Imaging of Cross-Sectional Elasticity in Short-Axis Plane of Arterial Wall by Transcutaneous Ultrasound

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Abstract—We have developed the phased tracking method [1] for measuring the minute change in thickness during one heartbeat and the elasticity of the arterial wall with transcutaneous ultrasound. When this method is applied to a plane perpendicular to the axis of the artery (short-axis plane) using a linear-type probe, only an ultrasonic beam which passes through the center of the artery coincides with the direction of the change in thickness. At other beam positions, the wall motion cannot be accurately tracked because the direction of wall expansion slips off the beam.

To obtain the cross-sectional image of elasticity in the short-axis plane using transcutaneous ultrasound, in this paper, the directions of ultrasonic beams are designed so that each beam always passes through the center of the artery; thus they always coincide with the direction of the wall expansion. In basic experiments, the accuracy in elasticity measurement was evaluated using a silicone rubber tube. In in vitro experiments using an extracted human femoral artery, the measured elasticity image were compared with the pathological image. In in vivo experiments, the minute change in wall thickness was measured along each ultrasonic beam, and the cross-sectional image of elasticity was obtained in the short-axis plane with transcutaneous ultrasound.

I. INTRODUCTION

Recently, increase in the number of patients suffering from myocardial infarction or cerebral infarction has become a serious social problem. Therefore, it is important to diagnose atherosclerosis in an early stage because such circulatory diseases are mainly caused by atherosclerosis. Because elasticity of the arterial wall changes as atherosclerosis develops [2], the evaluation of the regional elasticity of the arterial wall using ultrasound is useful for diagnosis of atherosclerosis.

Ultrasound B-mode imaging is widely used for the repetitive diagnosis of atherosclerosis because it is noninvasive and patients have few difficulties. Using the ultrasound B-mode image, the shape and the size of atherosclerotic plaque on the arterial wall can be observed in real time, but it is difficult to evaluate the stability of the plaque quantitatively. To evaluate the vulnerability of atherosclerotic plaque, we have developed a method, the phased tracking method, for measuring the minute change in wall thickness during one heartbeat and the regional elasticity of the arterial wall with transcutaneous ultrasound [1], [3], [4].

In this method, when the ultrasonic beam is not coincident with the direction of the change in thickness, the wall motion cannot be accurately tracked because the direction of wall expansion slips off the beam. Therefore, this method is efficient if applied to a plane parallel to the axis of the artery (long-axis plane) using a linear-type probe because the region where the ultrasonic beam is perpendicular to the arterial wall is wider than that perpendicular to the axial direction of the artery (short-axis plane). However, it is difficult to diagnose the entire portion of the plaque with only the measurement in the long-axis plane. Therefore, it is necessary to measure the elasticity of the plaque in the short-axis plane in addition to the measurement in the long-axis plane.

A method for measuring the cross-sectional image of elasticity of the arterial wall in short-axis plane using Intravascular Ultrasound (IVUS) has been reported. De Korte et al. measured the strain of the arterial wall caused by the change in inner pressure and calculated the elasticity during cardiac diastole when the motion of the IVUS probe caused by the pulsatile flow is negligible [5]. However, the elasticity can be estimated only during the cardiac diastole with this method. Mita et al. developed a method for measuring the strain during an entire heart cycle by compensating the change in the position of the IVUS probe caused by pulsatile flow [6]. Although these methods are useful for evaluating the vulnerability of the plaque, they are not suitable for repetitive diagnosis due to invasion during catheterization.

When the artery is measured transcutaneously in the short-axis plane by conventional linear scanning, only an ultrasonic beam which passes through the center of the artery coincides with the direction of wall motion (change in wall thickness). At other beam positions, wall motion cannot be accurately tracked because the direction of wall expansion slips off the beam. For assessment of the cross-sectional elasticity image in the short-axis plane, we designed the directions of the ultrasonic beams so that each beam always passes through the center of the artery and the direction of each beam is always perpendicular to the arterial wall. Under such a setting, the elasticity image of the posterior wall of carotid artery was measured with transcutaneous ultrasound in the short-axis plane [7].

In this paper, for measurement of both of the anterior and posterior walls, the focal position of electric focusing are set at the anterior wall to increase the sound pressure at the anterior wall. In basic experiments, the accuracy in elasticity measurement of both walls was evaluated using a
silicone rubber tube. Then, in in vitro experiments using an extracted human femoral artery, the measured elasticity images were compared with the pathological images. Finally, in in vivo experiments, the minute change in wall thickness was measured along each ultrasonic beam and the cross-sectional images of elasticity for both of the anterior and posterior walls were obtained in the short-axis plane with transcutaneous ultrasound.

II. PRINCIPLE

Figure 1 shows the schematic diagram of beam scanning. In this study, the ultrasonic beams are transmitted in the \((N+1)\) directions and designed so that each beam passes through the center, \(O\), of the artery \([7]\). Under such a setting, the ultrasonic beams are always perpendicular to the arterial wall if the cross-section of the artery can be assumed to be a circle. The beam scanning is designed as follows: The distance, \(d_k\), from the center, \(c_k\), of the transmit aperture of \(k\)-th beam \((k = -N/2, \cdots, 0, \cdots, N/2)\) to the center of the probe is expressed as

\[
d_k = 0.4 \cdot k \quad \text{[mm]},
\]

The beam angle, \(\theta_k\), of \(k\)-th beam is expressed as follows:

\[
\theta_k = \arctan \frac{d_k}{L_i} \quad \text{[rad]},
\]

where \(L_i\) is the distance from the surface of the probe to the point \(O\). In this paper, \(L_i\) is variable from 8.5 mm to 21.5 mm with a pitch of 1 mm \((i = 1, 2, \cdots, 14)\). The focal distance, \(f_k\) of electric focusing of the \(k\)-th beam is defined by

\[
f_k = \frac{L_i}{\cos \theta_k} - 3 \quad \text{[mm]}.\]

In eq. (3), the focal distance of electric focusing is set to be nearer than the point \(O\) by 3 mm along \(k\)-th beam so that the sound pressure at the anterior wall becomes similar to that at the posterior wall. The focal position by the acoustic lens are set at a depth of 20 mm (roughly corresponds to the posterior wall of the carotid artery), therefore, the focal position by electric focusing should be set at the anterior wall to equalize sound pressures at the anterior and posterior walls. Figure 2 shows the sound pressure distributions along a ultrasonic beam measured with a hydrophone in a water tank for three different settings (b), (c), and (f) of the electric focal position. In Fig. 2(2), it was found that the sound pressures at the anterior and posterior walls become similar in the setting shown by eq. (3).

By changing the distance, \(L_i\), each ultrasonic beam can be perpendicular to the arterial wall even in the case of a subject with a different distance from the skin surface to the artery.

III. BASIC EXPERIMENTS

The change in wall thickness of a silicone rubber tube (static elastic modulus: 5.7 MPa, sound speed: 992 m/s, inner diameter: 10 mm, outer diameter: 13 mm) caused by pulsatile flow generated by an artificial heart is measured in the short-axis plane with a linear-type probe (center frequency: 10 MHz).

Figures 3(a) and 3(b) show the B-mode images in the short-axis plane obtained by conventional linear scanning and the proposed method \((L_i = 11.5 \text{ mm}, \text{ the largest beam angle } \theta_{\text{max}} = 24.3^\circ)\), respectively. In comparison with conventional linear scanning, echoes from the interfaces of the tube wall can be clearly recognized by the proposed method.

Figures 4(1-a) and 4(2-a) show the mean values and the standard deviations of the maximum changes in thickness for 5 beats measured with respect to the anterior and posterior walls in the region of \(\pm 19.5\) degree (number of beams: 28). The mean values and the standard deviations of the elasticity, which were calculated by the maximum changes in thickness and the maximum change in inner pressure measured by the pressure sensor (NEC 9E02-P16), were shown in Figs. 4(1-b) and 4(2-b) for the anterior and posterior walls, respectively.
In Figs. 4(1-a) and 4(2-a), changes in thickness were measured with sufficient reproducibility at all beam positions (The (standard deviation)/(mean value) ranged from 2.4 to 7.3% for the anterior wall and from 2.2 to 8.4% for the posterior wall.).

In Figs. 4(1-b) and 4(2-b), the mean values of the elastic modulus measured at each beam agreed well with 5.8 MPa which was measured by the different static experiment (The (standard deviation)/(mean value) ranged from 2.1 to 7.2% for the anterior wall and from 2.7 to 6.6% for the posterior wall.).

The mean values of the elastic moduli measured at all beams for 5 beats were 5.7 MPa for the anterior wall and 5.4 MPa for the posterior wall. From these results, it was found that the elastic moduli both of the anterior and posterior walls can be accurately measured in the short-axis plane by the proposed method.

IV. In vitro EXPERIMENTS

Using the experimental setup which is same as the basic experiments, the elasticity image of an extracted human femoral artery was measured in the short-axis plane with a linear-type probe (center frequency: 10 MHz).

Figure 5(a) shows the elasticity image measured by the proposed method. After ultrasonic measurement, the pathological image of the measured section was made as shown in Figs. 5(b) and 5(c) for the posterior and anterior walls, respectively, and was compared with the measured elasticity image shown in Fig. 5(a). As shown in Fig. 5, the collagen-rich regions (regions 1, 3, and 5 in Figs. 5(b) and 5(c)) were harder than the smooth-muscle-rich regions (regions 2 and 4). The means and the standard deviations of regions 1 (collagen-rich region) and 4 (smooth-muscle-rich region) were 2.7±1.7 MPa and 0.47±0.1 MPa, respectively. By analyzing the pathological images shown in Figs. 5(b-1) and 5(c-4), ratios of the area, which was classified as collagen, were determined to be 29% and 15%, respectively. From these results, it was found that...
the largest beam angle, $\theta_1$ of elastic modulus was 80 $\mu$ at the upper arm. The resolution of the cross-sectional image was maximum change in thickness and the pulse pressure measured in Fig. 6(a), echoes from the lumen-intima interface were clearly recognized for both of the anterior and posterior walls. From these results, the elasticity image successfully showed that the collagen-rich region was harder than the smooth-muscle-rich region. The similar tendency was reported that the elastic modulus of the fibrous artery wall (0.91±0.23 MPa) is larger than that of the smooth-muscle-rich artery wall (0.51±0.22 MPa) [2].

V. In vivo EXPERIMENTS

The change in the thickness of a human common carotid artery of a 29-year-old male was measured in the short-axis plane. The B-mode images measured by conventional linear scanning and the proposed method with the 10 MHz linear-type probe are shown in Figs. 6(a) and 6(b). The B-mode image was drawn at the time of the R-wave of the electrocardiogram. In this experiment, $L_i = 14.5$ mm and the largest beam angle, $\theta_{\text{max}}$, was 21.1°. As shown in Fig. 6(b), in comparison with conventional linear scanning shown in Fig. 6(a), echoes from the lumen-intima interface were clearly recognized for both of the anterior and posterior walls at all ultrasonic beams by controlling each beam so as to be perpendicular to the wall.

Figure 6(c) shows the cross-sectional image of elastic modulus for both of the anterior and posterior walls obtained by the maximum change in thickness and the pulse pressure measured at the upper arm. The resolution of the cross-sectional image of elastic modulus was 80 $\mu$m in the depth direction and 1.43°±0.5° in the circumferential direction. The mean value and the standard deviation of the measured elastic modulus were 0.35 MPa and 0.25 MPa, respectively. From these results, using the proposed method, the elasticity distribution of the arterial wall could be measured transcutaneously in the short-axis plane.

VI. CONCLUSION

The ultrasonic beams were designed so that each beam is always perpendicular to the arterial wall in the short-axis plane. In basic experiments using a silicone rubber tube, changes in wall thickness were accurately measured along all scan lines for both of the anterior and posterior walls by the proposed method, and the measured elastic modulus agreed well with that measured by the different static experiment. In in vivo experiments, the elasticity image of an extracted human femoral artery was measured in the short-axis plane. By comparing the elasticity image with the pathological image, it was found that the elasticity image successfully showed that the collagen-rich region was harder than the smooth-muscle-rich region. In in vivo experiments, using the proposed method, echo from the lumen-intima interface was clearly recognized for both of the anterior and posterior walls. From the minute change in thickness of the wall measured at each beam position, the cross-sectional image of elasticity was obtained in the short-axis plane by the proposed method.

REFERENCES