Measurement of Local Elasticity of Human Carotid Arterial Walls and Its Relationship with Risk Index of Atherosclerosis

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Abstract— We have proposed a new method for evaluating the local elasticity of the arterial wall in order to diagnose the early stage atherosclerosis. In the case of the early stage atherosclerosis, the macular lesion is several millimeters in diameter. Therefore, it is necessary to find the local change in the elasticity of the arterial wall. In the proposed method, the small change in thickness of the arterial wall during cardiac cycle is accurately measured using ultrasound, and the elasticity of the arterial wall can be evaluated in every small region of about 1 millimeter, which corresponds to the width of the ultrasonic beam.

In this report, the proposed method is applied to human carotid arteries of 54 male patients and 30 healthy male subjects, where the patients have high risk factor of coronary heart diseases. From this results, the difference in the elasticity of the arterial walls between healthy subjects and patients is investigated.

I. Introduction

In recent years, atherosclerosis has been a serious problem due to its high influence on diseases of circulatory system such as myocardial infarction and cerebral infarction. It is, therefore, important to diagnose the early stage atherosclerosis. Atherosclerosis has been often diagnosed by measuring the thickness of the arterial walls or the area of the lumen, which change with the development of atherosclerosis (Fig. 1), from the sectional image obtained by computed tomography with contrast media, magnetic resonance imaging, or echocardiography. However, in the case of the early stage atherosclerosis, the thickness of the arterial wall is not remarkably increased. Therefore, it is difficult to diagnose the early stage atherosclerosis from the sectional image of the artery.

Then, the method for diagnosis of the early stage atherosclerosis has been proposed to measure the change in the elasticity of the arterial wall. The pulse wave velocity (PWV) method has been previously proposed as a noninvasive method for evaluating the elastic property of the arterial wall and numerous studies on measurement of the PWV have been reported [1]. In the standard method, the PWV is obtained from the transit delay time of the pressure wave propagating from the carotid artery to femoral artery [2]. Therefore, the sufficient spatial resolution cannot be obtained by using this method.

To increase the spatial resolution in the noninvasive evaluation of the elastic property of the arterial wall, we proposed the method for measuring the small velocity signals on the arterial wall using ultrasound [3]. In the proposed method, the small change in thickness of the arterial wall in one cardiac cycle is obtained by measuring the small velocity signals on intima and adventitia of the arterial wall [4]. The amplitude of this change in thickness of the arterial wall is several tenth micrometers, therefore, it cannot be measured from the B-mode image or M-mode image obtained by the standard ultrasonic diagnostic equipment. From the small change in thickness, the elastic property of the arterial wall is noninvasively evaluated. Using the proposed method, the elastic property of the arterial wall is evaluated in each local area of a few millimeters, which corresponds to the width of the ultrasonic beam in the focal area.

In this report, the change in the elasticity with age of the arterial walls are investigated by applying the proposed method to 54 human carotid arteries. Then, the results of patients are compared with those for 30 healthy subjects.

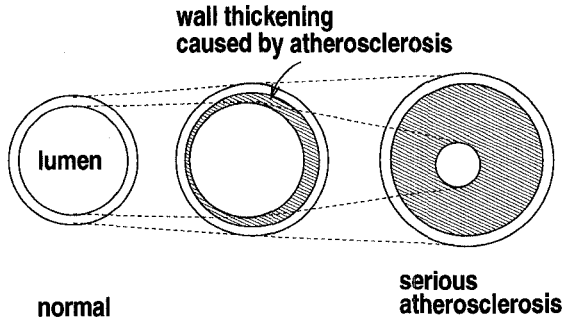

Fig. 1. Change in the wall thickness and the area of the lumen caused by atherosclerosis.

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II. Principle of Measurement of Small Velocity Signals on Arterial Wall

To obtain the change in thickness, $\Delta h(t)$, of the arterial wall, small velocity signals, $v_{in}(t)$ and $v_{ad}(t)$, on intima and adventitia of the arterial wall are accurately measured using ultrasound [3].

First, the phase difference, $\Delta\theta(x;t)$, between the received signals, $y(x;t)$ and $y(x;t+\Delta T)$, for the successively transmitted pulses during the interval ΔT is given by

$$\Delta\theta(x;t) = \theta(x;t+\Delta T) - \theta(x;t) = \frac{2\omega_0}{c_0}\Delta x(t), \qquad (1)$$

where x, ω_0, c_0, $\theta(x;t)$, and $\Delta x(t) = x(t+\Delta T) - x(t)$ are the distance of the object from the ultrasonic transducer, ultrasonic angular frequency, acoustic velocity, the phase of the received signal, and movement of the object during the period ΔT from a time t. By dividing the movement Δx by the period ΔT, the average velocity, denoted by $v(t+\frac{\Delta T}{2})$, of the object during the period ΔT is given by the phase difference $\Delta\theta(x;t)$:

$$v\left(t+\frac{\Delta T}{2}\right) = \frac{\Delta x(t)}{\Delta T} = c_0 \cdot \frac{\Delta\theta(x;t)}{2\omega_0 \cdot \Delta T}. \qquad (2)$$

From the resultant velocity signals, $v_{in}(t)$, and $v_{ad}(t)$, the change in thickness, $\Delta h(t)$, of the arterial wall with amplitude of several tenth micrometers is accurately obtained by integrating the difference between these two velocity signals

$$\Delta h(t) = \int_{-\infty}^{t} \{v_{in}(t) - v_{ad}(t)\}dt. \qquad (3)$$

In this measurement, the minimum value of the measurable velocity is 0.5 mm/s and the time interval, T_0, of integration is 222 μs. In this condition, the lowest value of the change in thickness is found to be about 0.1 μm. Such minute change in thickness cannot be measured by the B-mode or M-mode images obtained by the standard ultrasonic diagnostic equipment.

From the change in thickness, $\Delta h(t)$, of the arterial wall, the incremental strain, $\Delta\varepsilon_r(t)$, in radial direction is obtained by

$$\Delta\varepsilon_r(t) = -\frac{\Delta h(t)}{h_d}, \qquad (4)$$

where h_d is the thickness of the arterial wall.

Figure 2 illustrates the relationship between the incremental strain $\Delta\varepsilon_r(t)$ and the arterial inner pressure $p(t)$. From the incremental strain $\Delta\varepsilon_r(t)$, we define the instantaneous elastic modulus $E(t)$ of the arterial wall by

$$E(t) = \frac{\partial p(t)}{\partial\Delta\varepsilon_r(t)}, \qquad (5)$$

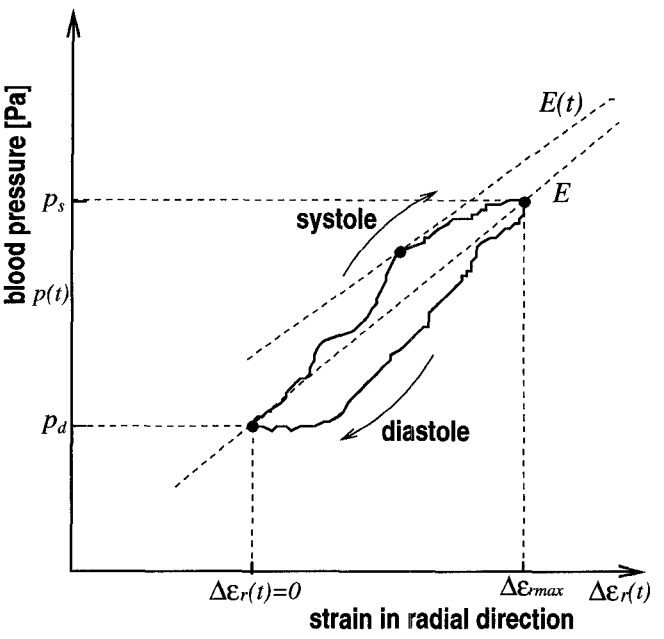

Fig. 2. Illustration of the relationship between the incremental strain $\Delta\varepsilon_r(t)$ and the arterial inner pressure $p(t)$.

where $p(t)$ is the instantaneous arterial inner pressure. However, it is difficult to noninvasively measure the instantaneous arterial inner pressure $p(t)$, the average elastic modulus E during one cardiac cycle is evaluated by

$$E = \frac{p_s - p_d}{\Delta\varepsilon_{rmax}}, \qquad (6)$$

where p_s, p_d, and $\Delta\varepsilon_{rmax}$ are the systolic blood pressure, diastolic blood pressure, and the maximum value of the incremental strain $\Delta\varepsilon_r(t)$ during the systole, respectively.

III. Evaluation of Elastic Modulus E of Human Carotid Artery in Vivo

By using the proposed method for measuring the small velocity signals, the elastic modulus E of the human carotid artery is noninvasively evaluated. The subject is a 36-year-old patient with hyperlipidemia and he has high risk factor of coronary heart diseases. Figures 3(e) and 3(f) show the measured small velocity signals, $v_{in}(t)$ and $v_{ad}(t)$, on intima and adventitia, respectively. These velocity signals have high reproducibility. The small change in thickness of the arterial wall is accurately obtained with amplitude of about 30 μm by integrating the difference between these velocity signals $v_{in}(t)$ and $v_{ad}(t)$. From the resultant change in thickness $\Delta h(t)$, the systolic blood pressure of 112 mmHg, and the diastolic blood pressure of 75 mmHg, the elastic modulus of the arterial wall is determined to be 0.18 MPa. Similarly, the elastic modulus E are obtained with respect to other 53 patients with high risk factors.

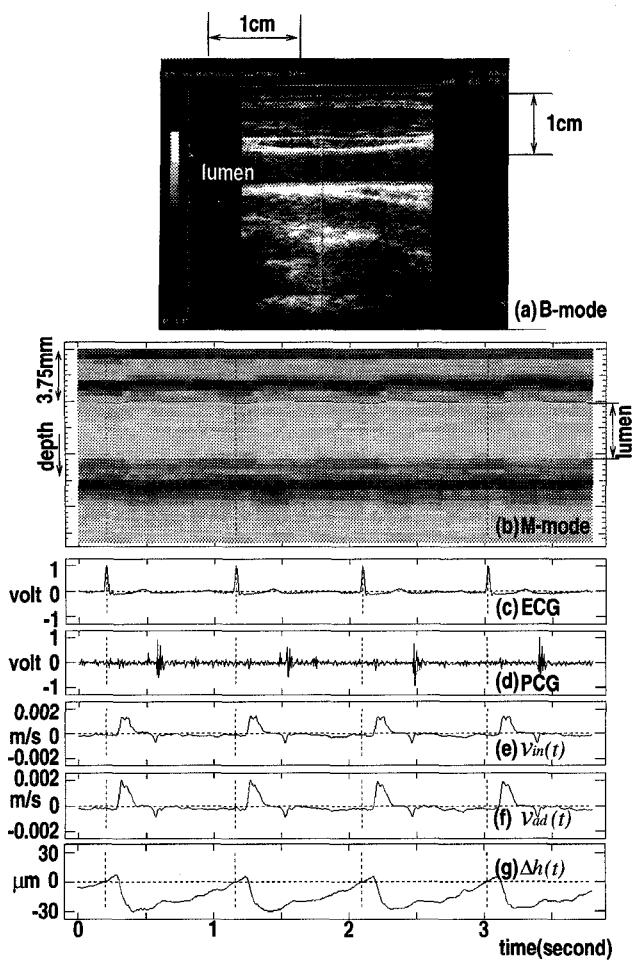

Fig. 3. (a) B-mode. (b) M-mode. (c) ECG. (d) PCG. (e) Small velocity signal $v_{in}(t)$ on intima. (f) Small velocity signal $v_{ad}(t)$ on adventitia. (g) Change in thickness $\Delta h(t)$ of the arterial wall.

IV. Evaluation of Reproducibility in Measuring Elastic Modulus E

Then, we evaluate the reproducibility in measuring the elastic modulus E for successive 3 cardiac cycles.

The average $\bar{E}$ and the standard deviation σ of the elastic modulus $\{E_i\}(i = 1, 2, 3)$ measured in 3 cardiac cycles are respectively defined by

$$\bar{E} = \frac{1}{3}\sum_{i=1}^{3} E_i \tag{7}$$

$$\sigma = \sqrt{\frac{1}{3}\sum_{i=1}^{3}(E_i - \bar{E})^2}. \tag{8}$$

Figure 4 shows the relationship between the average $\bar{E}$ and the standard deviation σ for 54 patients. The variance of the standard deviation σ becomes large with the increase of the average $\bar{E}$. This is caused by the following reason. When the change in thickness $\Delta h(t)$ becomes small, the ratio of the standard deviation to the mean of

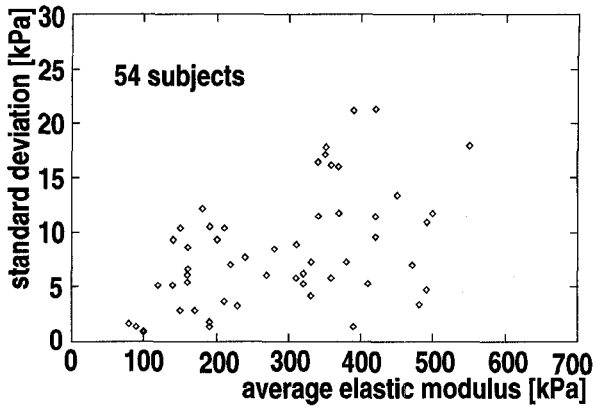

Fig. 4. Relationship between average $\bar{E}$ and the standard deviation σ in measuring elastic modulus E for 3 cardiac cycles.

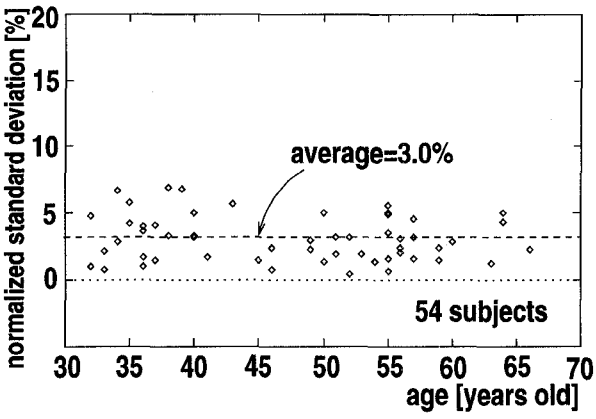

Fig. 5. Normalized standard deviation ε of 54 patients.

the change in thickness becomes high if the standard deviation of the change in thickness $\Delta h(t)$ is similar to the case of the large change in thickness $\Delta h(t)$. Therefore, we use the normalized standard deviation ε to evaluate the reproducibility in measuring the elastic modulus E, which is defined by [5]

$$\varepsilon = \frac{\sigma}{\bar{E}} \times 100 \qquad [\%]. \tag{9}$$

Figure 5 shows the normalized standard deviation ε of 54 patients. The elastic modulus E is found to be reproducibly measured because the average of the normalized standard deviation ε is 3.0 %.

V. *In Vivo* Measurement in Various Subjects

Figures 6(a) and 6(b) respectively show the average of the maximum change in thickness $\Delta h_m = \max\{|\Delta h(t)|\}$ and the average elastic modulus $\bar{E}$ of 3 cardiac cycles of 54 patients. From Fig. 6, the average of the maximum change in thickness Δh_m becomes small and the arterial wall are found to become stiffer with age.

Moreover, Figure 7 shows the average elastic modulus $\bar{E}$ of 3 cardiac cycles with respect to 54 patients and 30

healthy subjects. The arterial walls of patients are found to be relatively stiffer than that of healthy subjects.

On the other hand, Figure 8 shows the arterial wall thickness of 54 patients and 30 healthy subjects. The arterial wall thickness are not remarkably different between patients and healthy subjects.

These results show that the change in the elasticity of the arterial wall can be detected by using the proposed method even for the patients with the arterial walls of normal thickness.

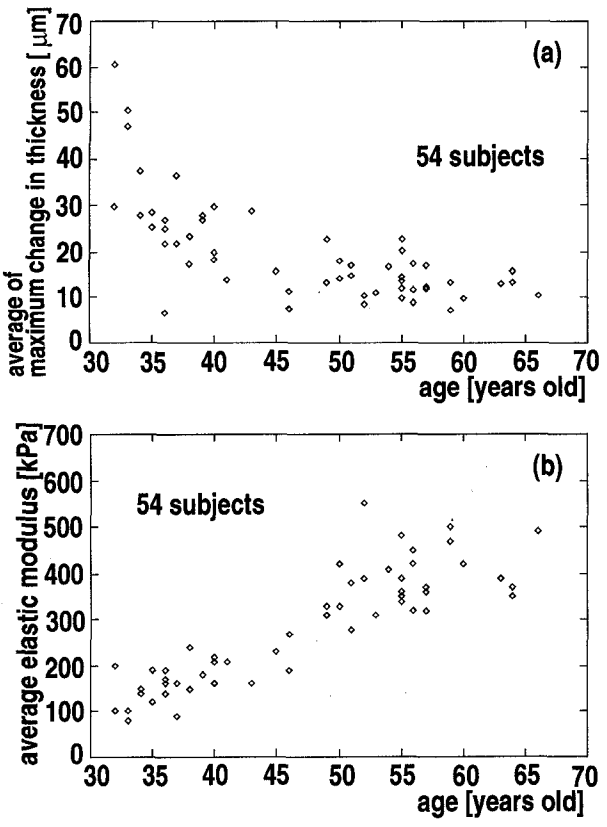

Fig. 6. *In vivo* experimental results for 54 patients. Values are mean measured in 3 cardiac cycles. (a) The average of the maximum change in thickness Δh_m. (b) The average elastic modulus $\bar{E}$.

VI. Conclusions

In this paper, the small change in thickness of the arterial wall with amplitude of several tenth micrometers is noninvasively and accurately obtained by measuring small velocity signals on the arterial wall using ultrasound. From this change in thickness, the elastic modulus E of the arterial wall is noninvasively evaluated.

From *in vivo* measurement in 54 patients, the elastic modulus E is found to increase with age. Moreover, these results are compared with those of the measurement in 30 healthy subjects. As a result, the arterial walls of patients are found to be stiffer than that of healthy subjects. However, there is no remarkable difference in their arterial wall thickness. These results show that by using the

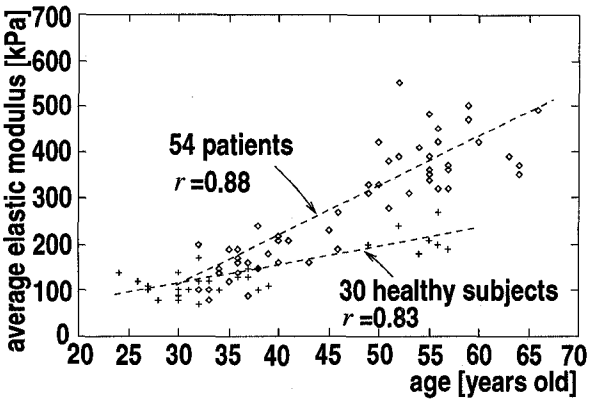

Fig. 7. The average elastic modulus $\bar{E}$ of 54 patients and 30 healthy subjects. Values are mean measured in 3 cardiac cycles.

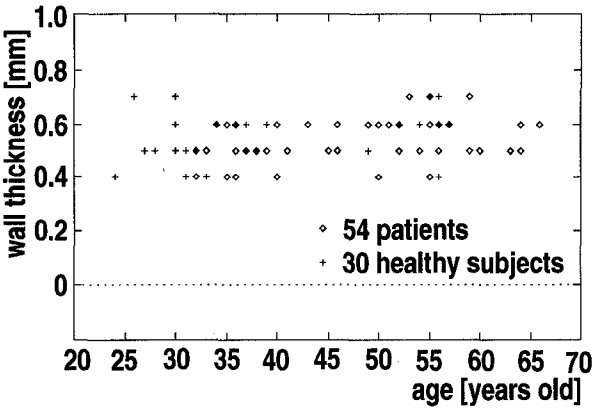

Fig. 8. The arterial wall thickness of 54 patients and 30 healthy subjects.

proposed method, the change in the elasticity can be detected in each local area of a few millimeters even for the subjects who has the arterial wall of normal thickness.

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