Accuracy evaluation in ultrasonic-based measurement of microscopic change in thickness

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For the diagnosis of atherosclerosis, one acoustical method involves measuring the change in thickness of the arterial wall during one cardiac cycle and then noninvasively evaluating the elastic properties of the arterial wall. An alternative method for obtaining such a diagnosis is proposed, the phased tracking method, which can be used to accurately measure the instantaneous displacement signals on the intima and adventitia of the arterial wall from the skin surface using pulsive ultrasonic waves. A minute change in the thickness of the arterial wall of several micrometres is obtained by integrating the difference between two instantaneous displacement signals. Using a rubber plate in a water tank, the accuracy of the proposed method is evaluated by measuring such microscopic changes in thickness.

Introduction: During the ejection period, a pressure wave from the heart expands the lumen of the artery, resulting in the arterial wall becoming slightly thinner. In the literature, the change in diameter of the lumen has been measured using ultrasound, and then based on this, the elasticity has been diagnosed by assuming that the arterial wall has homogeneous elasticity in the circumferential direction, an assumption which has been an obstacle to the evaluation of the regional characteristics of atherosclerotic plaque.

Conversely, the measurement of the change in wall thickness makes it possible to evaluate the elasticity of the arterial wall in each local area, the locality in the circumferential direction being indispensable to the diagnosis of the inner characteristics of atherosclerotic plaque. To this end, by tracking the instantaneous positions, $x_A(t)$ and $x_B(t)$, of two points A and B, which are preset at the end-diastole along an ultrasonic beam in the arterial wall, the small change in wall thickness, $\Delta h_{AB}(t)$, between these two points, A and B, is obtained during the cardiac cycle by keeping the ultrasonic beam perpendicular to the wall. From the ratio of the change in thickness, $\Delta h_{AB}(t)$, to the thickness, h_0, between these points preset at the end-diastole, the deformation is obtained. If the deformation is sufficiently small and is in the linear regime, the deformation shows the strain, and the regional elasticity of the wall is approximately evaluated using the pulse pressure noninvasively measured at the brachial artery [1].

The accuracy required in the simultaneous measurement of the instantaneous positions $x_A(t)$ and $x_B(t)$ of points A and B is estimated as follows: the thickness, h_0, of the wall is ~1 mm and the change in thickness, $\Delta h_{AB}(t)$, ranges from several micrometres to several tenths of a micrometre during one cardiac cycle for the carotid artery of normal adults. Therefore, the necessary spatial resolution in the measurement of the instantaneous position of a waveform is at least several micrometres.

Although motion (M)-mode echocardiography offers advantages in critically looking at the motion pattern of the wall, its spatial resolution along the ultrasonic beam is limited to a few wavelengths, i.e. at most ~1mm for ultrasound at 7MHz.

For the accurate detection of instantaneous displacement on or in the heart wall or arterial wall, we have developed the following phased tracking method [2, 3]. In this method, by calculating the constraint autocorrelation function between the sequentially received echoes, the phase change caused by the movement of each point (i), (i = A, B) during the pulse repetition period $\Delta T(= 1/PRF)$ is accurately determined and the instantaneous displacement $d_i(t)$ during the period is obtained. By adding $d_i(t)$ to the previous object position, $x_i(t)$, the next position, $x_i(t+\Delta T)$, is estimated by $x_i(t)$ + $d_i(t)$ and then the object position is recursively adjusted. This method has been applied to the *in vivo* detection of small velocity signals with sufficient reproducibility at points in the interventricular septum (IVS) of the human heart [2]. The detected instantaneous displacement shows rapid motion including high frequency components with small amplitudes, which cannot be recognised by M-mode echocardiography.

Moreover, the method has been applied to two points preset along an ultrasonic beam in the heart/arterial wall so that the instantaneous object positions are obtained for these two points in the IVS [2, 3] and the carotid artery [1]. From the results, by deleting the parallel component, the thickness change component during one cardiac cycle is detected.

The measurement accuracy of the change in thickness, which should be evaluated, is several micrometres during one cardiac cycle. However, such a microscopic change cannot be easily measured by any other methods in water. Thus, an apparatus with a rubber plate was assembled and changes in thickness were theoretically derived by assuming that its Poisson ratio was 0.5. The change in thickness detected by the phased tracking method was quantitatively compared to the theoretically obtained change and its accuracy evaluated.

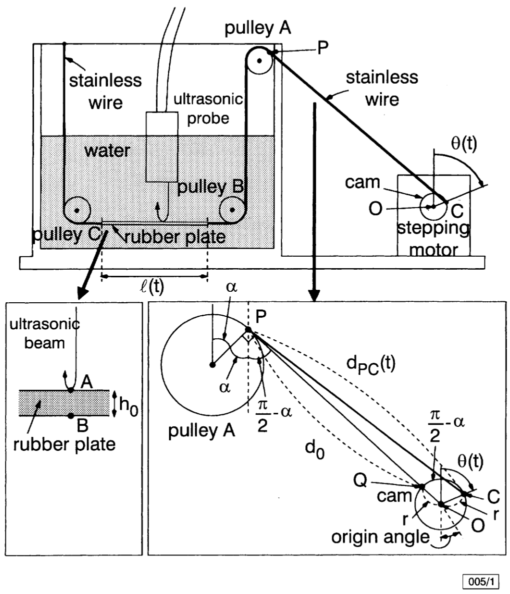

Fig. 1 *Experimental apparatus using rubber plate which is drawn by stepping motor to achieve minute changes in thickness*

Change characteristics theoretically derived using eqn. 3

Experimental apparatus: Fig. 1 shows the experimental apparatus. The rubber plate with a length l_0 of 100.5mm, a thickness h_0 of 1.65mm, and a width w_0 of 28mm is set in a water tank and both ends are connected to stainless steel wires with a diameter of 0.3mm, one end being drawn by a stepping motor with a rotation rate of 1.5Hz. At the bottom right of Fig. 1, by applying the cosine theorem to the triangle POC, the squared distance $d_{PC}(t)$ between point P on pulley A and rotating point C on the cam is given by

$$d_{PC}(t)^2 = r^2 + (d_0 + r)^2 - 2r(d_0 + r)\cos\left(\frac{\pi}{2} - \alpha + \theta(t)\right) \tag{1}$$

where d_0 = 285.9mm and r = 0.5mm are, respectively, the distance between P and Q and the radius of the locus of point C; angle α is 49.8°. The change in length, $\Delta l(t)$, of the rubber plate due to the rotation of point C is given by $\Delta l(t) = d_{PC}(t) - d_0$. From the definition of Poisson ratio σ,

$$\sigma = -\frac{\Delta h_t(t)/h_0}{\Delta \ell(t)/\ell_0} \tag{2}$$

where $\Delta h_T(t)$ is the theoretical value of the instantaneous change in thickness between points A and B on both sides of the rubber plate. By assuming that the Poisson ratio σ of the rubber is 0.5, $\Delta h_T(t)$ is described by

$$\begin{aligned}\Delta h_t(t) &= -\sigma\frac{\Delta\ell(t)}{\ell_0}h_0 \\ &= -\frac{d_{PC}(t) - d_0}{2\ell_0}h_0\end{aligned} \tag{3}$$

For ultrasonic measurement, on the other hand, standard ultrasonic diagnostic equipment and an ultrasonic probe operated at 5MHz are employed. The pulse repetition interval ΔT is 133μs. The received signal is amplified and demodulated. The resultant real and imaginary signals are simultaneously A/D converted with a 12bit A/D converter at a sampling rate of 2MHz. Using a computer, the phased tracking method is applied to the digital signals and the change in thickness, $\Delta h_{US}(t)$, of the rubber plate is obtained.

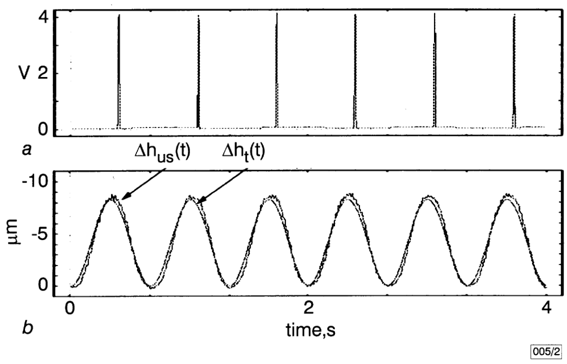

Fig. 2 *Experimental results*

a Output of position sensor for detection of origin angle of motor
b Change in thickness measured by phased tracking method ($\Delta h_{US}(t)$) and theoretical method ($\Delta h_T(t)$)

Experimental results: Fig. 2 shows the experimental results. Fig. 2*a* shows the output of the position sensor for the detection of the origin angle of the motor and Fig. 2*b* shows the experimental results, $\Delta h_{US}(t)$, obtained by the phased tracking method and the theoretical value, $\Delta h_T(t)$, calculated from eqns. 1 and 3. During the rotation of the cam, the peak-to-peak value of $\Delta l(t)$ is equal to $2r = 1$mm and then the theoretical value of the change in thickness, $\Delta h_T(t)$, ranges from 0 to 8.2µm as shown in the Figure. By comparing $\Delta h_{US}(t)$ with $\Delta h_T(t)$, such a minute change in thickness is successfully detected in $\Delta h_{US}(t)$. The root of the average squared difference of $\Delta h_{US}(t)$ from $\Delta h_T(t)$ is 0.499µm. From these experimental results, the small change in thickness is successfully detected with submicrometre order accuracy.

Conclusions: We have experimentally evaluated the accuracy of a new method for measuring small changes in the thickness of the arterial wall using ultrasonic techniques. The experimental results indicate that the measurement of minute changes in thickness of the arterial wall with an accuracy of < 1mm is achievable for the diagnosis of its acoustic characteristics.

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