Adaptive Beam Steering for Improved Imaging of Carotid Sinus

Hideyuki Hasegawa, Takashi Mashiyama and Hiroshi Kanai
Graduate School of Engineering, Tohoku University
Sendai 980-8579, Japan
E-mail: hasegawa@us.ecei.tohoku.ac.jp

Abstract—Recently, cardiovascular disease has become the second most common cause of death in Japan following malignant neoplasm formation. Therefore, it is necessary to diagnose atherosclerosis during its early stages because atherosclerosis is one of the main causes of cardiovascular diseases. The carotid sinus is a site that is easily affected by atherosclerosis [C. K. Zarins et al.: Circ. Res. 53 (1983) 502]; therefore, the diagnosis of this disease at this site is important [S. C. Nicholls et al.: Stroke 20 (1989) 175]. However, it is difficult to accurately diagnose atherosclerosis in the carotid sinus in the long-axis plane, which is parallel to the axis of the vessel, using conventional linear scanning because the carotid sinus is not flat along the axis of the vessel, and the ultrasonic beams used in linear scanning are perpendicular to the arterial wall in a limited region. Echoes from regions that are not perpendicular to the ultrasonic beams are very weak and the arterial wall in such regions is hardly recognized in a B-mode image. In this study, the position of the arterial wall was predetermined on the basis of the B-mode image obtained by conventional linear scanning, then ultrasonic beams were transmitted again so that all beams were almost perpendicular to the arterial wall. In basic experiments, a nonflat object made of silicone rubber was measured and it was shown that it is possible to image a nonflat object over the entire scanned area using the proposed beam steering method. Furthermore, in vivo experiments, the intima-media complex was imaged over the entire scanned area at the carotid sinus.

I. INTRODUCTION

Cardiovascular disease is now the second most common form of death in Japan following malignant neoplasm formation. The diagnosis of early-stage atherosclerosis has become increasingly important because atherosclerosis is one of the main causes of cardiovascular disease. The double line pattern of the arterial wall, which is shown in an ultrasound B-mode image, represents echoes from the lumen-intima and media-adventitia boundaries [1]. The area between these two lines corresponds to the intima-media complex. The intima-media thickness (IMT) is a useful marker for the diagnosis of atherosclerosis [1], [2]. Cross-sectional images of arteries are commonly obtained in the long-axis and short-axis planes, which are parallel and perpendicular to the axis of the artery, respectively. However, the intima-media complex is imaged in a limited region in the short-axis plane because ultrasonic beams are perpendicular to the wall in the limited region. Therefore, an alternative beam steering method was developed so that the ultrasonic beams were always perpendicular to the arterial wall in the short-axis plane by assuming that the cross section of the artery lumen is a circle [3]. Using this method, the IMT of the artery could be measured accurately in the short-axis plane, and this method was combined with the phased tracking method proposed by our group for measuring the regional strain and elasticity of the arterial wall [4], [5].

The carotid sinus is a site that is easily affected by atherosclerosis; therefore, the diagnosis of this disease at this site is important [6]. However, it is difficult to diagnose atherosclerosis in this site in the long-axis plane accurately using conventional linear scanning because the carotid sinus is not flat along the axis of the vessel, and the ultrasonic beams used in linear scanning are perpendicular to the arterial wall in a limited region. Echoes from regions that are not perpendicular to the ultrasonic beams are very weak and the arterial wall in such regions is hardly recognized in a B-mode image. To improve the quality of B-mode images, multiangle compound imaging [7] was developed. In this technique, images are recorded from multiple angles (typically 3 to 9), and these single-angle images are then combined to form the compound image. In most investigations on this technique so far, the individual single-angle images have been simply averaged to form the compound image.

In the method proposed in this study, the position of the arterial wall is predetermined on the basis of the B-mode image obtained by conventional linear scanning, then ultrasonic beams are transmitted again so that all beams are almost perpendicular to the arterial wall.

II. METHODS

Figure 1 shows a schematic diagram of the beam steering. The ultrasonic beam scans $M$ positions along the $x$-axis by conventional linear scanning. The depth of the arterial wall, $y_i$ ($i = 1, 2, ..., M$), at each beam position, $x_i$ ($i = 1, 2, ..., M$), is manually predetermined in the B-mode image obtained by conventional linear scanning. The interval between the neighboring ultrasonic beams is defined by $\Delta x = x_{i+1} - x_i$. With respect to each position, $(x_i, y_i)$, of the $i$-th ultrasonic beam on the wall, a regional slope, $a_{w,i}$, of the arterial wall to the surface of the ultrasonic probe is estimated by the least-squares method using positions, $\{(x_i, y_i)\}$, of neighboring $\pm N$
ultrasonic beams on the arterial wall as follows:

\[
\begin{align*}
a_{w,i} &= \frac{1}{2(N+1)} \left[ N \sum_{i=-N}^{N} x_i y_i - \left( \sum_{i=-N}^{N} x_i \right) \left( \sum_{i=-N}^{N} y_i \right) \right], \\
&= \frac{1}{2(N+1)} \left[ N \sum_{i=-N}^{N} x_i^2 - \left( \sum_{i=-N}^{N} x_i \right)^2 \right].
\end{align*}
\]

From the estimated \( a_{w,i} \), the slope, \( a_i \), and the angle, \( \theta_i \), of the beam that is perpendicular to the arterial wall at \((x_i, y_i)\) are determined as follows:

\[
a_i = \frac{1}{a_{w,i}},
\]

\[
\theta_i = \tan^{-1} a_i \quad \text{[rad].}
\]

![Fig. 1. Determination of optimum beam position and angle (N = 1).](image)

From the determined \( \theta_i \) and the \((x_i, y_i)\) of the arterial wall, the center, \( b_i \), of the aperture that transmits an ultrasonic beam to \((x_i, y_i)\) is determined as follows:

\[
b_i = x_i - \frac{y_i}{\tan \theta_i} = x_i - \frac{y_i}{a_i} \quad \text{[mm].}
\]

By determining \( \theta_i \) and \( b_i \) for all positions, \( \{(x_i, y_i)\} \), on the wall, all beams are designed to be perpendicular to the arterial wall.

In this study, \( \theta_i \) is assigned discrete values. Therefore, the discrete beam angle, \( \theta'_i \), that is nearest to \( \theta_i \) is selected from preassigned angles of \( K \) beams [Fig. 2(a)]. The \( b_i \) of the aperture is calculated again using \( \theta'_i \). The \( b_i \) of the aperture should be also assigned a discrete value that depends on the element pitch of the ultrasonic probe. As shown in Fig. 2(b), the discrete transmit position, \( b'_i \), of the aperture, which is nearest to \( b_i \), is selected, as well as \( \theta'_i \). In this way, the ultrasonic beam is transmitted to the position, \((x'_i, y'_i)\), on the wall as perpendicular as possible. Although the designed ultrasonic beam does not exactly pass through the \((x_i, y_i)\) because of the discrete values of \( b'_i \) and \( \theta'_i \), the difference, \(|x'_i - x_i|\), is less than half the element pitch.

![Fig. 2. (a) Determination of \( \theta'_i \) (dashed line: calculated beam with \( \theta_i \)). (b) Determination of \( b'_i \).](image)

### III. BASIC EXPERIMENTS

Figure 3 shows (a) the size and (b) cross section of a phantom made of silicone rubber. The shape of the phantom simulates the arterial wall at the carotid sinus and the phantom has a hollow. The width of the hollow is 15 mm, and the depth is 2.5 mm. The phantom was fixed in a water bath and it was measured using diagnostic equipment (Aloka SSD-6500) with a conventional linear-type ultrasonic probe at 10 MHz. The distance from the surface of the ultrasonic probe to the surface of the phantom was 13 mm. The focal distance was set to be 18 mm from the surface of the ultrasonic probe because the ultrasonic beam became wider and the measurement became more robust by setting the focal depth closer than the surface of the phantom [8]. The 105 ultrasonic beams with intervals, \( \Delta x \), of 0.2 mm are transmitted in a frame, and the beam angle was changed by 2° frame by frame from \( \theta'_1 = 70° \) to \( \theta'_{21} = 110° \). Therefore, the elapsed time for acquiring the RF data of 21 frames was 165 ms in the case of a frame rate of 127 Hz in this experiment. Ultrasonic RF echoes were acquired at a sampling frequency of 40 MHz.

![Fig. 3. (a) Size of phantom. (b) Cross-sectional picture.](image)
Figure 5(a) shows a B-mode image of the object obtained by conventional linear scanning using 105 ultrasonic beams \( (\theta_{11}' = 90^\circ) \). The surface of the phantom was manually assigned at 105 positions \( \{(x_i, y_i)\} \) \( (i = 1, 2, ..., 105) \) on the B-mode image [white dotted line in Fig. 5(a)]. On the basis of the principle in Sec. II, the beam, with angle \( \theta_i \) and transmit position \( b_i \), that is perpendicular to the surface of the phantom was determined using \( \{(x_i, y_i)\} \). The white lines in Fig. 5(b) show the calculated optimum beams. Then, the beam with \( \theta_i' \) and \( b_i' \) was selected as shown in Fig. 2. Figure 5(c) shows a B-mode image constructed from the ultrasonic RF echoes obtained using the calculated beams with \( \{(\theta_i', b_i')\} \).

As shown in the areas surrounded by circles in Fig. 5(a), the surface of the phantom could not be imaged clearly in the areas where the ultrasonic beams incline from a vertical direction by more than \( 20^\circ \) as shown in the B-mode image obtained by conventional linear scanning. On the other hand, strong reflected echoes were obtained in such areas using the proposed method, and the phantom was imaged over the entire scanned area as shown in Fig. 5(c).

IV. In vivo Measurement

A human common carotid sinus of a 25-year-old male was measured in the long-axis plane. To reduce the elapsed time for acquiring RF data, ultrasonic beams were transmitted every \( 5^\circ \) from \( \theta_5' = 70^\circ \) to \( \theta_9' = 110^\circ \) and discrete steered angles, \( \{\theta_k'\} \), were changed frame by frame. Ultrasonic RF data were acquired during 9 frames (82 ms at a frame rate of 110 Hz) just before the time of the R-wave of the electrocardiogram. Figure 6(a) shows a B-mode image obtained by conventional linear scanning, composed of 105 ultrasonic beams with intervals, \( \Delta x \), of 0.2 mm \( (\theta_5' = 90^\circ) \). The white dotted line in Fig. 6(b) shows the assigned \( (x_i, y_i) \) of the posterior wall, and the white lines in Fig. 7(a) show the calculated optimum beams. Figure 7(b) shows a B-mode image constructed from the ultrasonic RF echoes obtained using the calculated beams with \( \{(\theta_i', b_i')\} \).

As shown by the area surrounded by a circle in Fig. 6(a), the intima-media complex could not be imaged clearly by conventional linear scanning in the area where the ultrasonic beams incline from the perpendicular direction relative to the wall by more than \( 2.5^\circ \). However, sufficient reflected echoes were obtained in such an area using the proposed method, and the intima-media complex was almost imaged over the entire scanned area as shown in Fig. 7(b).
Fig. 6. (a) B-mode image obtained by conventional linear scanning. (b) Assigned posterior wall surface (white dashed line) superimposed on B-mode image of (a).

Fig. 7. (a) Calculated beams (white lines) superimposed on B-mode image of Fig. 6(a). (b) B-mode image obtained by the proposed method.

V. CONCLUSION

In this paper, a method of beam steering that makes ultrasonic beams perpendicular to the arterial wall at the carotid sinus in the long-axis plane was proposed. In basic experiments using a phantom made of silicone rubber, it was shown that it is possible to image a nonflat object over the entire scanned area using the proposed beam steering method. In in vivo experiments at a carotid sinus, it was shown that it is possible to image the intima-media complex over the entire scanned area using the proposed beam steering method.

REFERENCES


