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Accurate measurement of blood pressure by pulse transit time method for estimating of viscoelastic properties of radial artery with a single ultrasound probe

単一プローブによる橈骨動脈粘弾性推定のためのパルス伝播時間法による高精度血圧計測

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1. Introduction

Evaluation of vascular endothelial function is important for a very early diagnosis of arteriosclerosis. We developed an ultrasound probe that can simultaneously measure blood pressure and blood vessel diameter at the same position [1], and measured changes in viscoelastic properties during flow-mediated dilation (FMD) [2]. Calibration of the blood pressure waveforms is needed in advance in this method, and the obtained calibration coefficients are applied to the subsequent measurements. However, the difference of the pushing pressures of the ultrasonic probe to the artery and/or the body movements during the measurements affected the acquired waveforms and caused the large variation of the obtained blood pressures. To solve this problem, we applied the pulse transit time (PTT) method [3], which can determine the systolic and diastolic blood pressure values regardless of the absolute values of the acquired voltages, to the measured blood pressure waveforms.

2. Method

Since the blood pressure waveform measured by the developed ultrasonic probe [1] is output as voltage values, it is necessary to calibrate them to the blood pressure values. Letting us express the maximum and minimum values of $p(t)$ per measurement by p_{max} and p_{min}, respectively, the calibrated blood pressure $\widehat{p(t)}$ is given by

$$\widehat{p(t)} = \frac{p_{\mathrm{sys}} - p_{\mathrm{dias}}}{p_{\mathrm{max}} - p_{\mathrm{min}}}\{p(t) - p_{\mathrm{min}}\} + p_{\mathrm{dias}}. \quad (1)$$

In the conventional method, this calibration was applied in advance, and only $p(t)$ was used as a variable in subsequent measurements. In the present study, systolic and diastolic blood pressures, p_{sys} and p_{dias}, were also estimated using the PTT method for calibration at each heartbeat. In the PTT method, p_{sys} and p_{dias} are expressed by Eqs. (2) and (3) [3].

$$p_{\mathrm{dias}} = \frac{p_{\mathrm{sys}_0}}{3} + \frac{2p_{\mathrm{dias}_0}}{3} + \mathrm{A} \cdot \ln\left(\frac{t_{\mathrm{PT0}}}{t_{\mathrm{PT}}}\right) - \frac{p_{\mathrm{sys}_0} - p_{\mathrm{dias}_0}}{3}\,\frac{t_{\mathrm{PT0}}^2}{t_{\mathrm{PT}}^2} \quad (2)$$

$$p_{\mathrm{sys}} = p_{\mathrm{dias}} + \left(p_{\mathrm{sys}_0} - p_{\mathrm{dias}_0}\right)\frac{t_{\mathrm{PT0}}^2}{t_{\mathrm{PT}}^2}, \quad (3)$$

where t_{PT} is the pulse transit time from the R-wave of the electrocardiogram (ECG) to the peak of the blood pressure waveform and t_{PT_0} is set as t_{PT} at the first measurement, and p_{sys_0} and p_{dias_0} are p_{sys} and p_{dias} measured by a sphygmomanometer, respectively.

3. Experiment

Figure 1 shows a block diagram of the experimental system. The subject was a 22-year-old healthy male, and an FMD test was performed on the right upper arm using the FMD diagnosis apparatus (UNEX EF 38G, UNEX). At the same time, the vessel diameter and the blood pressure waveform were simultaneously measured at the same position in the right-hand radial artery with the developed linear array ultrasound probe [1]. The probe was connected to an ultrasound system (Prosound F75, Aloka). ECG was also measured. The sampling frequency and frame rate were set to 7.5 MHz and 252 Hz, respectively.

The pressure waveforms acquired by the ultrasonic probe were passed through an amplifier with a voltage amplification factor of 40 dB and a low-pass filter with a cut-off frequency of 30 Hz before being input to the ultrasound diagnostic system. The position of the blood pressure waveform was set so that the center of the ultrasound probe was located above the radial artery while confirming the B-mode image.

The blood pressure waveforms were calibrated at each heartbeat by substituting p_{sys} and p_{dias} estimated by Eqs. (2) and (3). First, blood pressure waveforms and vessel diameters were measured every 30 seconds for 5 minutes at rest before avascularization. Then, the radial artery was subjected to avascularization by pressurizing to the pressure 50 mmHg higher than the systolic blood pressure by a cuff attached to the right forearm for 5 minutes. The blood pressure waveforms and vessel diameters were measured every 15 seconds for 5 minutes after the recirculation, as well as at rest.

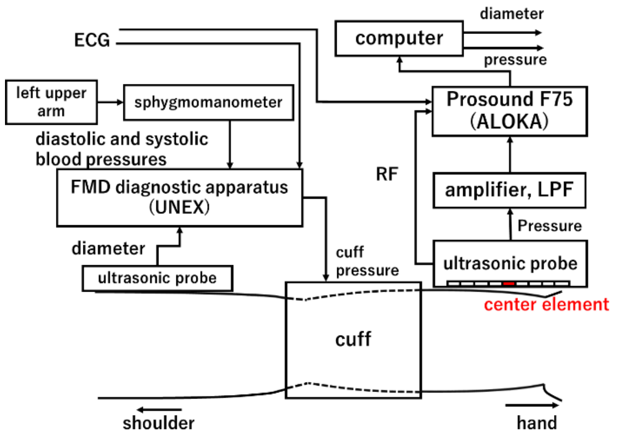


Fig. 1. Schematic diagram of the experimental system.

4. Result and Discussion

Figure 2 shows the change in the relationships between blood pressures and vessel diameters during the FMD. The measurement results before avascularization are shown with black lines, and those after recirculation are shown with the color according to the color bar shown on the right side of the figure corresponding to the elapsed time after recirculation. The diameter of the vessels gradually increased from immediately after recirculation to around 200 seconds, then it decreased. This result shows that the FMD reaction occurred. However, the diameter of the vessels varied by 0.2 mm even at rest before avascularization. This variation was caused by the difference in pressures by the ultrasound probe to the artery among the measurements and the change in the vessel position by minute body movements due to the breath.

Figure 3 shows the changes in the PTTs during the FMD. The PTT increased after recirculation and approached to the resting value with time. However, the PTT highly varied even at rest and did not change smoothly after the recirculation. Because PTT is the time difference between the R-wave of the ECG and the peak of the blood pressure waveform, the accuracy is greatly affected by the ECG waveform. In the present study, saturations of the ECG waveforms were observed around the R-wave of the ECG, and it might affect the PTT measurements and result in uneven values.

Figure 4 shows the changes in systolic and diastolic blood pressures. The systolic blood pressure decreased between 200 and 300 seconds after the recirculation in the conventional method, whereas it increased over time in the PTT method. After the recirculation, the blood pressure value should approach to the resting value as the FMD was completed. Therefore, the estimation accuracy by the proposed method was improved compared to the conventional method. The diastolic blood pressure was small immediately after the recirculation, and gradually approached to the value before avascularization. It is necessary to verify the accuracy of blood pressure measurement by comparing it with other blood pressure measurements during FMD to estimate the viscoelasticity of the vessel wall.

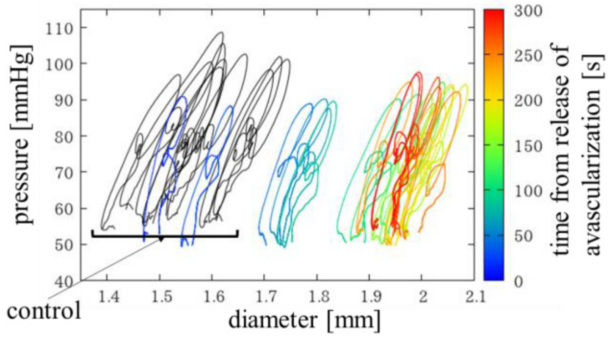
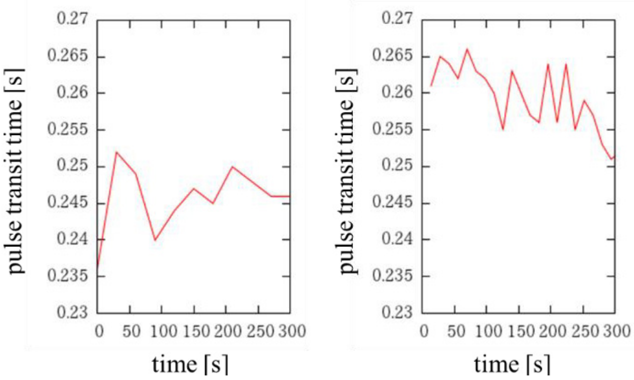
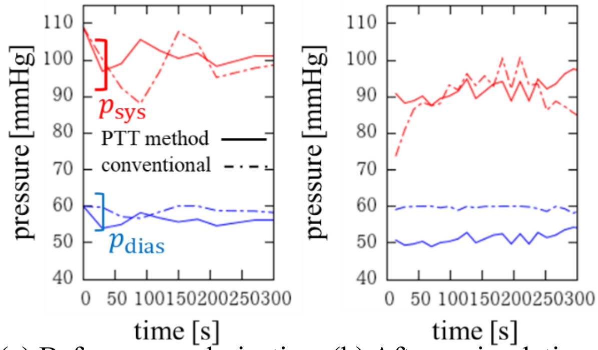


Fig. 2. Change in the relationships between blood pressure and diameter for 5 minites during FMD.



(a) Before avascularization. (b) After recirculation.
Fig. 3. Changes in the PTTs during FMD.



(a) Before avascularization. (b) After recirculation.
Fig. 4. Changes of systolic and diastolic blood pressures during FMD.

5. Conclusion

In the present study, the introduction of the PTT method to measure the viscoelastic properties of the radial artery wall during FMD with a single ultrasound probe was investigated. From now, we will verify the accuracy of blood pressure measurement using the PTT method and aim at the accurate measurement of viscoelasticity in the FMD.

Acknowledgment

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