1P5-14

Calibration-free estimation of pressure and elastic modulus of radial artery using ultrasound and photoplethysmography

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1. Introduction

Atherosclerosis is a major cause of cardiovascular diseases such as ischemic heart disease and stroke.[1)] The elastic modulus of the vessel wall changes significantly with the progression of atherosclerosis.[2)] We have been studying an ultrasonic method for measuring the elastic modulus of the vessel wall for early diagnosis of atherosclerosis.[3)] In this method, blood pressure must be obtained with a sphygmomanometer immediately before ultrasonic measurement. However, pulse pressure can vary by as much as 9% mainly owing to respiration,[4)] causing a 20% to 30% error in the measured elastic modulus. For a more accurate estimation of the elastic modulus, it is necessary to measure the pulse pressure simultaneously with strain measurement of the vessel wall. Therefore, we investigated a method to estimate the pressure and elastic modulus of the radial artery without calibration using a sphygmomanometer by measuring the pulse wave velocity using photoelectric sensors at the same time as measuring the vessel diameter with ultrasound.

2. Principle and method

2.1 Blood pressure estimation method

A blood pressure measurement method using pulse wave velocity and vessel diameter has been reported.[5)] Considering the nonlinearity of the elasticity of the vessel wall, the relationship between the blood pressure $P(t)$ and vessel diameter $D(t)$ can be expressed as follows:[5)]

$$P(t) = P_{\mathrm{d}} \exp\left(\beta\left(\frac{D(t) - D_{\mathrm{d}}}{D_{\mathrm{d}}}\right)\right), \tag{1}$$

where P_{d} is the diastolic blood pressure, β is the stiffness parameter, and D_{d} is the vessel diameter at the diastolic blood pressure. Differentiating Eq. (1) by the vessel diameter $D(t)$ and substituting $dP(t)/dA(t)$ for $dP(t)/dD(t)$ using the vessel cross-sectional area $A(t)(=\pi D(t)^2/4)$, Eq. (2) can be obtained as:

$$\frac{dP(t)}{dA(t)} = \frac{2\beta P(t)}{\pi D_{\mathrm{d}} D(t)}. \tag{2}$$

The relationship among $A(t)$, $P(t)$ and pulse wave velocity $c(t) = \left(\left(A(t)/\rho\right)\left(dP(t)/dA(t)\right)\right)^{1/2}$ is expressed as follows.[6)]

$$c(t)^2 = \frac{A(t)}{\rho}\frac{dP(t)}{dA(t)} = \frac{\beta P(t) D(t)}{2\rho D_{\mathrm{d}}} \tag{3}$$

where ρ is the density of blood. From Eq. (3), the systolic and diastolic blood pressures, P_{s} and P_{d}, were respectively obtained as follows:

$$P_{\mathrm{s}} = \frac{2\rho c_{\mathrm{s}}^2 D_{\mathrm{d}}}{\beta D_{\mathrm{s}}}, \tag{4}$$

$$P_{\mathrm{d}} = \frac{2\rho c_{\mathrm{d}}^2}{\beta}, \tag{5}$$

where c_{s} and D_{s} are the pulse wave velocity and vessel diameter at systolic pressure, respectively, and c_{d} and D_{d} are those at diastolic pressure. Substituting Eqs. (4) and (5) into Eq. (1) at systole, Eq. (6) can be obtained as follow:

$$\beta = \frac{\ln\left(\dfrac{c_{\mathrm{s}}^2 D_{\mathrm{d}}}{c_{\mathrm{d}}^2 D_{\mathrm{s}}}\right)}{\dfrac{D_{\mathrm{s}}}{D_{\mathrm{d}}} - 1}, \tag{6}$$

where P_{s} and P_{d} can be obtained using the vessel diameters D_{s} and D_{d} and pulse wave velocities c_{s} and c_{d}.

2.2 Elasticity estimation method

The elastic modulus of the vessel wall, E, is expressed as follows:[3)]

$$E = \frac{3}{8}\left(1 + \frac{2r_0}{h_0}\right)\frac{\Delta P}{-\Delta h/h_0}, \tag{7}$$

where r_0 and h_0 are the radius and thickness of the vessel wall at diastolic pressure, respectively, ΔP is the pulse pressure, and Δh is the thickness change of the vessel wall within a heartbeat.

3. Experiment

Fig. 1 shows the schematic of an in vivo experimental system. The subject was a healthy male in his 20's. An ultrasound diagnosis apparatus (ALOKA Prosound-F75) attached with the developed linear array ultrasound probe[7)] was used for ultrasound measurement. The transmission

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frequency, sampling frequency, and frame rate were set to 7.5 MHz, 40 MHz, and 252 Hz, respectively. Two photoplethysmography (PPG) sensors (SWITCH SCIENCE PULSE02) were placed at the elbow fossa and wrist, where the radial artery is close to the skin, to measure the photoelectric volume pulse wave. The pulse transit time between the two PPG sensors was measured and the pulse wave velocity $c(t)$ was obtained by dividing the distance between the sensors by the pulse transit time. The positions of the anterior and posterior vessel walls on the ultrasound beam passing through the center of the vessel at diastolic pressure were determined from B-mode images. The vessel diameter $D(t)$ during one heartbeat was then determined from the distance between the anterior and posterior walls using the phased-tracking method.[8] The pulse wave velocity $c(t)$ and vessel diameter $D(t)$ were measured simultaneously at two different times. Systolic blood pressure P_{s} and diastolic blood pressure P_{d} were estimated from the vessel diameter $D(t)$ and pulse wave velocity $c(t)$ using Eqs. (4)-(6). The elastic modulus E was estimated from Eq. (7) using P_{s} and P_{d} and the strain of the vessel wall obtained from ultrasonic measurement.

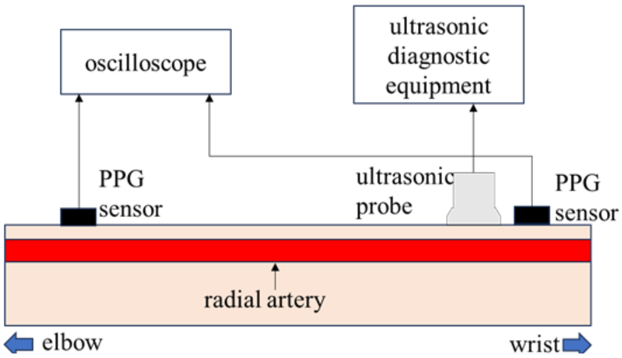

Fig. 1. Schematic of an in vivo experimental system.

4. Result and Discussion

Fig. 2 shows the photoplethysmogram waveforms and B-mode image of the first measurement. The systolic blood pressure, diastolic blood pressure, and elastic modulus E were estimated to be 118 mmHg, 61 mmHg, and 339 kPa, respectively, for the first measurement and 115 mmHg, 59 mmHg, and 311 kPa, respectively, for the second measurement. Systolic and diastolic blood pressures were 109 mmHg and 68 mmHg, respectively, measured with a sphygmomanometer immediately before the measurement; thus blood pressures were obtained only from $D(t)$ and $C(t)$ without a sphygmomanometer. The elastic modulus of the human radial artery was also measured using this method.

5. Conclusion

In this study, the blood pressure and elastic modulus of the radial artery were estimated using ultrasound and photoplethysmography measurements without calibration with a sphygmomanometer. In the future, we will measure the viscoelastic properties of the arterial wall by considering the deformation of the arterial cross-section caused by the pushing pressure by the probe during the blood pressure waveform measurement.

Acknowledgment

This work was partially supported by JSPS KAKENHI 24K03297 and AMED Translational Research Strategic Promotion Program H-55.

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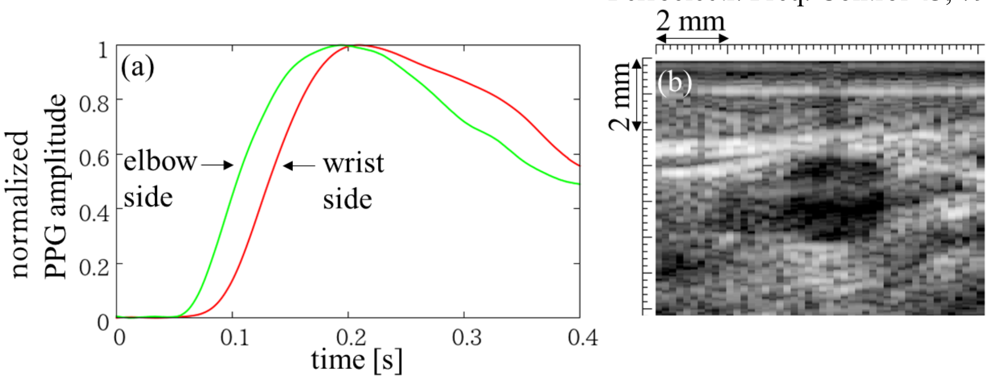

Fig. 2. (a) Photoelectric pulse waveform and (b) B-mode image of the first measurement.