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# Estimation of arterial stiffness by time-frequency analysis of pulse wave
## 脈波の時間周波数解析による血管硬化度の評価

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## 1. Introduction

The increase of arterial stiffness leads to cardiovascular disease or stroke. Therefore, diagnosis of elasticity of blood vessel is effective for reducing the incidence of these diseases [1].

We have then investigated the profile of the pulse wave, which corresponds to the displacement of the skin surface, for estimating arterial stiffness. The pulse wave is composed of incident and reflected waves. Because attenuation of the reflected wave changes markedly owing to arterial stiffness, the estimation of arterial stiffness becomes possible by analyzing the reflected wave. In this study, we tried to analyze this reflected component by the time-frequency analysis using continuous wavelet transform.

## 2. Continuous Wavelet Transform Analysis

Continuous Wavelet Transform (CWT) is a mathematical tool that analyzes signals in terms of scale and position. The CWT is defined as:

$$W_f(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)(t)dt \qquad (1)$$

where $f(t)$ is the original signal, $\psi^*_{a,b}(t)$ denotes the complex conjugate of the analyzing wavelet $\psi_{a,b}(t)$. The terms $a$ and $b$ are scale and shift parameters, which correspond to the reciprocal of the center frequency and time, respectively [2]. The original signal is analyzed by various profiles of analyzing wavelet owing to these parameters. In this study, we focused on the Morlet wavelet:

$$\psi(t)=\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{t^2}{2\sigma^2}}e^{j\pi t} \qquad (2)$$

where the term σ is the parameter for the window width. For unsteady signal analysis, the Morlet wavelet with short pulse width is necessary. Here, we adopted the optimum value $\sigma = 0.45$ which was suitable for analyzing the pulse waveform.

## 3. Experiments

The experimental subjects were 22 healthy men in their twenties to sixties. None of the subjects had a previous history of cardiovascular disease or was taking vasoactive agents. All subjects provided written informed consent for the measurement.

We measured electrocardiogram (ECG) and pulse wave at one point on carotid artery simultaneously. We began measurements with the subject in the resting state, two hours after eating, exercising, smoking and the subject lay down in the supine position for 15 min in a quiet room at 25°C. ECG signal was used as a trigger to synchronize the data. To measure the pulse wave, we used a customized piezoelectric transducer (Murata). The resonant frequency of the sensor was 40 kHz. The observed signal was amplified to 40 dB by a preamplifier (NF 5307) and digitized by an analog-to-digital converter (Keyence NR-500, NR-HA08). Here the measured pulse wave corresponded to the velocity waveform of the skin because of the characteristics of the sensor and the system [3].

## 4. Results and Discussion

**Figures 1** and **2** show examples of (a) measured velocity waveform of pulse wave and (b) the displacement waveform after integration. Amplitudes of waves are normalized. In previous study, we confirmed that main reflected waves are superposed on sites as shown in Figs. 1(b) and 2(b) [3]. Thus 2nd negative peak of Figs. 1(a) and 2(a) are caused by the reflected waves. In this study, we paid attention to the velocity waveform because the reflected component of the wave was clear compared with that of the displacement waveform. **Figures 3** and **4** show the results of wavelet transform of the waveform in Figs. 1(a) and 2(a). The contour lines in the scalogram show change of the absolute values of the wavelet coefficient. The amplitude around the reflected wave from the older

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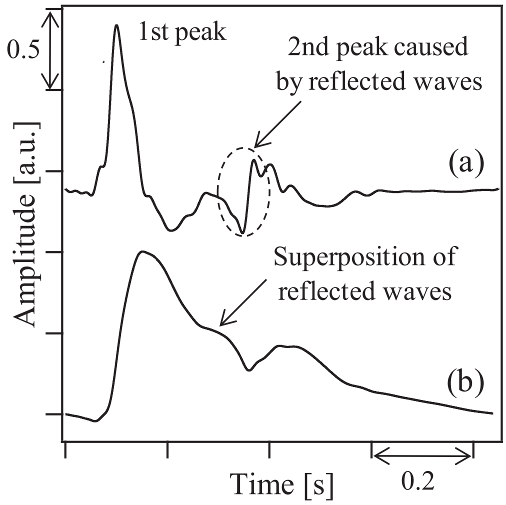

Fig. 1 Pulse waves in his 20s: (a) Measured velocity waveform and (b) the displacement waveform.

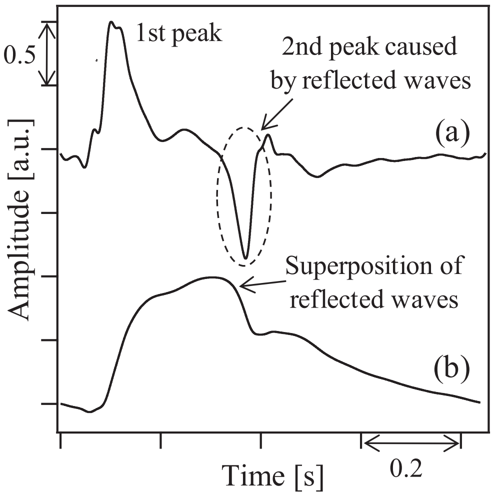

Fig. 2 Pulse waves in his 60s: (a) Measured velocity waveform and (b) the displacement waveform.

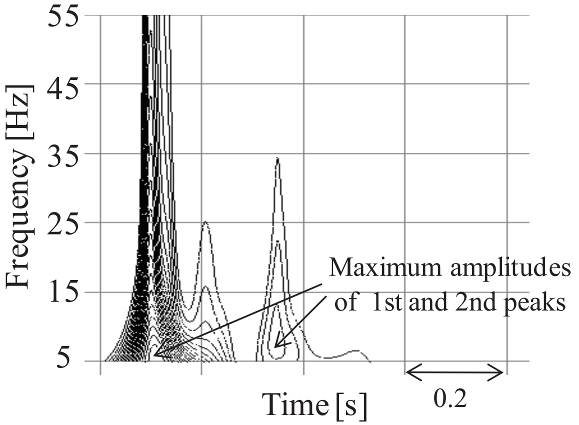

Fig. 3 Scaloglam of Measured wave in his 20s.

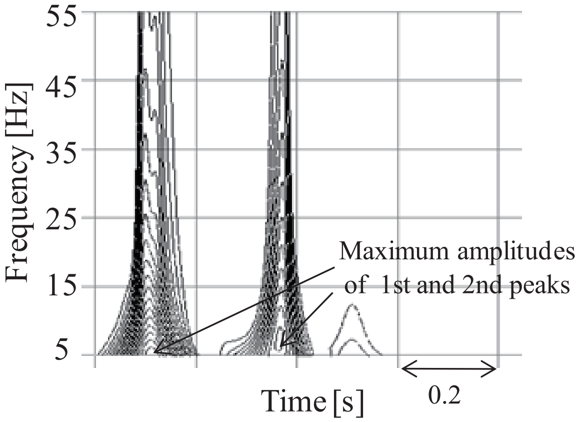

Fig. 4 Scaloglam of Measured wave in his 60s.

subject was larger than that from the younger subject. We then analyzed the 2nd peak amplitude of the scalogram. **Figure 5** shows the relationship between 2nd peak value ratio and age. Here peak value ratio is defined as the ratio of maximum amplitude of 1st peak that of 2nd peak as shown in the scalograms. The equation of the regression line was y=0.47x+18.55 R=0.7 (x: age, y: 2nd peak value ratio [%]). The positive slope confirms that peak values increase with age. This result is in good agreement with those of a previous study that indicate that the arterial stiffness increases with age[1]. Therefore, we conclude that CWT analysis of velocity pulse waveform is useful for estimating arterial stiffness.

## 5. Conclusion

We analyzed the 2nd peak of velocity waveform of pulse wave by CWT. In consequence, peak values increased owing to age, telling the elasticity of artery changes due to age. The application of CWT for the analysis of arterial stiffness is useful.

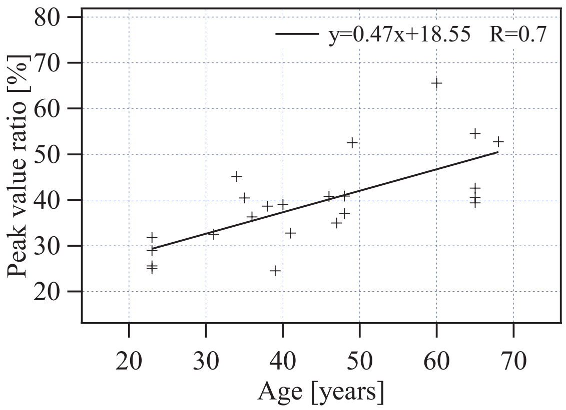

Fig. 5 Relationship between 2nd peak value ratio of scalogram and age.

**References**

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