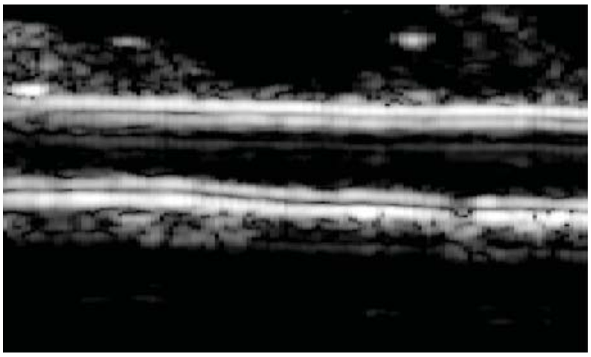

Fig. 7. Conventional B-mode image of a longitudinal section of a fresh swine femoral artery, where the size of region of interest is 1 x 1.67 cm.

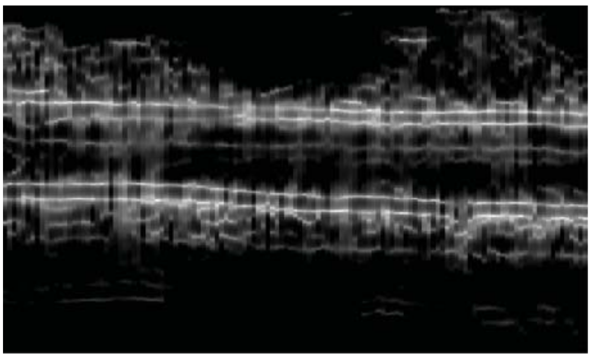

Fig. 8. Estimated intensity of a longitudinal section of a fresh swine femoral artery using the proposed method, where the size of region of interest is 1 x 1.67 cm.