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Modified Phased Tracking Method for Measurement of Change in Thickness of Arterial Wall

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In this study, the change in thickness of the arterial wall caused by the heartbeat was measured by the *phased tracking method* [IEEE Trans. UFFC. **43** (1996) 791] for noninvasive assessment of the regional elasticity of the arterial wall. In the *phased tracking method*, the change in thickness of the arterial wall is obtained from the difference between displacements of two points set along an ultrasonic beam. The displacement during the pulse repetition interval is determined by the phase of the complex correlation between the quadrature modulated ultrasonic waves. For suppressing noise components, the complex correlation function is spatially averaged in the region, which corresponds to the ultrasonic wavelength. However, spatial averaging of displacements is not desirable for measurement of the change in thickness, because the change in thickness is caused by the spatial inhomogeneity of displacements. In this paper, the *phased tracking method* was modified for direct estimation of the change in thickness without spatial averaging of displacements. [DOI: 10.1143/JJAP.41.3563]

KEYWORDS: phase shift, least-squares method, change in thickness of arterial wall, strain, elasticity, atherosclerosis

1. Introduction

The steady increase in the number of patients with myocardial infarction or cerebral infarction, both of which are considered to be mainly caused by atherosclerosis, is becoming a serious problem. Therefore, it is important to diagnose atherosclerosis in the early stage. Computed tomography (CT) and magnetic resonance imaging (MRI) are employed for the diagnosis of atherosclerosis. Although they subject patients to great physical and mental hardship, they provide information only on the shape of the artery such as the diameter of the lumen. The diameter of the lumen, however, is not changed by early-stage atherosclerosis.[1]

Since there are significant differences between the elastic moduli of the normal arterial wall and that affected by atherosclerosis,[2,3] evaluation of the elasticity of the arterial wall is useful for diagnosis of early-stage atherosclerosis.[4] In addition to diagnosis of early-stage atherosclerosis, it is also important to diagnose vulnerability of the atherosclerotic plaque, because rupture of the plaque causes acute myocardial infarction and cerebral infarction.[5–7] Evaluation of the mechanical properties such as elasticity of the atherosclerotic plaque is useful for these purposes.

To measure the elasticity of the arterial wall, the pulse wave velocity (PWV) method has been developed as a technique for the noninvasive diagnosis of atherosclerosis.[8] In this method, the elasticity of the arterial wall is evaluated by measuring the velocity of the pressure wave propagating from the heart to the femoral artery. Though it is useful in terms of the noninvasive evaluation of elasticity, the regional elasticity cannot be evaluated due to a low spatial resolution of several tenths of a centimeter, which almost corresponds to the distance from the heart to the femoral artery.

To increase the spatial resolution in measurement of PWV, we have previously proposed a method to accurately measure the propagation velocity of vibrations on the arterial wall using ultrasound.[9–11] Using this method, the PWV between two adjacent points, which are separated from each other by several centimeters, is noninvasively measured by estimating the time delay between the resultant vibrations at these two points set along the axial direction of the artery.

Methods for measurement of the change in artery diameter have been proposed[12–16] in order to obtain the circumferential distensibility of the arterial wall in the plane which is perpendicular to the axial direction of the artery. By assuming the artery to be a cylindrical shell, the average elasticity of the entire circumference in the plane has been evaluated.[17–19] However, the regional elasticity of the atherosclerotic plaque cannot be obtained by these methods, because an artery with atherosclerotic plaque cannot be assumed to be a cylindrical shell with uniform wall thickness.

In this study, we attempted to evaluate the elasticity of a more local region, even in the case of atherosclerotic plaque. Such a technique for measurement of the spatial distribution of the regional elasticity would be useful for diagnosis of the vulnerability of atherosclerotic plaque as well as for the diagnosis of early-stage atherosclerosis. For this purpose, the small change in the thickness of the arterial wall due to the heartbeat is accurately measured in each local region which corresponds to the focal area of the ultrasonic beam.[10,20,21] From the resultant change in thickness, the regional strain and the elasticity of the arterial wall are noninvasively evaluated.[22]

In the field of ultrasonic tissue characterization (such as evaluation of the elasticity of the arterial wall and detection of tumors), various methods have been proposed to measure the tissue displacement from the peak of the autocorrelation function between echoes[15,23–27] or the phase of the complex autocorrelation function[12,13,16,28] for measurement of the tissue strain. However, measurement of the small change in thickness ($< 100\,\mu$m) during one heartbeat of the dynamically moving arterial wall has not been reported. In the *phased tracking method*,[9] the instantaneous position of the arterial wall is tracked by the velocity estimated from the phase shift between two consecutively received echoes. The change in thickness of the dynamically moving arterial wall can be obtained from displacements, which are obtained by the integration of velocities, of the intimal side and the adventitial side of the arterial wall. In basic experiments, the accuracy in the

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estimation of the change in thickness is less than 1 μm using the *phased tracking method*.[10,29,30)]

In these methods (including the *phased tracking method*) for measurement of tissue displacement, the spatial averaged displacement is estimated in order to obtain the strain of the tissue. However, in case of measurement of the strain (change in thickness) of the tissue, spatial averaging of the displacements is not desirable because the change in thickness is caused by the spatial inhomogeneity of displacements. In this paper, we propose a method for direct estimation of the change in thickness (strain) of the arterial wall rather than estimation based on the difference of spatially averaged displacements.

2. Principle

2.1 *Measurement of the small change in thickness of the arterial wall by the phased tracking method*

As illustrated in Fig. 1, for measurement of the small change in thickness, the phase shift of the echo, which is caused by the displacement of the object, is estimated from two consecutive echoes.[9)] For this purpose, quadrature demodulation is applied to the received ultrasonic waves reflected by the object, and then the in-phase and the quadrature signals are A/D converted. From the demodulated signal, $z(t; d + x(t))$, reflected at a depth $d + x(t)$ at a time t, where d and $x(t)$ are the initial depth set at $t = 0$ and the displacement of the object in the depth direction, the phase shift, $\Delta\theta(t)$, between two consecutive echoes is obtained from the complex cross correlation function calculated for $M + 1$ samples in the depth direction as follows:

$$e^{j\Delta\widehat{\theta}(t)} = \frac{\displaystyle\sum_{m=-M/2}^{M/2} z(t+T; d+x(t)+mD)\cdot z^*(t; d+x(t)+mD)}{\left|\displaystyle\sum_{m=-M/2}^{M/2} z(t+T; d+x(t)+mD)\cdot z^*(t; d+x(t)+mD)\right|}, \tag{1}$$

where D and T are the interval of sample points in the depth direction and the pulse repetition interval, respectively, and $*$ represents the complex conjugate. In measurement of the change in thickness, $M + 1$ in eq. (1) is set at 5 ($= 0.4\,\mu$s) in consideration of the pulse length of 0.46 μs. In estimation of the phase shift by eq. (1), the object position is tracked by the integration of the average velocity, $v(t + T/2)$, during the pulse repetition interval, T, as follows:

$$\begin{aligned}\widehat{x}(t+T) &= \widehat{x}(t) + \widehat{v}\left(t+\frac{T}{2}\right)\times T\\ &= \widehat{x}(t) + \frac{c_0}{2\omega_0}\Delta\widehat{\theta}(t),\end{aligned} \tag{2}$$

where ω_0 and c_0 are the center angular frequency of the ultrasonic pulse and the speed of sound, respectively.

From displacements $x_1(t)$ and $x_2(t)$ of two points, which are set in the arterial wall along the ultrasonic beam, the small change in thickness, $\Delta h(t)$, of the arterial wall is obtained as follows:

$$\begin{aligned}\Delta\widehat{h}(t) &= \widehat{x}_1(t) - \widehat{x}_2(t)\\ &= \int_0^t \{\widehat{v}_1(t) - \widehat{v}_2(t)\}\mathrm{d}t.\end{aligned} \tag{3}$$

2.2 *Modified phased tracking method for direct measurement of small change in thickness of the arterial wall*

In the *phased tracking method*, the change in thickness is obtained by subtraction of the two spatially averaged displacements. In this section, the *phased tracking method* is modified to directly estimate the change in thickness.

As illustrated in Fig. 2, the complex signal, $\beta(t; d, d_{12})$,

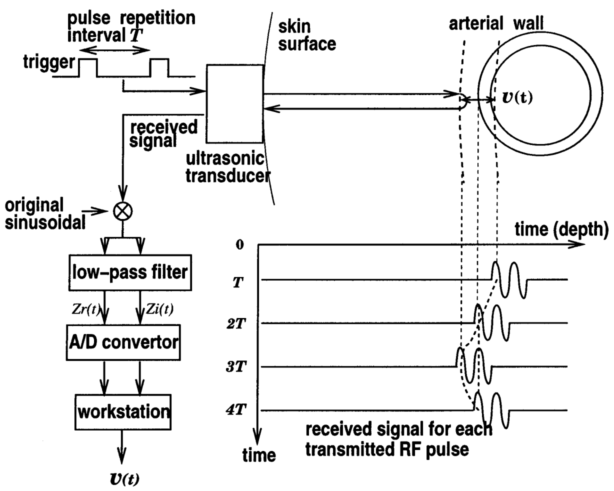

Fig. 1. Schematic diagram of the *phased tracking method*.

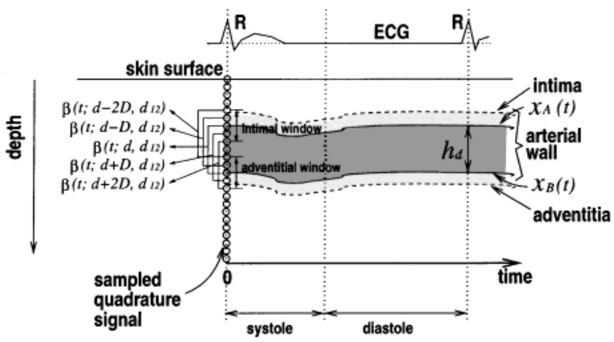

Fig. 2. Estimation of the change in thickness by the least-squares method.

which represents the phase difference between two points set along the ultrasonic beam, is expressed by eq. (4).

$$\beta(t; d, d_{12}) = z(t; d + x_1(t)) \cdot z^*(t; d + x_2(t) + d_{12}), \quad (4)$$

where d_{12} is the distance between two points initially set at $t = 0$, and $x_1(t)$ and $x_2(t)$ are displacements of these two points, which are estimated by the *phased tracking method* as described in §2.1.

Let us assume that the amplitude of $\beta(t + T; d, d_{12})$ and $\beta(t; d, d_{12})$ are equal because the pulse repetition interval, T, is sufficiently short. Thus, the complex signal, $\beta(t + T; d, d_{12})$, at the time $t + T$ is estimated from $\beta(t; d, d_{12})$ as follows:

$$\widehat{\beta}(t + T; d, d_{12}) = \beta(t; d, d_{12}) \cdot e^{j\Delta\theta_h(t)}, \quad (5)$$

where $\Delta\theta_h(t)$ is the phase shift which represents the change in thickness between these two points set along the ultrasonic beam. Then, the normalized mean squared difference, $\alpha(\Delta\theta_h(t))$, between $\beta(t + T; d, d_{12})$ and $\widehat{\beta}(t + T; d, d_{12})$ is defined by

$$\alpha(\Delta\theta_h(t)) = \frac{\displaystyle\sum_{m=-M/2}^{M/2} \left|\beta(t+T; d+mD, d_{12}) - \widehat{\beta}(t+T; d+mD, d_{12})\right|^2}{\displaystyle\frac{1}{2}\sum_{m=-M/2}^{M/2}\left\{\left|\beta(t+T; d+mD, d_{12})\right|^2 + \left|\widehat{\beta}(t+T; d+mD, d_{12})\right|^2\right\}}$$
$$= \frac{\displaystyle\sum_{m=-M/2}^{M/2} \left|\beta(t+T; d+mD, d_{12}) - \beta(t; d+mD, d_{12}) \cdot e^{j\Delta\theta_h(t)}\right|^2}{\displaystyle\frac{1}{2}\sum_{m=-M/2}^{M/2}\left\{\left|\beta(t+T; d+mD, d_{12})\right|^2 + \left|\beta(t; d+mD, d_{12})\right|^2\right\}}, \quad (6)$$

where $M + 1$ is the number of samples in the depth direction for calculating the difference $\alpha(\Delta\theta_h(t))$. By replacing the denominator of eq. (6) by A, eq. (6) can be rewritten as follows:

$$A \cdot \alpha(\Delta\theta_h(t)) = \sum_{m=-M/2}^{M/2} \left|\beta(t+T; d+mD, d_{12}) - \beta(t; d+mD, d_{12}) \cdot e^{j\Delta\theta_h(t)}\right|^2$$
$$= \sum_{m=-M/2}^{M/2} \left\{\left|\beta(t+T; d+mD, d_{12})\right|^2 \right.$$
$$- \beta(t+T; d+mD, d_{12}) \cdot \beta^*(t; d+mD, d_{12}) \cdot e^{-j\Delta\theta_h(t)}$$
$$\left. - \beta^*(t+T; d+mD, d_{12}) \cdot \beta(t; d+mD, d_{12}) \cdot e^{j\Delta\theta_h(t)} + \left|\beta(t; d+mD, d_{12})\right|^2\right\}. \quad (7)$$

By taking the partial derivative of eq. (7) with respect to $\Delta\theta_h(t)$, the following equation is obtained:

$$A \cdot \frac{\partial\alpha(\Delta\theta_h(t))}{\partial\Delta\theta_h(t)} = \sum_{m=-M/2}^{M/2}\left\{j\beta(t+T; d+mD, d_{12}) \cdot \beta^*(t; d+mD, d_{12}) \cdot e^{-j\Delta\theta_h(t)}\right.$$
$$\left. - j\beta^*(t+T; d+mD, d_{12}) \cdot \beta(t; d+mD, d_{12}) \cdot e^{j\Delta\theta_h(t)}\right\}. \quad (8)$$

In order to determine the phase shift, $\Delta\widehat{\theta}_h(t)$, which gives the minimum value of $\alpha(\Delta\theta_h(t))$, by setting the right hand side of eq. (8) to be zero,

$$e^{j\Delta\widehat{\theta}_h(t)} = \frac{\displaystyle\sum_{m=-M/2}^{M/2} \beta(t+T; d+mD, d_{12}) \cdot \beta^*(t; d+mD, d_{12})}{\left|\displaystyle\sum_{m=-M/2}^{M/2} \beta(t+T; d+mD, d_{12}) \cdot \beta^*(t; d+mD, d_{12})\right|}. \quad (9)$$

In measurement of the change in thickness, $M + 1$ in eq. (9) is set at 5 ($= 0.4\,\mu$s) in consideration of the pulse length of $0.46\,\mu$s.

From eq. (9), velocity, $v_h(t)$, of the change in thickness is obtained by the following equation:

$$\widehat{v_h}\left(t + \frac{T}{2}\right) = \frac{c_0}{2\omega_0}\frac{\Delta\widehat{\theta}_h(t)}{T}. \quad (10)$$

The change in thickness, $\Delta h(t)$, of the arterial wall is obtained by integrating the velocity, $v_h(t)$, of the change in

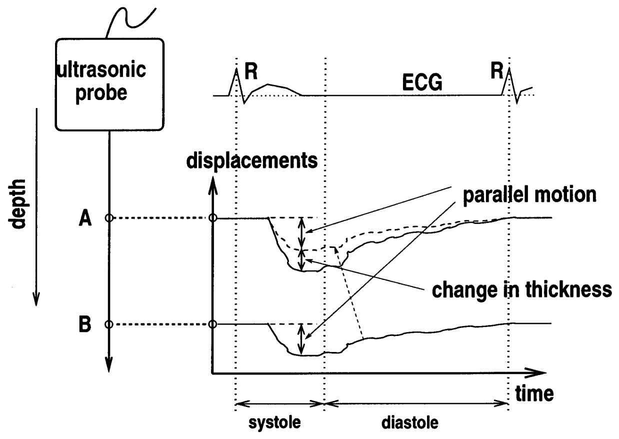

Fig. 3. Spatial inhomogeneity in displacement as a cause of the change in thickness.

thickness as follows:

$$\Delta\widehat{h}(t) = \int_0^t \widehat{v_h}(t)\mathrm{d}t. \tag{11}$$

As illustrated in Fig. 3, there are two components of displacements, namely, parallel motion and the change in thickness, at two points along the ultrasonic beam. The change in thickness is obtained by subtracting the parallel motion from the displacement when the displacements of these two points do not coincide with each other, that is, when they are spatially inhomogeneous.

In the *phased tracking method*, two correlation windows are set to obtain displacements of two points along the ultrasonic beam. Though there are many reflected pulses under *in vivo* conditions, influences of the spatial averaging of displacements can be illustrated from the simple model as shown in Fig. 4. In this model, there are three different pulses reflected by three different scatterers which have different displacements. In order to precisely obtain the change in thickness around the region where correlation windows are set, it is necessary to obtain differences in displacements of these pulses. However, in the *phased tracking method*, the difference in displacements cannot be obtained precisely due to the spatial averaging of displacements of different pulses, and the spatial averaging of displacements of different pulses is caused by inclusion of different pulses in the correlation window. On the other hand, the change in thickness can be estimated precisely by the *modified phased tracking method*, because the difference between displacements of each two points around the correlation window is obtained as shown in Fig. 5.

In the *phased tracking method*, the spatial averaging of displacements causes reduction of the amplitude of the estimated change in thickness in comparison with its true value when the same pulse is included in both correlation windows. In Fig. 4, pulse $e2$ is included in both correlation windows. Therefore, spatially averaged displacements obtained from both correlation windows become close to each other because the same displacement of pulse $e2$ is added to the spatial averaging in both correlation windows. As a result, the amplitude of the estimated change in thickness is reduced.

In this paper, influences of the interference between pulses is not taken into account. Further investigation is necessary to discuss influences of such interference.

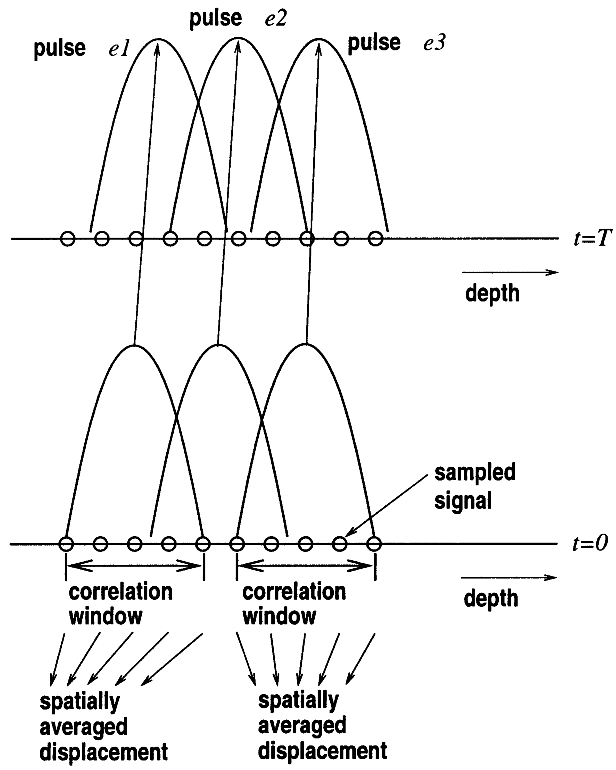

Fig. 4. Illustration of estimation of the change in thickness by the *phased tracking method*.

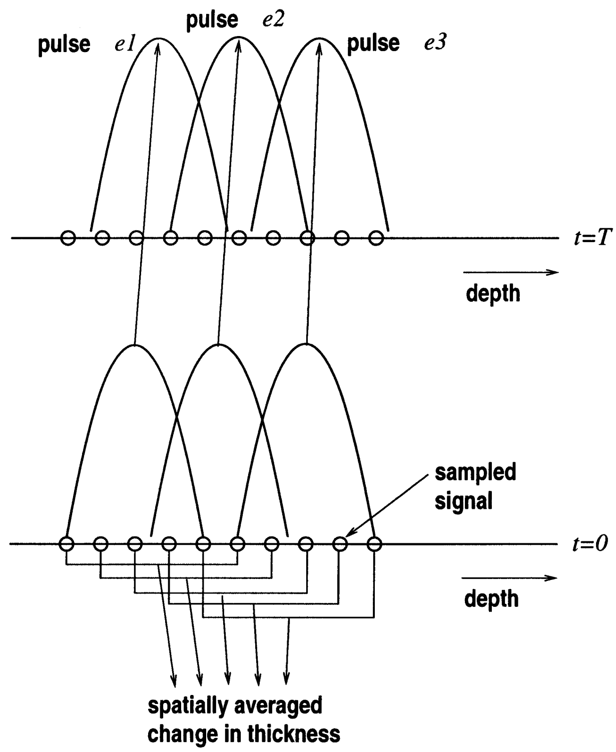

Fig. 5. Illustration of estimation of the change in thickness by the *modified phased tracking method*.

3. Basic Experiments Using a Rubber Plate

3.1 Experimental system for basic experiments

The experimental system for basic experiments is illustrated in Fig. 6.[30] In this system, the change in thickness of

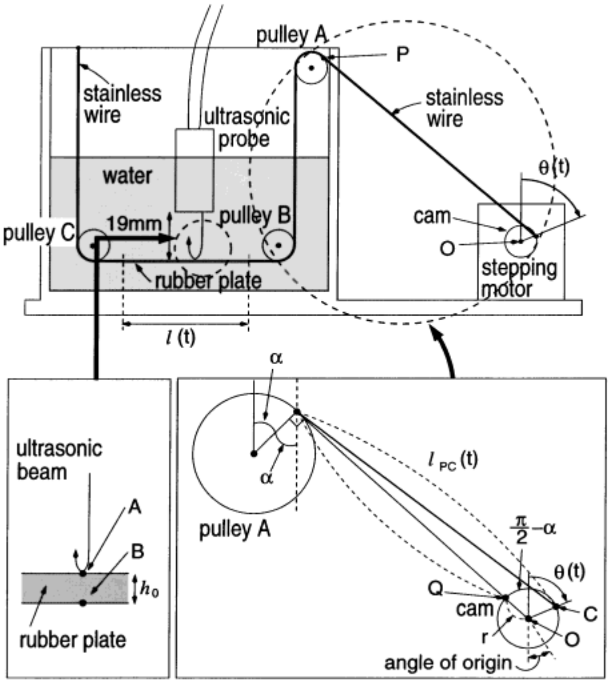

Fig. 6. Experimental system for basic experiments.

a rubber plate is generated by expanding it in the longitudinal direction by a motor. The theoretical value of the change in thickness is obtained from the change in length by assuming that the rubber is incompressible (Poisson's ratio ≈ 0.5). The error in the measured change in thickness is evaluated using this theoretical value.

3.2 Measurement system

The measurement system employed in this paper is illustrated in Fig. 7. The ultrasonic pulse (center frequency: 7.5 MHz) is transmitted and received by the ultrasonic probe in the standard ultrasonic diagnostic equipment. The received signal is amplified and demodulated. The resultant in-phase and quadrature signals are simultaneously A/D converted with a 12-bit A/D converter at a sampling frequency of 10 MHz. Measured digital signals are transfered to a computer, and the change in thickness of the rubber plate is obtained by applying two methods, the *phased tracking method* and the *modified phased tracking method*, mentioned in §2, to these digital signals.

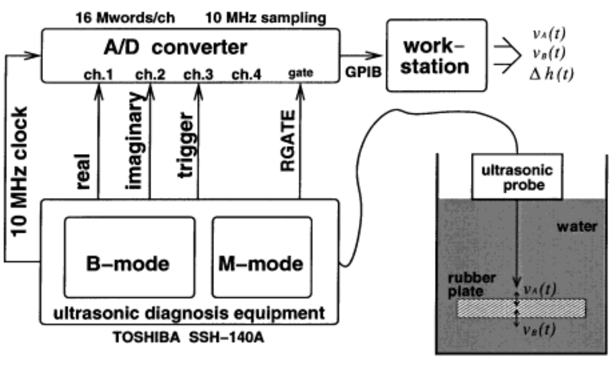

Fig. 7. Measurement system employed for basic experiments.

3.3 Basic experimental results

Figure 8 shows the results of measuring the change in thickness of the rubber plate. Figure 8(a) shows the amplitude of the quadrature modulated signals at a time of $t = 0$, which is plotted as a function of depth. Figure 8(c) shows the output of the position sensor for detection of the origin angle of the motor. By setting two points A and B at the near and far surface of the rubber plate in the M-mode image of Fig. 8(b), velocities, $v_A(t)$ and $v_B(t)$, of points A and B are obtained by the *phased tracking method* as shown in Figs. 8(d) and 8(e). By integrating the difference between the velocities of point A and B, the change in thickness, $\Delta h(t)$, is obtained as shown in Fig. 8(f) using the *phased tracking method*. The change in thickness, $\Delta h(t)$, is also obtained by the proposed method as shown in Fig. 8(h) by integrating the velocity, $v_h(t)$, of the change in thickness (Figs. 8(g)). In Fig. 9, the same procedure except for the setting of initial positions of tracked points is applied to the same data as in Fig. 8.

As shown in Fig. 8(a), two correlation windows are set at positions of different echoes, respectively. In this case, signals included in correlation windows A and B correspond to reflected echoes from the near and far surface of the rubber plate, respectively. Therefore, the change in thickness can be obtained precisely by the *phased tracking method* and the

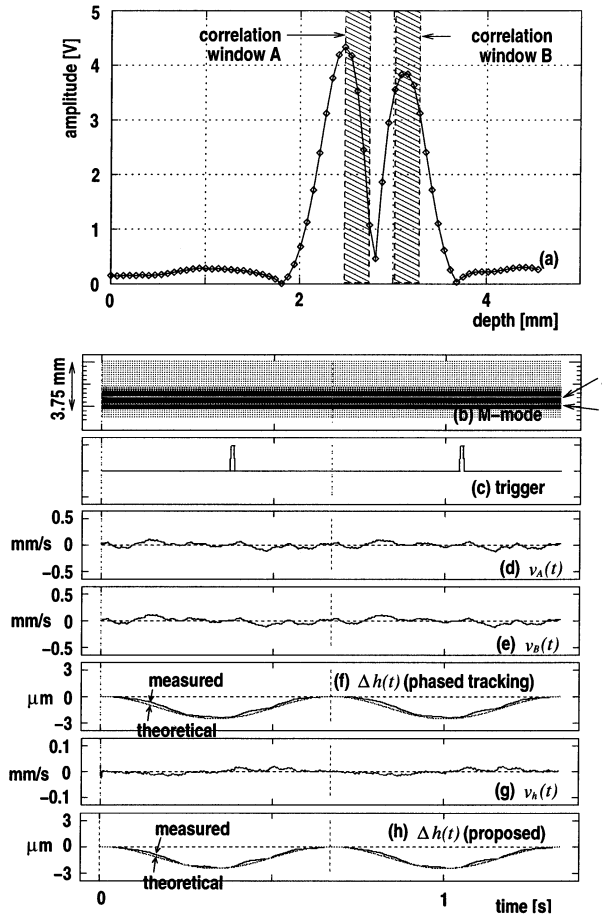

Fig. 8. Results of measurement of the change in thickness of a rubber plate under a setting of correlation windows. (a) Amplitude of the quadrature modulated signal. (b) M-mode image. (c) Output of sensor for detection of the angle of origin of the motor. (d) Velocity, $v_A(t)$, of point A. (e) Velocity, $v_B(t)$, of point B. (f) Change in thickness, $\Delta h(t)$, measured by the *phased tracking method*. (g) Velocity, $v_h(t)$, of the change in thickness. (h) Change in thickness, $\Delta h(t)$, measured by the proposed method.

modified phased tracking method. On the other hand, in case of Fig. 9, displacements in correlation window A are inhomogeneous because both pulses, which are reflected at the near and far surface of the rubber plate, are included in correlation window A. Therefore, displacement of the near surface cannot be obtained precisely from correlation window A due to spatial averaging of displacements of the near and far surface in correlation window A.

Figure 10 shows the mean, maximum, and minimum of displacements within correlation window A for cases of Figs. 8 and 9, which are obtained from the *phased tracking method* by setting $M + 1$ in eq. (1) at 1. In Fig. 10, means are shown by diamonds, and maximum and minimum of displacements are indicated by vertical bars. From Fig. 10, inhomogeneity in displacements within the correlation window in the case of Fig. 9 is larger than in the case of Fig. 8. Therefore, spatial averaging of displacements has a greater influence on the precision of the measured change in thickness for the case of Fig. 9.

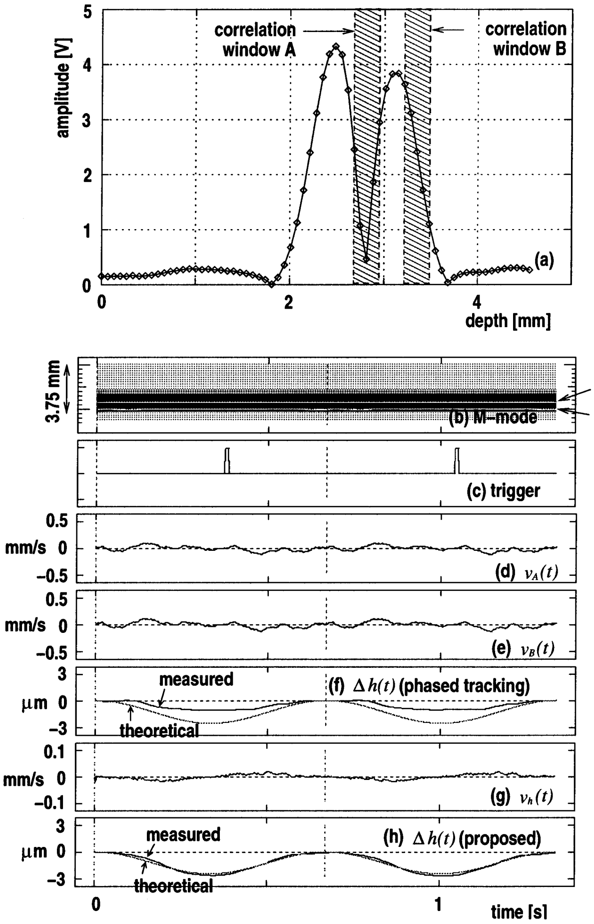

Fig. 9. Results of measurement of the change in thickness of a rubber plate under another setting of correlation windows. (a) Amplitude of the quadrature modulated signal. (b) M-mode image. (c) Output of sensor for detection of the angle of origin of the motor. (d) Velocity, $v_A(t)$, of point A. (e) Velocity, $v_B(t)$, of point B. (f) Change in thickness, $\Delta h(t)$, measured by the *phased tracking method*. (g) Velocity, $v_h(t)$, of the change in thickness. (h) Change in thickness, $\Delta h(t)$, measured by the proposed method.

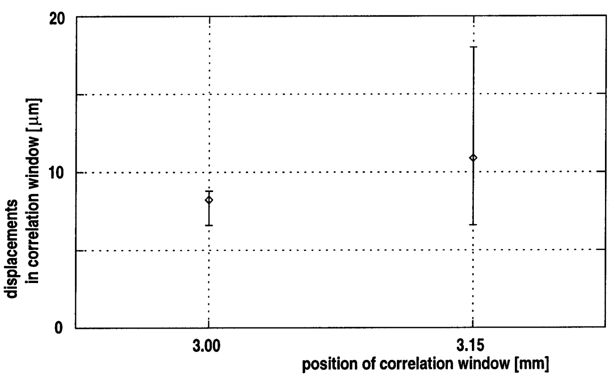

Fig. 10. Mean, maximum, and minimum of displacements within the correlation window.

4. *In vivo* Experimental Results for the Human Common Carotid Artery

The proposed method was applied to *in vivo* measurement of the human carotid artery of a 28-year-old male subject. Changes in thickness of the arterial wall were measured at two different positions, p_1 and p_2, on the arterial wall as shown in the B-mode image of Fig. 11. Figure 12 shows the results measured at the beam position p_1. Initial positions of the intimal side and the adventitial side (points A and B in Fig. 12(a)) are set in the M-mode image of Fig. 12(a) at the timing of the R-wave of the electrocardiogram shown in Fig. 12(b). Velocities, $v_A(t)$ and $v_B(t)$, of the intimal and adventitial sides were obtained by the *phased tracking method* as shown in Figs. 12(c) and 12(d), respectively. The change in thickness, $\Delta h(t)$, was obtained as shown in Fig. 12(e) by integrating the difference between these two velocities. By directly integrating velocity, $v_h(t)$, of the change in thickness (Fig. 8(f)), the change in thickness, $\Delta h(t)$, was also obtained by the *modified phased tracking method* as shown in Fig. 12(g). In results for the position p_1, there was almost no difference in amplitude of the measured changes in thickness by both methods.

Figure 13 shows results of measurement at position p_2. In Fig. 13, the amplitude of the change in thickness obtained by the *phased tracking method* decreases in comparison with that obtained by the proposed method, the same as is the basic experiments.

Figures 14(a) and 14(b) show the amplitude of quadrature modulated signals at positions p_1 and p_2, respectively. In Fig. 14(a), two reflected echoes, which are reflected by the intimal side and the adventitial side, respectively, are clearly sepa-

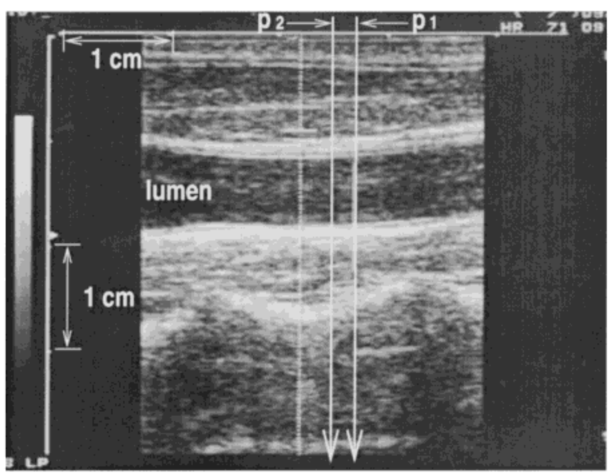

Fig. 11. B-mode image of the human carotid artery of a 28-year-old man obtained by standard ultrasonic diagnostic equipment.

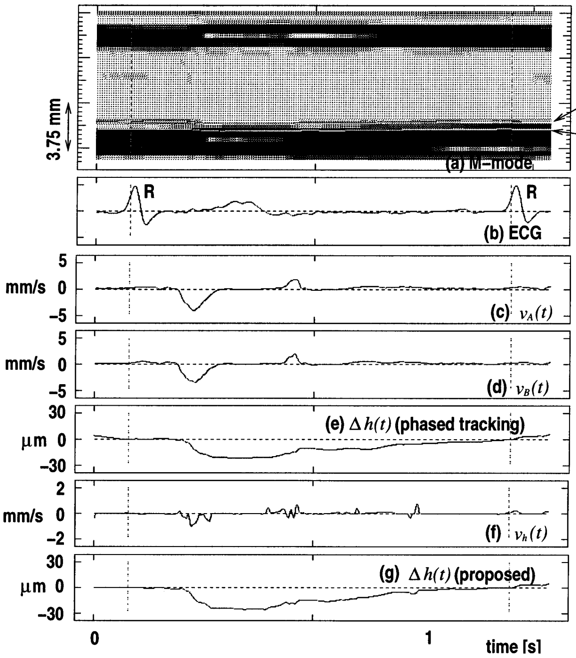

Fig. 12. Results of measurement of the change in thickness of the arterial wall at beam position p_1 (28-year-old man). (a) M-mode image. (b) Electrocardiogram. (c) Velocity, $v_A(t)$, of the intimal side. (d) Velocity, $v_B(t)$, of the adventitial side. (e) Change in thickness, $\Delta h(t)$, measured by the *phased tracking method*. (f) Velocity, $v_h(t)$, of the change in thickness. (g) Change in thickness, $\Delta h(t)$, measured by the proposed method.

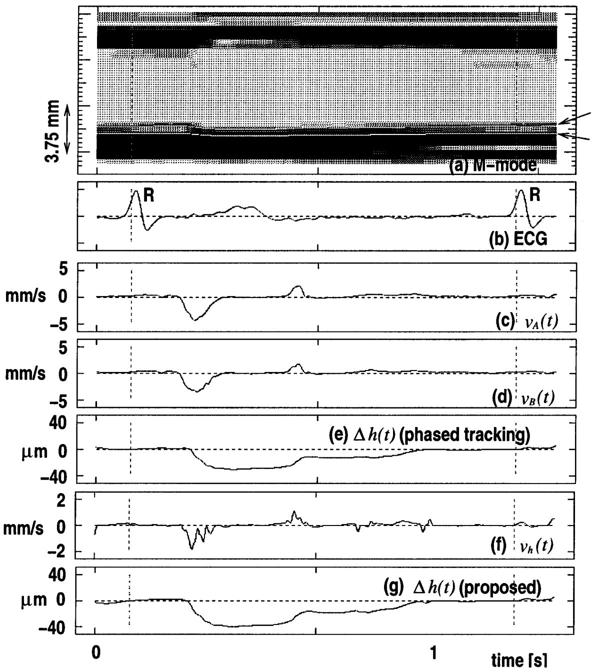

Fig. 13. Results of measurement of the change in thickness of the arterial wall at beam position p_2 (28-year-old man). (a) M-mode image. (b) Electrocardiogram. (c) Velocity, $v_A(t)$, of the intimal side. (d) Velocity, $v_B(t)$, of the adventitial side. (e) Change in thickness, $\Delta h(t)$, measured by the *phased tracking method*. (f) Velocity, $v_h(t)$, of the change in thickness. (g) Change in thickness, $\Delta h(t)$, measured by the proposed method.

rated from each other, and each correlation window is set at the position of each echo. In this case, two displacements, which are obtained from correlation windows A and B by the *phased tracking method*, correspond to displacements of the intimal side and the adventitial side, respectively.

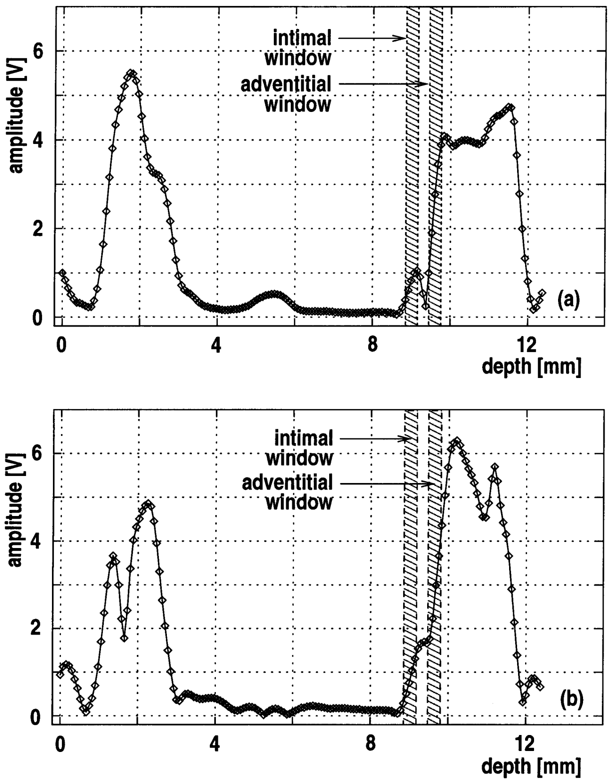

Fig. 14. Amplitude of the quadrature modulated signal. (a) Beam position p_1. (b) Beam position p_2.

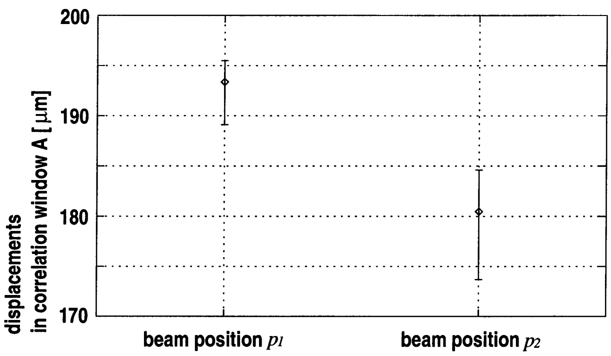

Fig. 15. Mean, maximum, and minimum of maximum value of displacement during one heartbeat at each point in the correlation window.

On the other hand, in Fig. 14(b), echoes which are reflected by the intimal side and the adventitial side are not clearly separated. In such a case, it is supposed that there are some reflected echoes besides those from the intimal side and the adventitial side. Under such condition, displacements in the correlation window are inhomogeneous because these echoes are reflected by different scatterers, which have different displacements. Therefore, the precision in measurement of the change in thickness (inhomogeneity in displacements) worsen due to spatial averaging of displacements by the *phased tracking method*. As a result, the change in thickness, which is obtained from the difference between spatially averaged displacements, becomes small in comparison with that by the proposed method, because the spatial inhomogeneity of displacements (which corresponds to the change in thickness) is suppressed due to spatial averaging.

As in the basic experiments, Fig. 15 shows mean, maximum, and minimum of displacements within correlation window A for the cases of Figs. 12 and 13, which were obtained by the *phased tracking method* by setting $M+1$ in eq. (1) at 1. In Fig. 15, means are shown by diamonds, and maximum and minimum of displacements are shown by vertical bars. From Fig. 15, inhomogeneity of displacements in the case of Fig. 13 is seen to be greater than in Fig. 12. Therefore, it is supposed that spatial averaging of displacements has a greater influence on the measured change in thickness in the case of Fig. 13.

5. Discussion

A question throughout this paper is whether the spatial averaging of displacements by the *phased tracking method* can be prevented by setting $M+1$ in eq. (1) (width of the correlation window) at 1. However, spatial averaging is necessary to obtain adequate results as described below.

In Fig. 16, the same procedure as described in Fig. 9 except for width of the correlation window ($M+1=1$) is applied to the same data shown in Fig. 9. In Fig. 16, the change in thickness is obtained by the *phased tracking method* (Fig. 16(f)) with large error. It is supposed that the phase of the sample point at correlation window A does not represent the displacement of the near surface of the rubber plate because this sample point is located on the edge of the pulse, which is reflected by the near surface. The quadrature modulation can extract the phase information of the stationary sinusoidal signal with a single frequency. Due to finite duration of the ultrasonic pulse, however, the phase information around the edge of the ultrasonic pulse cannot be obtained precisely because the ultrasonic pulse cannot be assumed as a stationary sinusoidal wave with a single frequency around its edge.

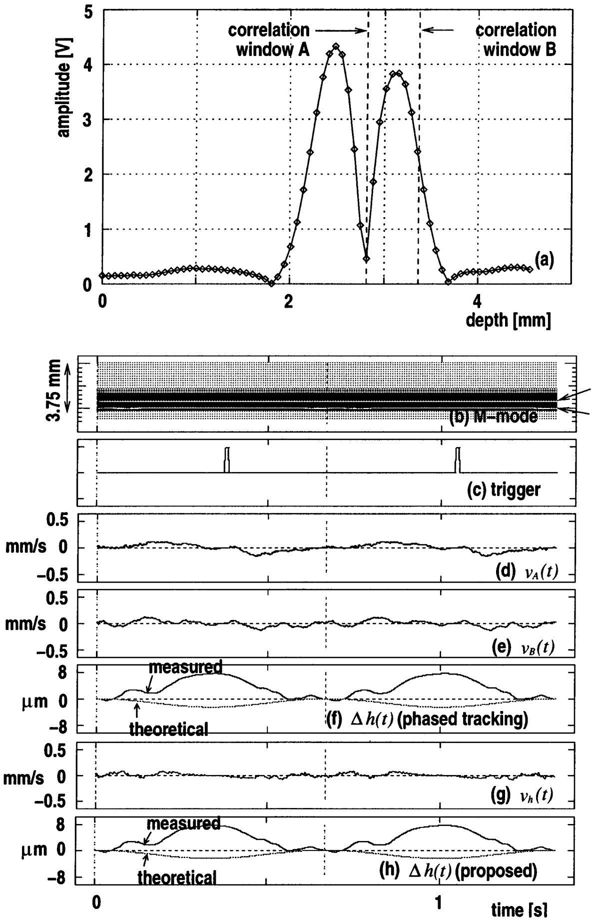

Fig. 16. Results of measurement of the change in thickness of a rubber plate with the narrower correlation window. (a) Amplitude of the quadrature modulated signal. (b) M-mode image. (c) Output of sensor for detection of the angle of origin of the motor. (d) Velocity, $v_A(t)$, of point A. (e) Velocity, $v_B(t)$, of point B. (f) Change in thickness, $\Delta h(t)$, measured by the *phased tracking method*. (g) Velocity, $v_h(t)$, of the change in thickness. (h) Change in thickness, $\Delta h(t)$, measured by the proposed method.

From this fact, spatial averaging during pulse duration in eq. (1) is necessary to prevent the displacement from being estimated only from the sample point around the edge of the ultrasonic pulse. The influence of the sample point around the edge of the ultrasonic pulse is suppressed by summation of eq. (1), which is weighted by the amplitude of sample points, because the amplitude of the sample point around the edge is smaller than that around the center of the ultrasonic pulse. In the proposed method, the influence of the incorrect phase information around the edge is suppressed by the same mechanism as that of the *phased tracking method*, spatial averaging in eq. (9). In the *modified phased tracking method*, by applying spatial averaging to the change in thickness rather than to the displacement, spatial inhomogeneity in displacements is not suppressed.

In consideration of these facts, spatial inhomogeneity of displacements in the correlation window in Fig. 9 is caused by the following two factors.

(1) Actual change in thickness (two echoes which represent displacements of the near and far surface of the rubber plate are included in the correlation window. There is a difference between displacements of these two echoes.).
(2) Incorrect phase information around the edge of the ultrasonic pulse.

The above-mentioned influence of the phenomenon of item (2) is suppressed by the spatial averaging in both the *phased tracking method* and the *modified phased tracking method* proposed in this paper. Thus, the spatial averaging is necessary for both methods to obtain adequate results. However, there is a difference between these two methods with regard to what spatial averaging is applied to. Worsening of the precision in measurement of the change in thickness by the *phased tracking method* is thought to be caused by the spatial averaging of different displacements in the correlation window.

In this paper, though the procedure for estimation of the change in thickness is modified, determination of the object position depends on the *phased tracking method*. In eq. (4), displacements, $x_1(t)$ and $x_2(t)$, which are still estimated by the *phased tracking method*, determine the sample points which are employed for estimation of the phase shift. Consequently, the precision in measurement of the change in thickness is not still completely independent from error in estimation of the displacements, $x_1(t)$ and $x_2(t)$.

6. Conclusions

In this paper, a method has been proposed for reduction of the estimation error in measurement of the small change in thickness of the arterial wall. The proposed method was evaluated by basic experiments using a rubber plate, and then applied to *in vivo* measurement of the human carotid artery. From these results, it was shown that the *modified phased* *tracking method* proposed in this paper has potential for measurement of the change in thickness with higher precision in comparison with the *phased tracking method*.

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