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# Accurate Measurement of Transient Change in Viscoelasticity of Radial Arterial Wall for Evaluation of Endothelial Function

内皮機能評価のための橈骨動脈壁粘弾性特性変化の高精度計測

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## 1. Introduction

The endothelial dysfunction is considered to be an initial step of atherosclerosis[1)]. Additionally, it is reported that the smooth muscle, which constructs the media of the artery, changes its characteristics owing to atherosclerosis[2)]. Consequently, it is important for early preventive treatment to noninvasively assess the endothelial function and the mechanical property of the media which is mainly composed of smooth muscle.

For the evaluation of the endothelial function and mechanical property of the media, we have proposed a new noninvasive method for measurement of the change in the stress-strain relationship caused by flow-mediated dilation (FMD) after the release of avascularization[3,4)]. Additionally, from the stress-strain relationship, the viscoelasticity of the intima-media region has been estimated using the least-square method to investigate the transient change in the viscoelasticity due to FMD[5)].

In this study, we improved the accuracy of the method of estimating viscoelasticity by filtering of the strain rate of the arterial wall, and the transient change in the viscoelasticity due to FMD was also measured.

## 2. Principles

### 2.1 Measurement of stress-strain relationship of the intima-media region in the arterial wall

To noninvasively assess the stress-strain relationship of the intima-media region of the radial arterial wall, it is necessary to measure waveforms of the change in thickness (strain) and the blood pressure (stress) continuously. The boundaries of the arterial wall were detected by the automatic and objective method using template matching[6)], and the minute change in the thickness of the radial arterial wall, $h(t)$, at time $t$ during a cardiac cycle was measured by the *phased-tracking method*[7)].

The blood pressure waveform $p(t)$ was simultaneously and continuously measured by a sphygmometer which automatically optimizes the position of the sensor for blood pressure measurement. Therefore, we could obtain the stress-strain relationship noninvasively.

### 2.2 Estimation of viscoelasticity of arterial wall using least-square method

The smooth muscle constructs the media and it is the main source of the viscoelasticity of the vessel wall[8)]. By assuming the Voigt model as a viscoelastic model of the intima-media region, the stress-strain relationship is modeled by

$$\hat{\tau}(t) = E_s \gamma(t) + \eta \dot{\gamma}(t) + \tau_0, \qquad (1)$$

where $\hat{\tau}(t)$ is the model stress and $\gamma(t)$, $\dot{\gamma}(t)$, $E_s$, and $\eta$ are strain, strain rate, static elasticity, and viscosity coefficient, respectively. The measured strain $\gamma(t)$ is the incremental strain due to the pulse pressure, whereas the measured stress includes the bias stress (diastolic blood pressure). Therefore, $\tau_0$ is added to the right-hand side of eq. (1) as the bias stress corresponding to diastolic pressure.

In this study, the strain rate was filtered for decreasing the high-frequency noise caused by the differentiation of the strain. **Figures 1(a)** and **1(b)** show a waveform and spectrum of strain rate of the arterial wall with and without filtering. Therefore, the eq. (1) was rewritten by

$$\hat{\tau}_{\mathrm{LPF}}(t) = E_s \gamma(t) + \eta \cdot \mathrm{LPF}[\dot{\gamma}(t)] + \tau_0. \qquad (2)$$

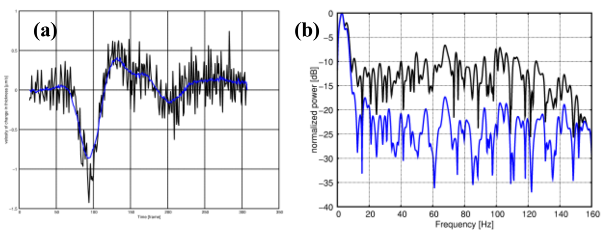


Fig. 1 (a) Waveform and (b) power spectrum of strain rate of the arterial wall (with (blue) and without (black) filtering).

The parameters in eq. (2), $E_s$, $\eta$, and $\tau_0$ , were estimated using the least-square method by minimizing the normalized mean squared error (MSE), $\alpha$, between the measured and model stresses $\tau(t)$ and $\hat{\tau}_{\mathrm{LPF}}(t)$, and the cutoff frequency of the low-pass filter (LPF), $f_c$, which gave minimum MSE, was adapted.

### 2.3 Procedure for *in vivo* measurement

In this study, the right radial artery of a healthy subject was measured. In the measurement

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of the radial artery, ultrasonic RF echoes (transmit: 22 MHz) were acquired at a sampling frequency of 66.5 MHz for 2 s. This acquisition was repeated at every 20 s for 2 minutes at rest before avascularization and every 12 s for 3 minutes after recirculation. At the same time, the waveform of blood pressure on the left radial artery was continuously measured with a sphygmometer. We applied this method to a healthy subject and evaluate the effect of filtering.

## 3. Results

**Figure 2** shows the measured and estimated stress-strain relationship of the radial arterial wall. The red line shows the measured hysteresis loop (reference). The black and blue lines in **Fig. 2** show the estimated loops without and with filtering, respectively. The normalized MSE was decreased from 10.1% to 1.1% by filtering ($f_c$ = 12.3 Hz). Additionally, the inner small loop which corresponds to the reflection from peripheral artery, can be observed using the adaptive LPF.

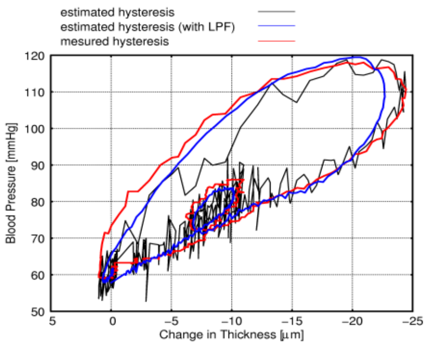


Fig. 2 Measured and estimated stress-strain relationships of the radial arterial wall.

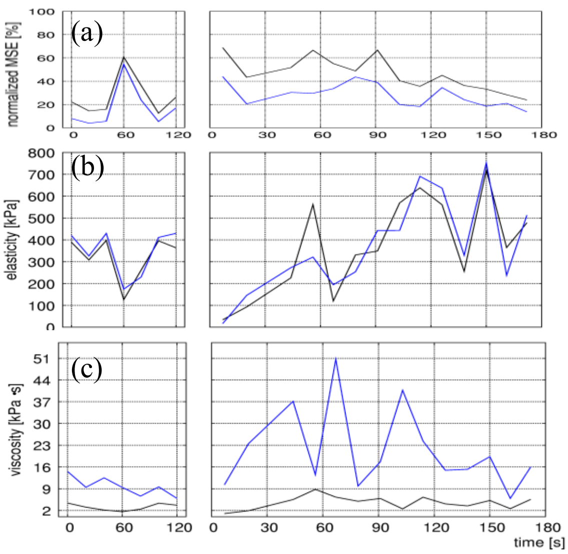


Fig. 3 Transient changes in (a) normalized MSE, (b) static elasticity, and (c) viscosity, with and without filtering (blue and black lines, respectively).

The blue and black lines in **Figs. 3(a), 3(b) and 3(c)** respectively show the transient change in the normalized MSE, static elasticity, and viscosity with and without filtering. The static elasticity have little difference between estimations with and without LPF, and the temporal decrease after avascularization can be observed, as in our previous study[5, 6]. In contrast, the viscosities have large difference because of the filter applied to the strain rate. Additionally, the fluctuation of the transient change in the viscosity becomes larger. However, the change in viscosities decreased the difference between the shapes of hysteresis loop and the normalized MSE.

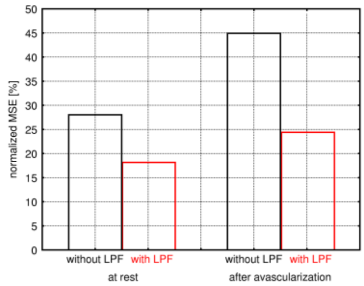


Fig. 4 Averaged normalized MSE before and after avascularization.

**Figure 4** shows the averaged normalized MSE before and after avascularization. The error was decreased about 9.9% at rest and 20.6% after avascularization. These results showed a potential for the improvement of accuracy of the viscoelasticity estimation by filtering of the measured strain rate of the arterial wall.

## 4. Conclusion

As described above, there are some aspects of this study that should be further investigated. However, the filtering of the strain rate yielded the smaller error and the shape of hysteresis became similar. Therefore, these results showed the potential of the proposed method for the improvement of the accuracy of viscoelasticity estimation for the diagnosis of early stage atherosclerosis.

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