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Comparison Between Red, Green and Blue Light Reflection Photoplethysmography for Heart Rate Monitoring During Motion

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***Abstract*— Reflection photoplethysmography (PPG) using 530 nm (green) wavelength light has the potential to be a superior method for monitoring heart rate (HR) during normal daily life due to its relative freedom from artifacts. However, little is known about the accuracy of pulse rate (PR) measured by 530 nm light PPG during motion. Therefore, we compared the HR measured by electrocadiography (ECG) as a reference with PR measured by 530, 645 (red), and 470 nm (blue) wavelength light PPG during baseline and while performing hand waving in 12 participants. In addition, we examined the change of signal-to-noise ratio (SNR) by motion for each of the three wavelengths used for the PPG. The results showed that the limit of agreement in Bland-Altman plots between the HR measured by ECG and PR measured by 530 nm light PPG (±0.61 bpm) was smaller than that achieved when using 645 and 470 nm light PPG (±3.20 bpm and ±2.23 bpm, respectively). The ΔSNR (the difference between baseline and task values) of 530 and 470nm light PPG was significantly smaller than ΔSNR for red light PPG. In conclusion, 530 nm light PPG could be a more suitable method than 645 and 470nm light PPG for monitoring HR in normal daily life.**

I. Introduction

Photoplethysmography (PPG) is a popular optical technology for the monitoring heart rate (HR) in normal daily life due to its simplicity and convenience, in its simplest form only requiring the attachment of a light emitting diode (LED) and a photodetector (PD) [1,2]. However, the reliability of PPG signals measured during normal daily life can be reduced by motion artifacts [3,4]. Thus, various techniques for the robust measurement of PPG signals during motion have been studied [1]. One approach, based on the optical characteristics of tissue, can be the choice of light wavelength [5-8]. The light sources used with PPG have been chosen at various wavelengths including the near-infrared (NIR) (e.g., 810 or 940 nm), red, green, and blue [7]. NIR and red wavelengths are generally used in PPG research and for routine clinical applications [1]. But, among the possible light colors, green light PPG has been shown to have the least influence from motion artifacts when compared with the NIR light PPG [6]. In fact, green light PPG is now often used in smartphone HR measurement, which is available not only in the laboratory but also during normal daily life. HR measured by iPhysioMeter, a smartphone application, during laboratory mental stress tasks has already been validated [8].

Naturally, the influences of artifacts on the PPG signal are related to the wavelength of the light source [5,6], simply because of the wavelength dependence of the light absorption (e.g., water, melanin, oxy- and deoxyhemoglobin) and therefore the penetration depth into the tissue [9]. Absorption of the longer wavelengths such as red and NIR is relatively low giving deeper tissue penetration [9]. The PPG signal using red and NIR wavelengths arises mainly from the larger arterioles and possibly arteries in the deep dermis [7,10]. On the other hand, the shorter wavelengths of light, such as the green and blue, are strongly absorbed by melanin, and the penetration depth into the tissue is therefore relatively shallow [9]. According to Cui et al. [5], the influences of artifacts are larger in deeper site than in shallower site. Therefore, red and NIR light PPG is subject to artifacts, while the green and blue light PPG is relatively free from artifacts [5,6].

Despite the possible advantages of green light PPG, in terms of susceptibility to artifact little is known about the accuracy of pulse rate (PR) measured by green light PPG during motion. Although Maeda and colleagues have examined the influence of artifacts on green light PPG signals as compared with NIR light PPG signal [6], they did not compare with other wavelengths during motion. The purpose of our present study was to investigate the use of red, green, and blue light PPG (PPG_red, PPG_green, and PPG_blue, respectively) to discover which of these is the most suitable for measuring HR during normal daily life, where motion is likely to be a significant issue. We compared the HR measured by electrocardiography (ECG) as a reference with PR measured by red, green, and blue light reflection mode PPG during a stationary state and with two kinds of intentional motion. The horizontal and vertical waving of the hand connected to the sensor was performed to produce these motion artifacts. In addition, we examined the change of SNR

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values produced by motion in the red, green, and blue light reflection mode PPG.

II. METHODS

A. Participants

Twelve healthy male participants, with a mean age of 22.8 ± 1.8 S.D. years, without known cardiovascular disorders participated in this study. All subjects agreed to take part in this study voluntarily and signed an informed consent statement. The experimental design was approved by the ethics committee of the Kanazawa University.

B. Measurements and instruments

The light sources and detectors used were as follows: a red LED source (645nm, BW 22nm, LHT674, OSRAM opto semiconductors, Germany) with a PIN photodiode detector (BPW34S, OSRAM opto semiconductors, Germany); a green LED source (530nm, BW 33nm, LTT67C, OSRAM opto semiconductors, Germany) with a PIN photodiode detector (TEMD5510FX01, Vishay semiconductors, USA); a blue LED source (470nm, BW 25nm, LBT67C, OSRAM opto semiconductors, Germany) with a PIN photodiode detector (TEMD5510FX01). In each case the LED and its accompanying photodiode were placed side by side, thereby constituting the reflection mode PPG. The distance between the red, green and blue LED and its accompanying photodiode are 5, 3 and 3 mm, respectively. The LEDs were operated in the pulsatile mode, receiving 250 us pulses at 16.6 ms intervals, to allow simultaneous measurement without interference between the three channels on the hand. The ECG was derived from limb leads (standard lead II) using disposable foam-pad electrodes connected to biopotential amplifier built in the authors' laboratory [11]. Peak points of the PPG signal and the ECG (R) were detected using a differentiating algorithm. PR and HR were determined from peak-to-peak interval from the PPG and the R-R interval of the ECG, respectively. A 3-axis accelerometer (±6G, MMA7260Q, Freescale semiconductor, USA) was placed on the distal part of the finger to measure motion. The signals were recorded by a data acquisition card (NI USB-6218, National instruments, USA) with 1,024 Hz sampling rate, for storage and off-line analysis using LabVIEW (National instruments, Austin, USA).

C. Procedure

The experiments were performed in an air-conditioned laboratory (temperature: 26 °C, humidity: 62 %). The participants sat on a chair, and then the foam-pad electrodes, the accelerometer, and the three pairs of photo-sensors were attached. The photo-sensors were allocated sequentially in rotation between participants to either the index, middle and ring finger on the right hand so that each finger was used an equal number of times over the whole experiment. Each photo-sensor (size: width = 10, length = 20, thickness = 5 mm) was fixed with the elastic adhesive bandage on the fingertip. Three PPG signals were controlled by adjusting the intensity of the LED to achieve the same pulse amplitude.

The experiment was started with a 3 min rest period. Next, the participant underwent three conditions, each for 16sec: horizontal motion (HM), vertical motion (VM), and the stationary state as a baseline (BL) [5]. Each condition was separated by an 8 sec rest period, and the order of each condition was counter-balanced across participants. The set of three conditions was repeated three times. In the HM and VM periods, the participants waved their right hand connected to the sensor at a rate of 8 Hz paced by a computer metronome.

D. Data analysis

All the stored data were equally subject to 30 Hz low pass digital filtering based upon the fast Fourier transform (FFT) algorithm. Beat-by-beat HR measured by the ECG was averaged for the each 16 sec condition.

Firstly, beat-by-beat PR measured by each PPG was averaged for each 16 sec condition. Next, Pearson's correlation analysis was performed between HR measured by ECG as a reference and PR measured by the red, green, and blue light reflection mode PPGs, respectively. We also conducted Bland-Altman analysis to evaluate their correspondence more closely [12].

Secondly, frequency spectral analysis was performed using the pulse and acceleration wave by the 16,384 point FFT. FFT analysis was performed using BIMUTUS II for Windows (Kissei Comtec Co., Ltd., Japan). The SNR value was calculated for each 16 sec condition. SNR is defined as the power ratio of pulse wave between the PR band with the motion artifacts band, and it is expressed using the logarithmic decibel scale, as shown in equation (1).

$$\mathrm{SNR(dB)} = 10\log_{10}\left(\frac{P_{\text{pulse rate band}}}{P_{\text{motion artifacts band}}}\right) \qquad (1)$$

where P is the integrated power. The center frequency of the PR band and motion artifacts band are the mean frequency of HR measured by ECG and the peak frequency of motion measured by the accelerometer, respectively. Bandwidth of PR band and motion artifacts band are the mean HR frequency, while these bandwidths are the same (i.e., if mean HR = 60 bpm (1 Hz) and motion artifacts peak frequency = 8 Hz, then PR band is 0.5 ~ 1.5 Hz, motion artifacts band is 7.5 ~ 8.5 Hz). This bandwidth was selected to include all PR frequency despite the difference between HR and PR due to the influence of artifacts on pulse wave during the motion. SNR values from the three repeated measurements were further averaged to produce single values for HM, VM, and BL, respectively. SNR changes (ΔSNR) were calculated by subtracting the BL values from the HM and VM values. These values were separated into two series: the HM series and the VM series. Next, each series was compared statistically by means of the one-way analysis of variance (ANOVA), and then post-hoc comparison was performed by the Tukey's Honestly Significant Difference (Tukey HSD) test at the significance level of 5%.

All statistical analyses were performed using the SPSS 19.0 for Mac OS X (SPSS Inc., Chicago, IL, USA).

III. RESULT

The signal vector magnitude measured by the accelerometer periodically changed according to the motion of the right hand. The mean and standard deviation (S.D.) values of acceleration during HM (X-axis) and VM (Z-axis) were 8.71 ± 1.37 G and 8.84 ± 1.31 G, respectively. A typical example of simultaneous recordings of the PPG_red, PPG_green, PPG_blue, and X-axis acceleration wave during the HM are shown in Fig. 1.

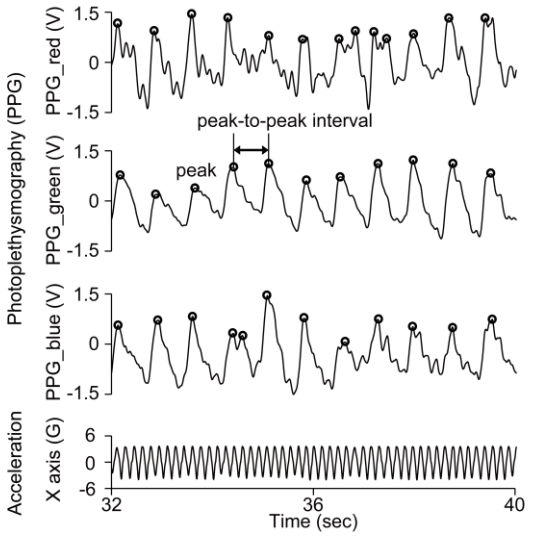

Figure 1. Typical trend-charts showing simultaneously recorded waveforms of the red, green, and blue light reflection mode photoplethysmography (PPG) (PPG_red, PPG_green, and PPG_blue, respectively), and X-axis acceleration during horizontal motion.

A. *Correlation between the HR measured by ECG and the PR measured by PPG using R, G, and B light*

Pearson's coefficient of correlation between HR measured by ECG (HR_ecg) as a reference and PR measured by the PPG using the red light (PR_red), green light (PR_green), and blue light (PR_blue) are summarized in Table1 for the BL, HM, and VM, respectively. The three Bland-Altman plots between HR_ecg and PR_red, PR_green, and PR_blue are shown in Fig. 2(a), 2(b), and 2(c), respectively. According to the Bland-Altman analysis, the mean differences (fixed biases) between HR_ecg and PR_red, PR_green, and PR_blue were −0.07 bpm, +0.18 bpm, +0.20 bpm, and limits of agreement were ±3.20 bpm, ±0.61 bpm, ±2.23 bpm, respectively.

TABLE I. PEARSON'S COEFFICIENT OF CORRELATION BETWEEN HEART RATE (HR) MEASURED BY ELECTROCADIOGRAPHY (ECG) AND PULSE RATE (PR) MEASURED BY R, G, AND B LIGHT PHOTOPLETHYSMOGRAPHY (PPG)

	HR_ecg versus PR_red	***HR_ecg versus PR_green***	***HR_ecg versus PR_blue***
Baseline	0.999^{***}	0.999^{***}	0.999^{***}
Horizontal motion	0.967^{***}	0.999^{***}	0.991^{***}
Vertical motion	0.995^{***}	0.999^{***}	0.992^{***}

HR_ecg = heart rate measured by ECG as a reference; PR_red = pulse rate measured by the red light reflection mode PPG; PR_green = pulse rate measured by the green light reflection mode PPG; PR_blue = pulse rate measured by the blue light reflection mode PPG. ***$P < 0.001$.

B. *Signal-to-noise ratio change*

Mean and S.D. of ΔSNR of the PPG_red, PPG_green, and PPG_blue by the HM and VM are shown in Fig. 3. The one-way ANOVA revealed the main effect of PPG light color: $F_{2,22} = 15.06$, $p < 0.001$, $\eta_p^2 = 0.58$ for ΔSNR by HM. Significant differences among each PPG were found by Tukey HSD test: ΔSNR by HM was significantly smaller for the PPG_green (−7.41 ± 3.64 dB) and PPG_blue (−7.49 ± 3.69 dB) as compared to the PPG_red (−13.60 ± 4.19 dB), but the difference of ΔSNR by HM between the PPG_green and PPG_blue was not significant. Additionally, the one-way ANOVA revealed the main effect of PPG light color: $F_{2,22} = 10.81$, $p < 0.001$, $\eta_p^2 = 0.50$ for ΔSNR by VM. Significant differences among each PPG were found by Tukey HSD test: ΔSNR by VM was significantly smaller for the PPG_green (−8.64 ± 4.39 dB) and PPG_blue (−7.49 ± 3.75 dB) as compared to the PPG_red (−13.43 ± 5.09 dB), but the difference of ΔSNR by VM between the PPG_green and the PPG_blue was not significant.

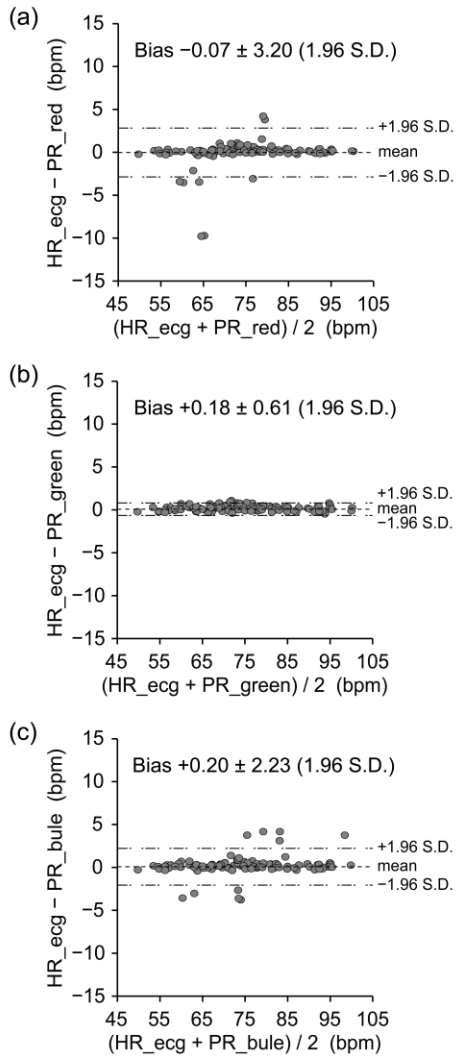

Figure 2. The three Bland-Altman plots between the heart rate (HR) measured by electrodardiography (ECG) (HR_ecg) as a reference and pulse rate (PR) measured by the reflection mode photoplethysmography (PPG) using the (a) red (PR_red), (b) green (PR_green), and (c) blue (PR_blue) light, respectively. Among the all condition (baseline, horizontal and vertical motion).

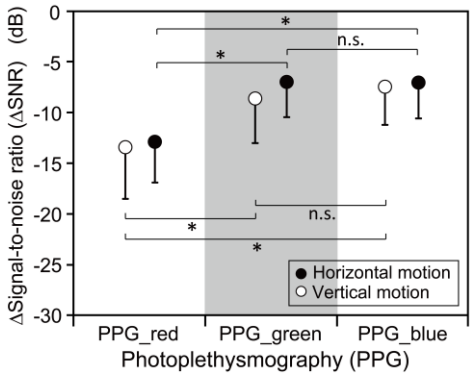

Figure 3. Mean and standard deviation of the signal-to-noise ratio (SNR) changes (ΔSNR; the difference between baseline and task values) of the red, green, and blue light reflection mode photoplethysmography (PPG) (PPG_red, PPG_green, and PPG_blue, respectively) by horizontal and vertical motion, respectively. *$p < 0.05$.

IV. Discussion

Our result clearly showed that, in terms of susceptibility to motion artifact, the green light PPG is better for the monitoring of HR during motion than both the red and the blue light reflection mode PPG, and these results appear to be comparable to other studies for green light PPG [6]. The limit of agreement between the PR measured by green light PPG and HR measured by ECG as a reference was smaller than that between the PR measured by red and blue light PPG and HR measured by ECG (Fig. 2). Furthermore, the statistical analysis of our results showed that ΔSNRs of the green light PPG produced by the HM and VM conditions were smaller than those of the red light PPG (Fig. 3). Taken together, these findings suggest that the green light PPG appears to be the most suitable method for the monitoring of HR during normal daily life.

In contrast to the PR measured by green light PPG, the PR measured by red and blue light PPG gave poorer results. These results could be explained by the penetration depth of light into the tissue, but the reasons for these results probably differ from each other. The red light has a deep penetration depth into the tissue [9]. So, the red light PPG signal was quite sensitive to motion artifacts. That is, the poor results of PR measured by red light PPG could be caused by the large influence of motion artifact on the pulse wave itself. On the other hand, the ΔSNR of blue light PPG were comparable to the ΔSNR of green light PPG (Fig. 3), while the limit of agreement between the PR measured by blue light PPG and HR measured by ECG was larger than that between PR measured by green light PPG and HR measured by ECG (Fig. 2). These poor results of PR measured by blue light PPG could be caused by the different shape of the pulse wave. The shape of the pulse wave depends upon the properties of the blood vessels [1]. The blue light PPG reflects the volume change in small blood vessel in the skin surface due to the relatively shallow penetration depth of blue light into the tissue [9].

In this study, we have measured only the PPG at the finger-tip during waving motion. However, there are several body sites which pulses can easily be detected, examples including the ear, forehead, limb, and toe [1,13]. Furthermore, the waving motion used in laboratory experimentation does not necessarily reflect normal daily life situations. Therefore, further studies are needed to examine green light PPG at other sites during normal daily life.

V. Conclusion

The PR measured by green light PPG demonstrated good agreement as compared to the HR measured by ECG. Furthermore, the green light PPG was found to have relative freedom from motion artifacts as compared with red and blue light PPG. Therefore, we conclude that the green light PPG might be more suitable for monitoring of HR in the daily life than either red or blue light PPG.

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