Pulse Transmission Time based on Temporal Difference in the Instantaneous Phase between Electrocardiogram and Photoplethysmogram Signals

M. Murakoshi[*1], M. Yoshizawa[*2], N. Sugita[*3], M. Abe[*2], N. Homma[*2], T. Yambe[*4], S. Nitta[*4]

[*1] *Graduate School of Biomedical Engineering, Tohoku University, Aoba 6-6-05, Aramaki, Aoba-ku, Sendai, Japan*
[*2] *Cyberscience Center, Tohoku University, Aoba 6-6-05, Aramaki, Aoba-ku, Sendai, Japan*
[*3] *Graduate School of Engineering, Tohoku University , Aoba 6-6-05, Aramaki, Aoba-ku, Sendai, Japan*
[*4] *Institute of Development, Aging and Cancer, Tohoku University, Seiryo-machi 4-1, Aoba, Senda, Japan*
(Tel : 81-22-795-7130; Fax : 81-22-263-9163)
(murakoshi@yoshizawa.ecei.tohoku.ac.jp)

Abstract: Analysis of the baroreflex characteristics is useful for the earlier detection of diseases such as hypertension. However, a continuous blood pressure signal must be measured with a comparatively-expensive device for this analysis. If information which has high correlation with the Mayer wave (0.05-0.15Hz) component of blood pressure can be obtained by an easy method, it will be possible to estimate the baroreflex characteristics in equipment for home healthcare and telemedicine systems. In this study, pulse transmission time (PTT), which is known to be correlated with blood pressure, was calculated by using not only a traditional method but also a new algorithm based on the temporal difference in the instantaneous phase between electrocardiogram and photoplethysmogram signals. Analysis of 94 healthy subjects' data showed that information which has a relatively high correlation with the Mayer wave component of blood pressure could be obtained from the two PTTs by selecting one of them on the basis of their powers in the Mayer wave-related band.

Keywords: blood pressure, pulse transmission time, instantaneous phase, photoplethysmogram, telemedicine

I. INTRODUCTION

Recently, not only the escalation of medical costs caused by rapid aging of the population, but also health disparities caused by a shortage of physicians are big problems in Japan. The utilization of information and communication technology (ICT) for medicine is one of methods to solve these problems because the number of Internet users reached 90.91 million, with a 75.3% diffusion rate in Japan [1]. In particular, telemedicine systems using ICT enable people living in small provincial towns to get advanced medical treatments. Furthermore, the telemedicine system may lead to the early detection of diseases if people can have clinical examinations frequently by using it. Using this system, a medical doctor can hear symptoms of diseases, check appearance of affected parts of the body and see data of electrocardiogram (ECG) and/or blood pressure of patients being somewhere away from him. However, more physiological information of the patient should be provided for accurate diagnosis.

In this study, we pay attention to the characteristics of the baroreflex system as new information used in the telemedicine system. The baroreflex system is the feedback control mechanism to attenuate the effect of perturbation in arterial blood pressure by changing heart rate and/or vascular resistance, and it is known that cardiovascular diseases such as hypertension are associated with malfunctions of this system [2]-[5].

However, to estimate the baroreflex characteristic (BRC), a continuous blood pressure signal must be measured with a comparatively-expensive device. This is making it difficult to use BRC-related indices in the telemedicine system. To solve this problem, we are trying to develop a method to estimate BRC without the measurement of the continuous blood pressure signal. In concrete terms, we calculate a physiological index reflecting BRC using pulse transmission time (PTT) which correlates with blood pressure [6] and can be measured with a compact and low-cost device. PTT is defined as the time interval between the time when a R-wave of ECG appeared and that when a pulse wave arrived at a peripheral point. Therefore, the accuracy of PTT depends on the method to detect the time when the pulse wave arrived at the position of a sensor. In most conventional methods, the time when the pulse wave begins to rise in photoplethysmogram (PPG) was used as the hitting time. However, these points observed in PPG are easily disturbed by noise and artifacts. In addition to this, the most appropriate method to detect the point of the hitting time has not been clear. So there are some methods to find the position of the arriving point [7]. Compared with this, we proposed a new method of calculating PTT based on the temporal difference in the instantaneous phase between ECG and PPG waves, and compared the proposed parameter with PTT obtained from the traditional method.

II. METHODS

1. Measurement

Ninety four healthy adults (69 males and 25 females; 23.4 ± 2.61 years) participated in this study. None of them was on cardiovascular medication. Informed consent was obtained from all the subjects before the experiment. They were instructed to sit on a chair and biological signals were measured for 5 minutes in the way hereinafter described.

ECG and PPG signals were measured from electrodes placed on the subject's chest and a photoplethysmographic sensor attached on the subject's finger, respectively. The continuous arterial blood pressure was measured non-invasively using a finger plethysmography (PORTAPRES Model-2; Finapres) or a tonometoric pressure sensor (Nihon Corin; JENTOW 7700). These signals were amplified and converted to digital data by a 16-bit A/D converter (MP100; BIOPAC System Inc.). The sampling frequency was 1 kHz.

2. Analysis

A. PTT obtained from the conventional method

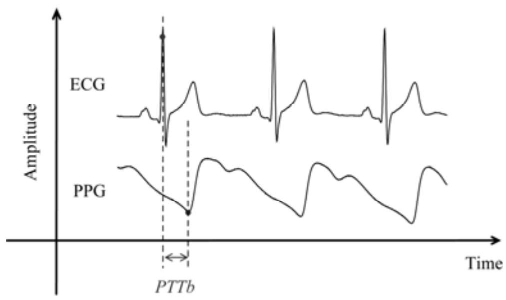

Fig.1. Definition of the pulse transmission time, *PTTb*, between ECG R-wave and the point at which PPG begins to rise

Figure 1 shows the definition of the pulse transmission time *PTTb* which is the time interval between the peak of ECG R-wave and the point at which PPG begins to rise.

B. PTT based on the temporal difference in the instantaneous phase between ECG and PPG signals

A biological signal $s(t)$ is given by

$$s(t) = \sum_k C_k \cos\theta_k(t) \tag{1}$$

$$\theta_k(t) = k\omega_0 t + \psi_k + \phi_k(t) \tag{2}$$

where ω_0 is a base angular frequency, C_k is a Fourier coefficient, ψ_k is an initial phase, and $\phi_k(t)$ is an instantaneous phase of the k-th harmonic wave. If k =1 and $t = t_m$ which is the time when a feature point (e.g. top point of ECG R-wave) appears at the m-th beat, eq. (2) is

$$\begin{aligned}\theta_1(t_m) &= \omega_0 t_m + \psi_1 + \phi_1(t_m) \\ &= 2m\pi\end{aligned} \tag{3}$$

The time interval between two consecutive feature points at the m-th beat is given by

$$TI_m = \theta_1^{-1}(2m\pi) - \theta_1^{-1}\{2(m-1)\pi\} \tag{4}$$

where $\theta_1^{-1}(n)$ is the inverse function of $\theta_1(t)$. Here, suppose that $s(t)$ is an ECG signal, TI_m means the R-R interval at the m-th beat. In a similar way, if $s(t)$ is a PPG signal, TI_m is the heartbeat interval at the m-th beat obtained from the PPG signal.

Next, PTT is considered as the time interval between a feature point of ECG and that of PPG at the same beat. So we defined the same phase temporal difference (*SPTD*) at the m-th beat as follows:

$$SPTD_m = \theta_{\mathrm{ECG}}^{-1}(2m\pi) - \theta_{\mathrm{PPG}}^{-1}(2m\pi) \tag{5}$$

where $\theta_{\mathrm{ECG}}^{-1}(n)$ and $\theta_{\mathrm{PPG}}^{-1}(n)$ are the inverse function of $\theta_1(t)$ when $s(t)$ is ECG and that when $s(t)$ is PPG, respectively.

Figure 2 shows the flowchart of the calculation of *SPTD*. The base angular frequency ω_0 is obtained as the center frequency in the short-time Fourier transform of PPG signal. The time series of the instantaneous phase $\theta_{\mathrm{ECG}}(t)$ and $\theta_{\mathrm{PPG}}(t)$ are calculated using the Hilbert transform. The initial phase of $\theta_{\mathrm{PPG}}(t)$, ψ, is set to minimize the difference in the value of time average between *SPTD* and *PTTb*. Finally, the time series of *SPTD* is given by

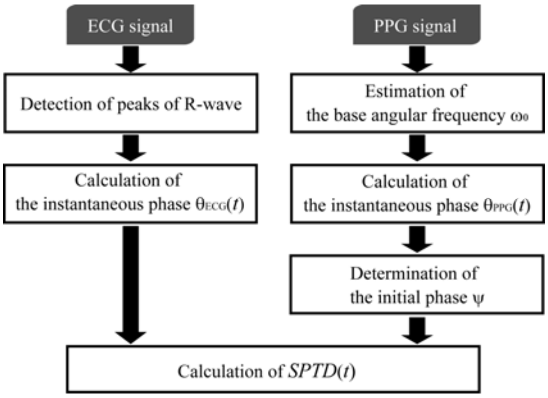

Fig.2. Flowchart of the calculation of *SPTD*

$$SPTD(t) = \theta_{\mathrm{PPG}}^{-1}\left[\theta_{\mathrm{ECG}}(t)\right] - t \tag{6}$$

In this study, the maximum cross-correlation coefficient $R_{\max}$ between PTT and the mean blood pressure (*MBP*) is defined as shown in Fig.3 to check the correlation between them in consideration of their lags. The values of $R_{\max}$ were calculated between -*PTTb* and *MBP* ($R_{PTTb\text{-}MBP}$), and between -*SPTD* and *MBP* ($R_{SPTD\text{-}MBP}$) whose frequency components were limited to the Mayer wave-related band (0.05-0.15Hz).

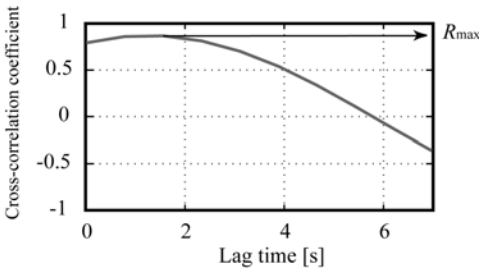

Fig.3. Definition of the maximum cross-correlation coefficient $R_{\max}$ between two parameters

III. RESULTS

Figure 4 shows changes in the Mayer wave component of *PTTb* and *SPTD* of a subject. As shown in this figure, the change in *SPTD* was roughly similar to that in *PTTb*. Fig.5 shows the scatter diagram for $R_{PTTb\text{-}MBP}$ and $R_{SPTD\text{-}MBP}$. In this figure, points above a diagonal line (dotted line) show data of subjects whose *SPTD* had a higher correlation with *MBP* than *PTTb*. This result indicates that it is possible to obtain the information which has higher correlation with blood pressure by using *SPTD* in addition to *PTTb*.

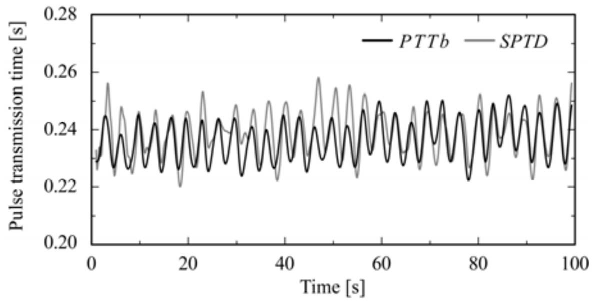

Fig.4. Changes in the Mayer wave component of *PTTb* and *SPTD* of a subject

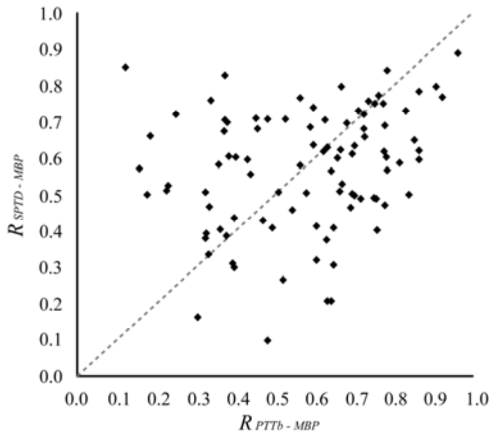

Fig.5. Scatter diagram for $R_{PTTb\text{-}MBP}$ and $R_{SPTD\text{-}MBP}$

Next, the power ratio (*PR*) of *SPTD* to *PTTb* in the Mayer wave-related band is defined as a criterion to determine whether *SPTD* should be used as the information of blood pressure instead of *PTTb* or not without the measurement of *MBP*. *PR* is given by

$$PR = \sqrt{\frac{P_{SPTD}}{P_{PTTb}}} \tag{7}$$

where P_{SPTD} and P_{PTTb} are the power of *SPTD* and that of *PTTb* in the Mayer wave-related band, respectively. Fig. 6 shows the scatter diagram for *PR* and the difference value of $R_{SPTD\text{-}MBP}$ and $R_{PTTb\text{-}MBP}$. This figure indicates that $R_{SPTD\text{-}MBP}$ was higher than $R_{PTTb\text{-}MBP}$ in most data whose *PR* is higher than 3. So we defined *PTTx* as follows:

$$PTT_x = \begin{cases} SPTD & \text{if } PR \geq 3 \\ PTTb & \text{otherwise} \end{cases} \tag{8}$$

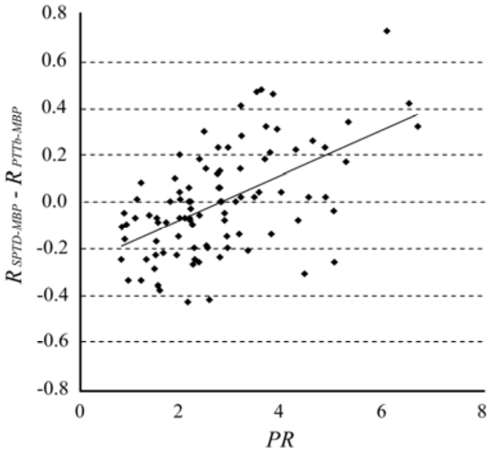

Fig.6. Scatter diagram for *PR* and the difference value of $R_{SPTD\text{-}MBP}$ and $R_{PTTb\text{-}MBP}$. *PR* is the power ratio of *SPTD* to *PTTb* in the Mayer wave-related band (0.05-0.15Hz)

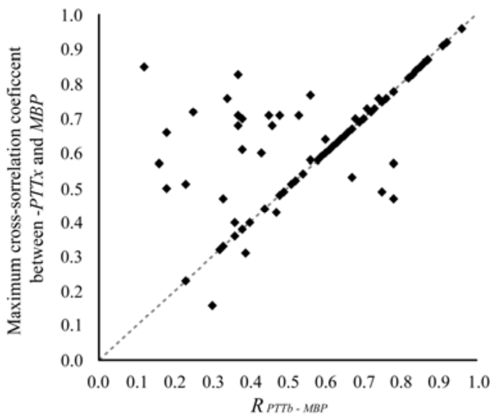

Fig.7. Scatter diagram for $R_{PTTb\text{-}MBP}$ and $R_{\max}$ between *-PTTx* and *MBP*. *PTTx* is selected from *PTTb* or *SPTD* based on *PR*

The scatter diagram for $R_{PTTb\text{-}MBP}$ and $R_{\max}$ between *-PTTx* and *MBP* is shown in Fig.7. This result shows that $R_{\max}$ of 25 subjects increased while that of 7 subjects decreased by using *SPTD* instead of *PTTb*.

The accuracy of detecting the position at which the pulse wave begins to rise is important for the estimation of *PTTb*. Thus disturbances in the PPG signal or decreased SN ratio at these points significantly reduces the accuracy of *PTTb*. On the other hand, *SPTD* is considered to be strong against short-term noise and artifacts in the PPG because the global pattern of waves was used for the estimation. The result of this study holds a possibility to obtain the blood pressure information in more accuracy by using *SPTD* in addition to *PTTb*.

IV. CONCLUSION

In this study, we focused on the pulse transmission time as a parameter which has information of blood pressure variability to estimate the baroreflex characteristics without the measurement of a continuous blood pressure signal. We proposed a parameter based on the temporal difference in the instantaneous phase between ECG and PPG signals. Analysis of the proposed parameter and the traditional pulse transmission time for 94 healthy subjects revealed that information which has a relatively high correlation with the Mayer wave component of blood pressure could be obtained by selecting one from the proposed or the conventional parameter based on the power of their Mayer wave components.

In future studies, an evaluation of baroreflex characteristic using the proposed parameter is needed. And a method to obtain the information which has higher relationship with the blood pressure variability should be developed by combining parameters other than *PTTb* and *SPTD*.

REFERENCES

[1] Communications Usage Trend Survey in 2008, The Ministry of Internal Affairs and Communications

[2] Guo GB and Abboud FM (1984), Impaired central mediation of the arterial baroreflex in chronic renal hypertension. Am J Physiol Heart Circ Physiol 246: H720-H727

[3] Guido G, Bianca MC, Gino S et al (1998), Baroreflex Control of Sympathetic Nerve Activity in Essential and Secondary Hypertension. Hypertension 31:68-72

[4] Parati G, Rienzo MD, Bertinieri G et al (1988), Evaluation of the baroreceptor-heart rate reflex by 24-hour intra- arterial blood pressure monitoring in humans. Hypertension 12:214-222

[5] Mancia G, Ludbrook J, Ferrari A et al (1978), Baroreceptor reflexes in human hypertension. Circulation Research 43:170-177

[6] Chen W, Kobayashi T, Ichikawa Y et al (2000), Continuous estimation of systolic blood pressure using the pulse arrival time and intermittent calibration. Medical and Biological Engineering and Computing 5(38): 569-574

[7] Kazanavicius E, Gircys R, Vrubliauskas A et al (2005), Mathematical Methods for Determining The Foot Point of The Arterial Pulse Wave and Evaluation of Proposed Methods. Info. Tech. Contl. 34(1): 29-36