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Analysis of Local Pulse Wave Velocity by Ultrasonic Measurement of Vibrations at Multiple Points on Arterial Wall
多数点で超音波計測された動脈壁振動の解析による局所脈波伝播速度の算出

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1. Introduction

As progressing of aging society, serious diseases such as heart disease and cerebral vascular disease have become a social problem. The pulse wave velocity (PWV) is generally known as a diagnostic criterion for arteriosclerosis that is the main cause of these diseases. In the conventional PWV measurement methods, there are problems that the measurement range is wide and it's assumed that the pulse wave has only an incident component. In the present study, we calculated the local PWV by analyzing the vibration simultaneously measure at multiple points on carotid arterial wall using ultrasound.

2. Materials and Methods

The pulse wave velocity c_{PWV} is calculated by Moens-Korteweg equation[1]

$$c_{\mathrm{PWV}} = \sqrt{\frac{Eh}{\rho D}}, \tag{1}$$

where E is Young's modulus of the arterial wall, h is the thickness of the arterial wall, ρ is blood density, D is inside diameter of the artery. The stiffer the artery is, the higher c_{PWV} becomes in proportion to the square root of the Young's modulus.

We measured the small vibration at the multiple points on arterial wall as the velocity waveform by the phased-tracking method [2]. We obtained the analytic signal of velocity waveform by the Hilbert transform. Furthermore, the phase unwrapping was applied to the phase component of the resultant analytic signals in order to keep the continuities of phase waveforms. Finally, we determined the same phase line for the phase components by the least squares method as described below, and estimated the component that propagates with the velocity of c_{PWV}.

First, when we assume a value of c_{PWV}, the arrival time $t_{i,j,c_{\mathrm{PWV}}}$ of the pulse wave on ith ultrasound beam is given by

$$t_{i,j,c_{\mathrm{PWV}}} = \frac{\Delta d \cdot i}{c_{\mathrm{PWV}}} + \Delta T \cdot j, \qquad (i = 0,1,\dots,N) \tag{2}$$

where Δd is the interval of beams, ΔT is the sampling interval of the velocity waveform, and $\Delta T \cdot j$ is the arrival time of the pulse wave on 0th beam of the selected jth frame. The instantaneous phase values at the time $t_{i,j,c_{\mathrm{PWV}}}$ for ith beam is given by $\theta_i\left(t_{i,j,c_{\mathrm{PWV}}}\right)$ from the analytic signal described above.

Second, the pulse wave velocity $c_{\mathrm{PWV}}(\Delta T \cdot j)$ at the time $\Delta T \cdot j$ is determined by minimizing the following variance $\alpha(c_{\mathrm{PWV}}, \Delta T \cdot j)$ of $\theta_i\left(t_{i,j,c_{\mathrm{PWV}}}\right)$ along the straight line determined by Eq. (2) in all beams $(i = 0,1,\dots,N)$ concerned with $\Delta T \cdot j$:

$$\begin{aligned}\alpha(c_{\mathrm{PWV}}, \Delta T \cdot j) &= \frac{1}{N+1}\sum_{i=0}^{N}\left|\theta_i\left(t_{i,j,c_{\mathrm{PWV}}}\right) - \bar{\theta}\right|^2 \\ &= \frac{1}{N+1}\sum_{i=0}^{N}\left|\theta_i\left(\frac{\Delta d \cdot i}{c_{\mathrm{PWV}}} + \Delta T \cdot j\right) - \bar{\theta}\right|^2,\end{aligned} \tag{3}$$

where $\bar{\theta}$ is a mean value defined by

$$\bar{\theta} = \frac{1}{N+1}\sum_{i=0}^{N}\theta_i\left(t_{i,j,c_{\mathrm{PWV}}}\right), \tag{4}$$

$(N+1)$ shows the number of ultrasound beams.

In vivo measurement, we set the 11 ultrasound beams (beam0, beam1, …, beam10) in the longitudinal direction along the arterial wall with intervals of Δd=3.2 mm, and measured the velocity of the small vibration at boundary between media and adventitia on the posterior wall of the carotid artery. The frame rate was $1/\Delta T = 521$ Hz and we analyzed one cardiac cycle. The phase components were interpolated at seven points between each sampling point in advance.

3. Results

Figure 1 shows the six velocity waveforms of the small vibration on arterial wall that were measured on six beams (beam0, beam2, beam4, beam6, beam8, beam10) among 11 beams and

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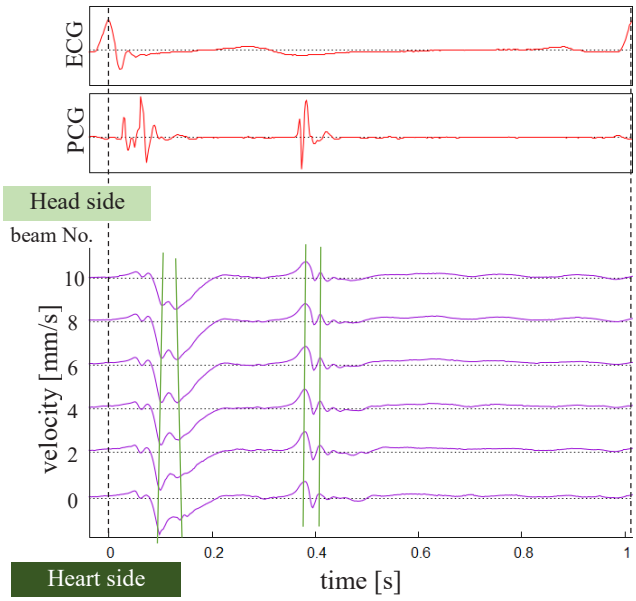

Fig. 1 Velocity waveforms of the small vibration on arterial wall for beam0, 2, 4, 6, 8, 10 and Electrocardiogram (ECG) and Phonocardiogram (PCG) of a subject

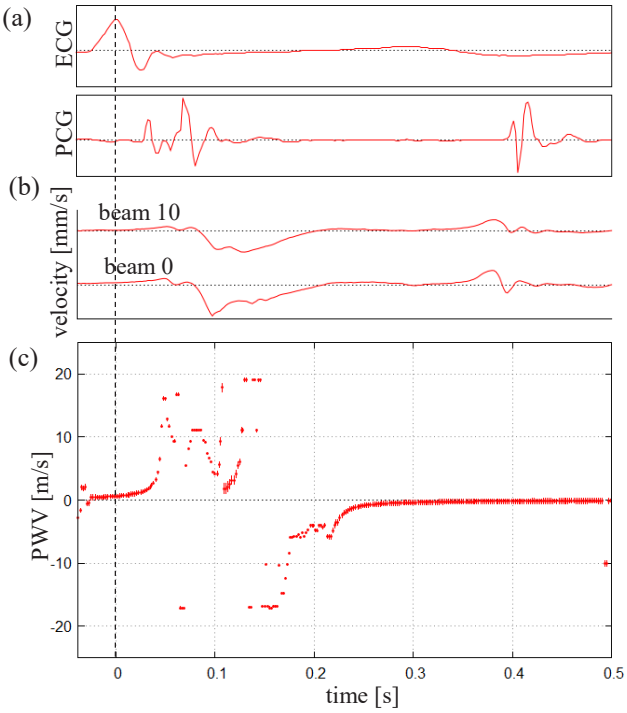

Fig. 2 (a) ECG and PCG of the subject. (b) Velocity waveforms of the small vibration on arterial wall of beam0 and beam10. (c) Pulse wave velocity by the least squares method.

Electrocardiogram (ECG) and Phonocardiogram (PCG) of a 24-years old healthy male. The velocity waveforms of the small vibration have negative peaks just after aortic valve opening, and positive peaks just after aortic valve closing. It was assumed that pulse wave velocity was constant regardless of the measurement position and we focused on the time when the velocity waveforms of the small vibration have peaks on each beam. Then, we confirmed that some pulse wave propagations like green lines and discriminated the incident and reflected components of pulse wave from inclination of lines just after first heart sound in PCG.

In addition, **Fig. 2** shows the pulse wave velocity (PWV) measured by the least squares method from R-wave of ECG to the second heart sound of PCG. If the PWV is positive, the component is incident and if it is negative, the component is reflection. The error bars show the phase variance of the least squares method. The phase variance was large from 0.1 to 0.13 s.

It was considered that the interference between the incident wave component and the reflected wave component was large. The incident component of the pulse wave was calculated around 0.1 s and the reflected component of the pulse wave was calculated around 0.14 s just after first heart sound in PCG. Additionally, a component of about 10 m/s, which was a propagation component faster than the pulse wave, was confirmed around 0.08 s just before the arrival of the incident component of the pulse wave. This component would be the propagation of the mechanical vibration. The reason that the phase variances was large after about 0.4 s was caused by the phase unwrapping process, in which beams performed and unperformed in the phase unwrapping coexisted and phase values greatly differed depending on the beams because of the worse S/N of the phase waveforms and the drastic phase changes.

4. Conclusion

In the present study, we measured the velocity of small vibrations on arterial wall *in vivo* by the phase-tracking method. Furthermore, we applied the phase unwrapping to the phase of the analytic signals to make it continuous waveforms and calculated the pulse wave velocity by the least squares method. In the conventional method, the pulse wave velocity can only be calculated at a characteristic time such as the rise time of the blood pressure waveforms. In the proposed method, in contrast, it became possible to calculate change with time of the local pulse wave velocity at every time for every phase by using the phase of the analytic signals.

References

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