Non-invasive evaluation of Poisson's ratio of arterial wall using ultrasound

H. Hasegawa, H. Kanai, N. Chubachi and Y. Koiwa

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A new method for non-invasively evaluating the Poisson ratio of an arterial wall using ultrasound is presented.

Introduction: In the early stage of atherosclerosis, fibrous spots several millimetres in diameter are scattered on the surface of the artery. After growth of these spots, the arterial wall becomes homogeneously hard in the final stage of atherosclerosis. A major concern in the early diagnosis of atherosclerosis has been, therefore, to develop a non-invasive method for evaluating the elasticity of each local area on the arterial wall.

In this Letter, velocity signals on the surface of the intima and adventitia are simultaneously measured and any change in the thickness of the arterial wall is accurately obtained by integrating the difference between these two velocity signals. Similarly, small velocity signals on the surface of the anterior and the posterior wall are simultaneously measured and a change in the diameter of the lumen is obtained by integrating the difference between these signals. Based on these changes in thickness and diameter, the Poisson ratio of the wall is evaluated. From *in vivo* experiments, the Poisson ratio is obtained for human carotid artery and abdominal aorta.

Principle: Small velocity signals, $v_{IN}(t)$ and $v_{AD}(t)$, on the intima and adventitia of the arterial wall are accurately measured using ultrasound by the following procedure [1]. RF pulses with angular frequency, $\omega_0 = 2\pi f_0$, are transmitted at a time interval of ΔT from an ultrasonic transducer on the skin surface. Defining the acoustic velocity as c_0, the instantaneous distance of an object on the arterial wall from the ultrasonic transducer is denoted by $x(t) = c_0 \cdot \tau(t)$, where $\tau(t)$ is the instantaneous period required for one-way transmission from the ultrasonic transducer to the object. The ultrasonic pulse reflected by the object is received by the same ultrasonic transducer and is amplified. Applying quadrature demodulation to the signal, the resultant in-phase and quadrature signals are simultaneously A/D converted and then separated into the response signals $\{y(x; t)\}$ for each transmitted pulse, where x denotes the distance of the object from the ultrasonic transducer.

The phase $\theta(x; t)$ of the resultant sectional complex signal $y(x; t)$ is given by ω_0 multiplied by twice the delay time $\tau(t)$:

$$\theta(x;t) = 2\omega_0\tau(t) = 2\omega_0\frac{x(t)}{c_0}$$

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

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

where $\Delta x(t) = x(t + \Delta T) - x(t)$ is the displacement of the object in the period ΔT at a time t. By dividing the displacement Δx by the period ΔT, the average velocity, denoted by $v(t + \Delta T/2)$, of the object during the period ΔT is given by the phase difference $\Delta\theta(x; t)$:

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

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

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

The minimum value of the measurable vibration velocity is 0.5mm/s and the time interval T_0 of integration equals 222μs. Thus, by multiplying these two values, the lowest value of the change in thickness is found to be ~0.1μm.

Similarly, small velocity signals $v_{IN}(t) = v_A(t)$ on the anterior wall and $v_P(t)$ on the posterior wall of the artery are simultaneously measured and the change in inner diameter, $\Delta d(t)$, of the blood vessel with amplitudes of several hundred micrometres is also obtained by integrating the difference between these two velocity signals:

$$\Delta d(t) = \int_{-\infty}^{t}\{v_p(t) - v_a(t)\}dt \quad (4)$$

The amplitude of the change in thickness, $\Delta h(t)$, of the arterial wall is <100μm and $\Delta h(t)$ varies in time. Thus, such minute changes in thickness cannot be measured by the B-mode or M-mode images obtained in standard ultrasonic diagnostic equipment. From $\Delta h(t)$ and $\Delta d(t)$, the strain in radial direction, $\epsilon_H(t)$, and the strain in circumferential direction, $\epsilon_D(t)$, are defined by

$$\epsilon_h(t) = \frac{\Delta h(t)}{h_d} \quad (5)$$

$$\epsilon_d(t) = \frac{\pi\Delta d(t)}{\pi d_d} = \frac{\Delta d(t)}{d_d} \quad (6)$$

where h_D and d_D are the arterial wall thickness and arterial diameter at the end of diastole, respectively.

From these two values, the Poisson ratio $\sigma(t)$ is given by

$$\sigma(t) = \frac{\epsilon_h(t)}{\epsilon_d(t)} = \frac{\Delta h(t)}{\Delta d(t)}\frac{d_d}{h_d} \quad (7)$$

which shows the instantaneous Poisson ratio. In this Letter, however, the following average Poisson ratio σ_0 during one cardiac cycle is evaluated:

$$\sigma_0 = \frac{\epsilon_h(t_s)}{\epsilon_d(t_s)} = \frac{\Delta h(t_s)}{\Delta d(t_s)}\frac{d_d}{h_d} \quad (8)$$

where t_s is the instant when the blood pressure becomes maximum during systole.

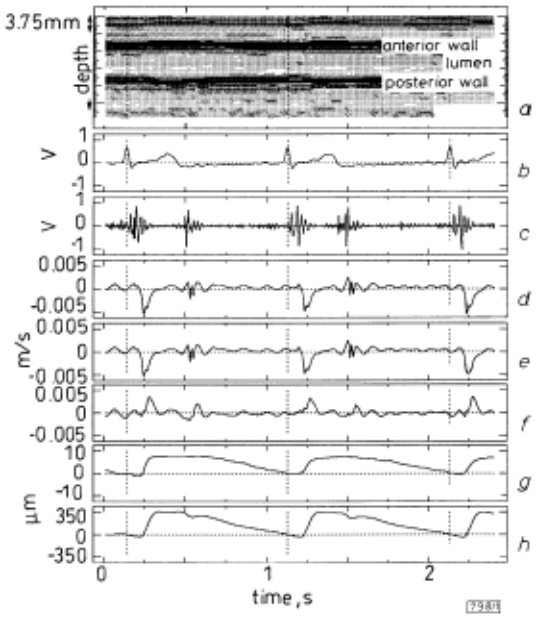

Fig. 1 *Vibration signals measured in human carotid artery of normal young subject*

a M-mode
b ECG
c PCG
d Small velocity signal $v_{IN}(t) = v_A(t)$ on intima
e Small velocity signal $v_{AD}(t)$ on adventitia
f Small velocity signal $v_P(t)$ on posterior wall
g Change in thickness, $\Delta h(t)$, of anterior wall
h Change in diameter, $\Delta d(t)$, of lumen

In vivo experimental results: Fig. 1 shows the *in vivo* experimental results obtained by applying the proposed method to the human carotid artery in a normal young subject. Figs. 1*d*, *e*, and *f* show the velocity signals $v_{IN}(t) = v_A(t)$, $v_{AD}(t)$, and $v_P(t)$, respectively. Figs. 1*g* and *h* show the change in thickness, $\Delta h(t)$, of the anterior wall and

the change in diameter, $\Delta d(t)$, of the lumen. Each signal has sufficient reproducibility even for the minute change in thickness, $\Delta h(t)$, with 10μm. Fig. 2 shows the relationship between the strain $\epsilon_H(t)$ in the radial direction and the strain $\epsilon_D(t)$ in the circumferential direction. The average Poisson's ratio σ_0, which is the gradient of the dashed line in Fig. 2, is 0.12.

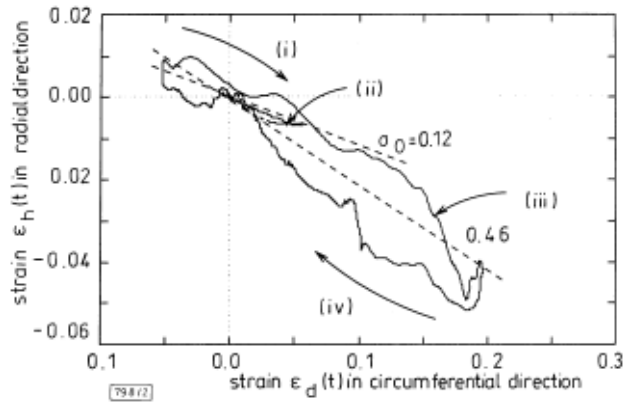

Fig. 2 *Relationship between strain, $\epsilon_H(t)$, in radial direction and strain, $\epsilon_D(t)$, in circumferential direction for carotid artery and abdominal aorta of same normal young subject*

Gradient of each trajectory shows average Poisson's ratio σ_0
(i) systole
(ii) carotid artery
(iii) abdominal aorta
(iv) diastole

Similarly, the proposed method is applied to the human abdominal aorta, and the change in thickuess, $\Delta h(t)$, of the anterior wall and the change in diameter, $\Delta d(t)$, of the lumen are obtained. The relationship between the strain $\epsilon_H(t)$ in radial direction and the strain $\epsilon_D(t)$ in circumferential direction is shown in Fig. 2 and the average Poisson's ratio, σ_0, is determined to be 0.46. These results show the variation of the average Poisson ratio, σ_0, of the two types of arteries.

Measurement of the change in thickness, $\Delta h(t)$, of the arterial wall and the change in diameter, $\Delta d(t)$, of the lumen is effective for two reasons. (i) These values are measured with high spatial resolution (in the axial direction of the artery) of the focal area of the ultrasonic beam. (ii) Since the spatial resolution in the depth direction of the ultrasonic beam is also high, the change in thickness of the intima, media, and adventitia can be separately measured.

Conclusions: In this Letter, the change in thickness, $\Delta h(t)$, of the arterial wall and the change in diameter, $\Delta d(t)$, of the blood vessel are accurately and non-invasively obtained using ultrasound. The minute change of several micrometres in thickness is measured with sufficient reproducibility. From *in vivo* experimental results with respect to the human carotid artery and the human abdominal aorta of the same normal young subject, there is variation of the average Poisson's ratio, σ_0, of the two types of arteries. A spatial resolution of several millimetres is achieved by the proposed method which is sufficient for diagnosis of the fibrous spots on the arterial wall in the early stage of atherosclerosis. Therefore, the proposed method has potential for the evaluation of local elasticity of the arterial wall.

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H. Hasegawa, H. Kanai and N. Chubachi (*Department of Electrical Engineering, Faculty of Engineering, Tohoku University, Sendai 980-77, Japan*)

Y. Koiwa (*First Department of Internal Medicine, Tohoku University, School of Medicine, Sendai 980-77, Japan*)

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