Evaluation of Baroreflex Function Using Green Light Photoplethysmogram in Consideration of Resistance to Artifacts

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Abstract The maximum cross-correlation coefficient ($\rho_{\max}$) between blood pressure (BP) and heart rate (HR) variability for frequency components limited to the Mayer wave-related band is useful for the evaluation of baroreflex function. However, continuous BP measurement with an expensive and bulky measuring device is required to calculate $\rho_{\max}$. This study proposes a simpler method to obtain $\rho_{\max}$ using a green light photoplethysmogram (PPG). A green PPG sensor is less affected by motion artifacts than a near-infrared PPG sensor. In this study, an electrocardiogram, continuous BP, green PPG, and near-infrared PPG were obtained from the subjects. HR, mean BP, and pulse transit time were estimated from the signals, and $\rho_{\max}$ was subsequently calculated. Compared to the $\rho_{\max}$ obtained from the near-infrared PPG signal, the $\rho_{\max}$ obtained from the green PPG signal is closer in value to the $\rho_{\max}$ obtained from mean BP. These results show that the green PPG sensor can be used to estimate baroreflex function instead of using continuous BP measurement.

Keywords: baroreflex function, green light emitting diode, photoplethysmogram.

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1. Introduction

In Japan, the growth in medical expenditure has become a serious problem. In order to reduce costs for medical care, prevention and early recognition of lifestyle-related diseases are important. An abnormal baroreflex system is linked to circulatory diseases such as hypertension [1, 2]. The baroreflex is a mechanism that controls heart activity based on information from blood pressure constantly sensed by the carotid sinus baroreceptor and the aortic arch baroreceptors. Therefore, we hypothesize that monitoring baroreflex function may lead to prevention of lifestyle-related diseases.

To evaluate baroreflex function based on autonomic nervous activity, methods related to heart rate variability, such as coefficient of variation of RR intervals (CVRR), RR at 50% of QTmax (RR50), and low frequency/high frequency ratio (LF/HF), have been used [3–6]. However, these indices have problems with time resolution and reproducibility. We previously proposed a physiological index, $\rho_{\max}$, representing the maximum cross-correlation coefficient between blood pressure (BP) and heart rate (HR) variability for frequency components limited to the Mayer wave-related band [7–9]. We confirmed that $\rho_{\max}$ is effective to estimate

baroreflex function based on autonomic nervous activity. However, $\rho_{\max}$ requires continuous BP measurement using an expensive and bulky device, and is not practical or convenient for measurement at home.

We have established an easier method to obtain $\rho_{\max}$ using near-infrared photoplethysmogram (PPG) signals. This method involves analysis of the pulse transit time (PTT) obtained from an R-wave on the electrocardiogram (ECG) signal and a feature point on the PPG signal, or independent component analysis to extract the BP-related parameters [9, 10]. However, PPG sensors with near-infrared LEDs are highly sensitive to motion artifacts [11, 12], an issue that has to be resolved for monitoring $\rho_{\max}$ at home.

In this paper, we propose a method to obtain $\rho_{\max}$ with a PPG sensor using green LED. Previous studies indicate that green PPG sensors are more resistant to motion artifacts than near-infrared PPG sensors [13–15]. Therefore, a green PPG sensor is often used to estimate the state of blood flow and to measure heart rate. However, few researchers have estimated baroreflex function based on autonomic nervous activity using an index obtained from green PPG signals.

Therefore, we verified whether a green PPG signal can be used to estimate baroreflex function and replace the conventional continuous BP measurement device.

2. Methods

2.1 Photoplethysmogram

A photoplethysmogram is obtained optically from volumetric measurement of the arteries in the fingers or ears. A commonly used PPG sensor consists of a near-infrared LED and a photodiode to detect reflection at the surface of the fingers or ears. PPG signals can be measured noninvasively, easily, and inexpensively.

Recently, a PPG sensor consisting of a green LED has been studied. The main difference between the near-infrared PPG and the green PPG is the depth of light penetration from the skin [16, 17]. The green PPG signal reflects the blood flow in the arteries

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Fig. 1 Definition of the pulse transit time (PTT).

near the skin surface.

The PTT has been used to obtain a BP-related index from a PPG [18], and it is defined as the time interval from the R-wave on the ECG to a feature point on the PPG (**Fig. 1**). The PTT correlates inversely with BP because PTT reflects the compliance of the arteries. The PTT can be calculated using a near-infrared PPG signal or a green PPG signal. In this study, we used the PTT calculated from PPG signals to obtain $\rho_{\max}$ in the same manner as BP variability.

2.2 Maximum cross-correlation coefficient

The maximum cross-correlation coefficient, $\rho_{\max}$, was calculated as described previously [7–9].

First, let $u(t)$ and $v(t)$ [$t = i \cdot \Delta t$ s, ($i = 0, 1, 2, \dots$)] denote the time series data (BP and HR variability, respectively) sampled every $\Delta t = 0.5$ s. These data are filtered through a band-pass digital filter with a bandwidth between 0.08 and 0.12 Hz to limit the frequency components to the Mayer wave-related band. At a certain time, a Hamming window with an interval between $t - 60$ s and $t + 60$ s is applied to $u(t)$ and $v(t)$, where the length of the Hamming window was decided experimentally based on the response time of autonomic nervous activity. The cross-correlation coefficient, $\rho_{uv}(\tau)$, for a lag of $\tau = j \cdot \Delta t$ s where $j = \dots, -1, 0, 1, \dots$, was calculated as follows:

$$\rho_{uv}(\tau) = \frac{\varphi_{uv}(\tau)}{\sqrt{\varphi_{uu}(0) \cdot \varphi_{vv}(0)}}, \quad (1)$$

where $\varphi_{uv}(\tau)$ is the cross-correlation function between $u(t)$ and $v(t)$, and $\varphi_{uu}(\tau)$ and $\varphi_{vv}(\tau)$ are the autocorrelation functions for $u(t)$ and $v(t)$, respectively. The maximum cross-correlation coefficient, $\rho_{\max}$, and its delay, $\tau_{\max}$, are defined as

$$\rho_{\max} = \max_{0 \leq \tau \leq 10s} \rho_{uv}(\tau) \quad (2)$$

$$\tau_{\max} = \arg \max_{0 \leq \tau \leq 10s} \rho_{uv}(\tau) \quad (3)$$

In this study, $\rho_{\max}$ was successively calculated every second between $t = 60$ s (start time for calculating $\rho_{\max}$) and $t = T - 60$ s (end time for calculating $\rho_{\max}$), where T is the end time for the experimental data.

The $\rho_{\max}$ is an index representing the linear correlativity between BP and HR variability in the time domain. In this study, $\rho_{\max}$ was calculated using PTT obtained from the green PPG signals and HR variability, and also using PTT obtained from the near-infrared PPG signals and HR variability.

Fig. 2 Experimental setup.

2.3 Experiment

Nine healthy subjects (8 males and 1 female, aged 23.3 ± 1.6 years) participated in this study. The experiment setup is shown schematically in **Fig. 2**. The subject rested in a sitting posture in a chair for 5 min. The subject's ECG, continuous BP, near-infrared PPG, and green PPG were recorded during the experiment. The ECG was measured by limb leads, and continuous BP was measured from the left middle finger using a Portapres (Finapres Medical Systems). The reference signal of the near-infrared PPG (Nellcor manufactured by EnviteC) was recorded from the left index finger, as in previous study [10]. The near-infrared PPG sensor and the green PPG sensor both consisted of an LED and a phototransistor called a photoreflexor. Four pairs of near-infrared and green PPG sensors were applied to the left ring finger, medial side of the wrist, lateral side of the forearm, and lateral side of the upper arm. These PPG sensors were made from commercially available photoreflexors. All signals were stored in a personal computer through an amplifier and 16-bit analog-to-digital converter (MP150 manufactured by BIOPAC systems Inc.) at a sampling frequency of 1 kHz.

The experimental protocol was approved by the Tohoku University Internal Review Board, and informed consent was obtained from all subjects before commencing experiments.

3. Results

Figure 3(a) and (b) show examples of the PTT data obtained from the near-infrared and green PPG, respectively. IRPTT represents the PTT obtained from the near-infrared PPG sensor, and GPTT represents the PTT obtained from the green PPG sensor. IRPTT_i and GPTT_i are the measurements from four sites on the body, where $i = 1$ denotes the ring finger, $i = 2$ denotes the wrist, $i = 3$ denotes the forearm, and $i = 4$ denotes the upper arm. In all subjects, GPTT_i had smaller standard deviation than IRPTT_i , except for the ring finger measurement ($i = 1$). These results indicate that the green PPG is superior to the near-infrared PPG for measurement of multiple sites.

Figure 4(a) shows the comparison between the $\rho_{\max}$ calculated from the near-infrared PPG [$\rho_{\max}(\text{IRPTT}_i)$] and the $\rho_{\max}$ calculated from continuous BP [$\rho_{\max}(\text{BP})$]. **Figure 4(b)** shows the

Fig. 3 Example of PTT data obtained from the (a) near-infrared PPG and (b) green PPG.

Fig. 4 The $\rho_{\max}$ obtained from (a) near-infrared PPG and (b) green PPG ($n = 9$).

Table 1 RMSE between $\rho_{\max}(\text{BP})$ and the other $\rho_{\max}$ s ($n = 9$).

	$i = 1$ (finger)	$i = 2$ (wrist)	$i = 3$ (forearm)	$i = 4$ (upper arm)
near-infrared PPG	0.068	0.268	0.202	0.264
green PPG	0.089	0.080	0.080	0.031

Fig. 5 Signal-to-noise ratio for each PTT ($n = 9$).

comparison between the $\rho_{\max}$ calculated from the green PPG [$\rho_{\max}(\text{GPTT}_i)$] and $\rho_{\max}(\text{BP})$. Each $\rho_{\max}$ reported was the average of the values obtained every 30 s for a single subject, and then the $\rho_{\max}$ was averaged for all subjects, as in previous studies [9, 10]. In addition, **Table 1** shows the root mean square errors (RMSEs) between $\rho_{\max}(\text{BP})$ and the other $\rho_{\max}$. The results of **Fig. 4** and **Table 1** show that compared to $\rho_{\max}(\text{BP})$, $\rho_{\max}(\text{GPTT}_i)$ is closer in value to $\rho_{\max}(\text{BP})$ in all measurements except that at the ring finger ($i = 1$). Furthermore, $\rho_{\max}(\text{IRPTT}_i)$ (excluding the ring finger) is low even though the subjects were in a resting condition. Therefore, $\rho_{\max}(\text{IRPTT}_i)$ has lower reliability.

The signal-to-noise ratio (SNR) for each PTT is shown in **Fig. 5**. In this figure, the error bar represents standard deviation of each SNR. A desirable signal is defined as one having frequency components less than 0.3 Hz, based on the frequency band related to autonomic nervous activity. Two-way analysis of variance was used to test for differences between near-infrared PPG and green PPG and differences between four measurement sites. From the results of this analysis, there was a significant difference ($p < 0.05$) between near-infrared PPG and green PPG but no significant difference between four measurement sites. These results indicate that GPTT_i is more resistant to noise, such as motion artifacts, than IRPTT_i . In particular, the SNR for GPTT_4 was higher than those for other PTT. This result implies that the feature point on the green PPG used to calculate PTT was determined more accurately when measured at the upper arm because it is least affected by motion artifacts.

4. Discussion

The results of **Figs. 3, 4, 5** and **Table 1** show that GPTT is more stable than IRPTT .

In **Fig. 3(a)**, IRPTT_i (excluding IRPTT_1) vary by approximately 100 ms. In **Fig. 4(a)**, $\rho_{\max}(\text{IRPTT}_i)$ [excluding $\rho_{\max}(\text{IRPTT}_1)$] have low values for the resting condition. These results are not physiologically rational. IRPTT changed widely

Fig. 6 Raw signals from (a) near-infrared PPG and (b) green PPG placed on the upper arm.

because of inaccurate detection of the feature point on PPG (**Fig. 1**). **Figure 6** shows the raw signals obtained from a near-infrared PPG and a green PPG placed on the upper arm of a subject. As shown in this figure, the feature points of the near-infrared PPG signal is obscure compare to that of the green PPG signal. Therefore, **Fig. 5** indicates that the IRPTT cannot be calculated accurately because of its susceptibility to noise or motion artifacts, despite the subject being in a resting condition. This advantage of the green PPG is consistent with the conclusions from previous studies [13–15]. We speculate that this is due to the fact that the light path length of green LED is shorter than that of near-infrared LED.

An important finding is that the green PPG sensors provide reliable PTT data from multiple sites (**Fig. 5**). Therefore, we may be able to calculate PTT at two different sites using the green PPG signals, without the need for ECG signal. This indicates that the green PPG sensor is more suitable as a wearable device for monitoring baroreflex function at home than the near-infrared PPG sensor.

While we obtained good results using the proposed method, there are some issues to be considered. A larger number of subjects is required to enhance the credibility of these results statistically and to determine individual differences. For example, the best site to measure PPG for each subject should be investigated. Furthermore, we should conduct an experiment to confirm that $\rho_{\max}(\text{GPTT}_i)$ reflects the change in autonomic nervous activity. For example, we have to ascertain whether it reflects the change in sympathetic activity with exercises, Valsalva maneuver and other activities. Since the depth of penetration of green LED is lower than that of near-infrared LED, we should examine the effects of this difference on $\rho_{\max}$.

5. Conclusion

To evaluate baroreflex function based on autonomic nervous activity, we propose a method to estimate BP-related parameters using a green light PPG instead of a near-infrared PPG. Experi-

mental results showed that the $\rho_{\max}$ obtained from a green light PPG is more stable than that from a near-infrared PPG.

The main limitation of this study was the small number of subjects. Further experiments with more subjects under various conditions should be conducted.

In addition, we have to verify that the $\rho_{\max}$ obtained from the green light PPG reflects the change in autonomic nervous activity. We are planning an experiment to change autonomic nervous activity by varying BP intentionally.

Conflict of Interest

We have no conflicts of interest relationship with any companies or commercial organizations based on the definition of Japanese Society of Medical and Biological Engineering.

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