Noninvasive Evaluation of Local Elastic Property of Arterial Wall Using Ultrasound

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INTRODUCTION
To quantitatively diagnose atherosclerosis, it is significant to quantitatively evaluate the elastic property of the arterial wall. Moreover, high spatial resolution in axial direction of the artery is required in diagnosis of early stage atherosclerosis because its macular lesion is several millimeters. A major concern in the early diagnosis of atherosclerosis has been, therefore, to develop a noninvasive method for evaluating the elasticity of each local area on the arterial wall.

To evaluate the elasticity of the arterial wall more locally in this letter, the local change in thickness of the arterial wall during one cardiac cycle, which amplitude is several tenth micrometers, is firstly measured by ultrasonic-based method [1]. Such small change in thickness of the arterial wall has not been accurately measured. It is necessary to develop a new parameter for evaluating the elastic property of the arterial wall. In this report, we propose a new parameter for evaluating the elastic property of the arterial wall, and evaluate the relationship between the proposed elastic parameter and the elasticity of the arterial wall. From in vivo experiments, the elastic property of the arterial wall is evaluated in human carotid artery.

PRINCIPLE
To obtain the change in thickness, $\Delta h(t)$, of the arterial wall during one cardiac cycle, small velocity signals, $v_{in}(t)$ and $v_{ad}(t)$, on intima and adventitia are noninvasively measured by the ultrasonic-based method [1] from the skin surface. From the resultant velocity signals, $v_{in}(t)$ and $v_{ad}(t)$, the change in thickness of the arterial wall is obtained by integrating the difference between these two velocity signals as follows:

$$\Delta h(t) = \int_{-\infty}^{t} \{v_{in}(t) - v_{ad}(t)\} dt. \quad (1)$$

From this change in thickness, $\Delta h(t)$, of the arterial wall, the maximum change of strain, $\Delta \epsilon_r$, in radial direction of the artery during one cardiac cycle is given by

$$\Delta \epsilon_r = \frac{\Delta h_s}{h_d}, \quad (2)$$

where $\Delta h_s$ is the maximum amplitude of $\Delta h(t)$ in systole, and $h_d$ is the thickness of the arterial wall at the end-diastole. $\Delta \epsilon_r$ shows the change in strain when the blood pressure increases from the diastole blood pressure $p_d$ to the systole blood pressure $p_s$.

From these change in strain $\Delta \epsilon_r$, we define the following elastic parameter $E$ by

$$E = \frac{p_s - p_d}{\Delta \epsilon_r}. \quad (3)$$

IN VIVO EXPERIMENTAL RESULTS
Figure 1 shows the in vivo experimental results obtained by applying the proposed method to the human carotid artery in a healthy young subject. Figures 1(e) and 1(f) show the velocity signals $v_{in}(t)$ and $v_{ad}(t)$, respectively. Figure 1(g) shows the change in thickness, $\Delta h(t)$, of the anterior wall. It has sufficient reproducibility even for the minute change in thickness, $\Delta h(t)$, with about 10 $\mu$m. Since the systole blood pressure $p_s$ and diastole blood pressure $p_d$ are 118 mmHg and 71 mmHg, the elastic parameter $E$ is determined by 0.77 MPa using Eq. (3). Figure 2 shows the relationship between the elastic parameter $E$ of the arteries and age measured in 8 healthy human subjects. There is a tendency of increasing the elastic parameter $E$ with aging.

DISCUSSION
We consider the relationship between the elastic parameter $E$ and elastic modulus of the arterial wall. In the small region of the arterial wall, when its inner pressure increases from the diastole blood pressure $p_d$ to the systole blood pressure $p_s$, there are changes of strain $\Delta \epsilon_{\theta}, \Delta \epsilon_r, \Delta \epsilon_z$ and changes of stress $\Delta \sigma_{\theta}, \Delta \sigma_r, \Delta \sigma_z$ in circumferential direction, in radial direction, and in axial direction, respectively. Using the incremental Poisson’s ratio $\nu_r$ between circumferential direction and radial direction and the incremental Poisson’s ratio $\nu_{r\theta}$ between axial direction and radial direction, the change of stress $\Delta \sigma_r$ in radial direction is described as follows [2]:

$$\Delta \sigma_r = - \frac{\nu_{r\theta} \Delta \sigma_{\theta}}{E_{\theta}} + \frac{\Delta \sigma_r}{E_r} - \nu_{r\theta} \frac{\Delta \sigma_z}{E_z}, \quad (4)$$

where $E_{\theta}, E_r,$ and $E_z$ are the elastic modulus in circumferential direction, in radial direction, and in axial direction, respectively. By assuming that the artery is a round tube with a thin wall, the changes of stress, $\Delta \sigma_{\theta}$ in circumferential direction, $\Delta \sigma_r$, in radial direction, and $\Delta \sigma_z$ in axial direction are respectively given by [3]

$$\Delta \sigma_{\theta} = \frac{-p_s R}{R} + \frac{p_d R_0}{R_0}, \quad (5)$$

$$\Delta \sigma_r = \frac{p_s}{R} - \frac{p_d}{R_0}, \quad (6)$$

$$\Delta \sigma_z = \frac{p_s}{R_0} - \frac{p_d}{R}, \quad (7)$$
where $R$ and $h$ are radius of the artery and wall thickness at the inner pressure $p_s$, $R_0$ and $h_0$ are radius and wall thickness at the inner pressure $p_d$, and $F$ is the tension in axial direction caused by tethering. In human carotid artery, the change of radius, $(R-R_0)/R_0$, and the change in thickness, $(h-h_0)/h_0$, of the arterial wall are about 1/20 and 1/200, respectively, during one cardiac cycle, we approximate $R$ and $h$ by $R_0$ and $h_0$, respectively. Thus, $\Delta \sigma_\theta$ of Eq. (5) and $\Delta \sigma_z$ of Eq. (7) are approximated by

$$
\Delta \sigma_\theta \approx -(p_s - p_d) \frac{R_0}{h_0},
$$

(8)

$$
\Delta \sigma_z \approx \frac{p_s - p_d R_0}{2 h_0}.
$$

(9)

From Eqs. (3) and (6), the elastic parameter $E$ is given by

$$
E = \frac{p_s - p_d}{\Delta \sigma_\theta} = \frac{p_s - p_d}{-\frac{\nu_\theta \Delta \sigma_\theta}{E_\theta} + \frac{\Delta \sigma_z}{E_z}}
$$

$$
\approx 1 + 2 \nu_\theta \frac{E_\theta}{E_\theta + \frac{\Delta \sigma_\theta}{E_\theta}} - \frac{\nu_\theta \Delta \sigma_\theta}{E_\theta + \frac{\Delta \sigma_\theta}{E_\theta}}.
$$

(10)

By substituting Eqs. (8), and (9) into Eq. (10),

$$
E = \frac{2 \Delta \sigma_z}{1 + 2 \nu_\theta \frac{E_\theta}{E_\theta + \frac{\Delta \sigma_\theta}{E_\theta}} - \frac{\nu_\theta \Delta \sigma_\theta}{E_\theta + \frac{\Delta \sigma_\theta}{E_\theta}}}
$$

(11)

From in vitro experiments of the canine aorta based on the three constant theory [4], $\nu_\theta, E_\theta, E_r, E_z$ and their values are about 0.40, 0.60, 0.663 $\times 10^6$ dyn/cm$^2$, 0.433 $\times 10^6$ dyn/cm$^2$, and 0.512 $\times 10^6$ dyn/cm$^2$, respectively. Thus, $\nu_\theta E_r/E_\theta$ and $\nu_\theta E_z/E_\theta$ are 0.26 and 0.50. From these values, we can approximately describe the terms $\nu_\theta E_r/E_\theta$ and $\nu_\theta E_z/E_\theta$ by the constant $\alpha$ and $2\alpha$, respectively, where $\alpha = 0.25$. From these approximations, $E$ of Eq. (11) is approximated by

$$
E \approx \frac{2 \Delta \sigma_z}{1 + 4 \alpha \frac{E_\theta}{E_\theta + \frac{\Delta \sigma_\theta}{E_\theta}}} \approx \frac{2 \Delta \sigma_z}{1 + \frac{4 \alpha}{1 - \frac{\Delta \sigma_\theta}{E_\theta}}},
$$

(12)

This equation shows the relationship between the elastic parameter $E$ obtained by the proposed measurement method and the elasticity of the arterial wall.

CONCLUSIONS

In this report, the change in thickness, $\Delta h(t)$, of the arterial wall is accurately and noninvasively obtained using ultrasound. The minute change of several micrometers in thickness is measured with sufficient reproducibility. From in vivo experimental results with respect to the human carotid artery of 8 normal subjects aged from 30 to 70, the elastic parameter $E$ is evaluated. There is a tendency of increasing the elastic parameter $E$ with aging. The spatial resolution in axial direction of the artery achieved by the proposed method is a few millimeters, which is sufficient for diagnosis of the fibrous spots on the arterial wall in the early stage of atherosclerosis. Therefore, the proposed method has a potential for evaluation of local elasticity of the arterial wall.

REFERENCES


