

The Advantages of Wearable Green Reflected Photoplethysmography

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Abstract This report evaluates the efficacy of reflected-type green light photoplethysmography (green light PPG). Transmitted infrared light was used for PPG and the arterial pulse was monitored transcutaneously. The reflected PPG signal contains AC components based on the heartbeat-related signal from the arterial blood flow and DC components, which include reflectance and scattering from tissue. Generally, changes in AC components are monitored, but the DC components play an important role during heat stress. In this study, we compared the signal of green light PPG to infrared PPG and ECG during heat stress. The wavelengths of the green and infrared light were 525 nm and 880 nm, respectively. Experiments were performed on young healthy subjects in cold (10°C), hot (45°C), and normal environments. The pulse rates were compared among three measurement devices and the AC and DC components of the PPG signal were evaluated during heat stress. The pulse rates obtained from green light PPG were strongly correlated with the R–R interval of an electrocardiogram in all environments, but those obtained from infrared light PPG displayed a weaker correlation with cold exposure. The AC components were of similar signal output for both wavelengths during heat stress. Also, the DC components for green light PPG were similar during heat stress, but showed less signal output for infrared light PPG during hot exposure. The main reason for the reduced DC components was speculated to be the increased blood flow at the vascular bed. Therefore, reflected green light PPG can be useful for pulse rate monitoring because it is less influenced by the tissue and vein region.

Keywords Photoplethysmography · Green light · Infrared light · Reflection · Heat stress

Introduction

The increase in the elderly population and the prevention of lifestyle diseases such as hypertension, dyslipidemia, and diabetes highlight the importance of personal health care. The aim of personal health care is to make the care of ordinary people more readily available and to reduce hospital admissions. To prevent lifestyle diseases, factors such as exercise, sleep, and nutrition are important.

The estimation of exercise is important to controlling personal health. Specifically, the magnitude and duration of exercise must be monitored for safe and effective workouts. Several health care devices are now on the market, such as the Polar® device, a portable electrocardiography (ECG) monitor that the subject wears as a belt-type electrode, from which signals from the electrode are transmitted to a watch-type receiver so the user can look at his/her heart rate on the watch display. However, the attachment of the electrode is rather troublesome and only those who are interested in running and jogging are monitored for their exercise ability.

Another candidate device uses watch-type photoplethysmography (PPG). Since its development by Hertzman in 1938 [1], PPG has been used widely to monitor pulse rates. PPG is a simple and low-cost optical technique that can be used to detect blood volume changes in the microvascular bed. That is, it is often used for noninvasive measurement of the blood flow volume at the skin surface [2]. Basic PPG requires only a few optoelectronic components. The sensor consists of a light source to illuminate the skin tissue, and a photodetector to measure small variations in light intensity associated with changes in perfusion in the tissue volume.

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With the exception of powerful sources such as lasers, light has little direct effect on the human body. Light can be used not only for noninvasive measurements, but also to obtain biometric signals quickly and easily.

PPG is used as a simple pulse rate monitor in sports medicine. Furthermore, exact positioning sites are not necessary to obtain the signal. However, the main disadvantage is the large effect by motion artifact: if the subject moves, obtaining a measurable signal becomes difficult. In addition, the environmental effect with cold exposure is also considered.

PPG has two types: transmitted and reflected. For the transmitted type, an infrared light source (wavelength 600–1,300 nm) is generally used. This wavelength range has a large penetration depth in the skin. According to the Beer–Lambert Law, the penetration depth depends mainly on the absorption of hemoglobin, and thus, light of shorter wavelengths such as blue or green light penetrates less than light of longer wavelengths such as infrared. However, the arterial pulsations are recorded from the skin with light transmitted through the skin. The light source and detector are placed on the finger. Therefore, the measurement site should be in the peripheral, such as in the ear or in the finger.

In contrast, reflected PPG can be applied to any part of the body. Furthermore, if the distance between the light source and detector is short, the signal can be obtained from a short penetration region. In superficial tissue, the shorter penetration depth of green reflected light can be used to obtain a clear indication of blood volume. This report describes the possible use of reflected wavelengths shorter than infrared for PPG [3].

The PPG signal consists of AC and DC components. The AC component is based on heartbeats and the DC component is based on reflected and scattered light from the arterial, venous, and tissue layers, which are the components without a pulsatile signal [4]. The DC component affects the PPG signals themselves and changes in the body movement. Thus, the reflected type PPG needs to contain a small DC component and a large AC component.

The present study was performed to evaluate the use of reflected green light for PPG in different environments, to compare the results with those obtained using reflected infrared PPG and by ECG, and to identify the advantages of using the reflected-type green light PPG.

Materials and methods

The structure and diameter of blood vessels in the skin is depicted in Fig. 1. The DC component contains the tissue and arterial and vein layers, and the AC component contains the pulsatile flow of the blood vessel. The DC component is the main signal component of the signal. The obtained DC signal has a greater effect on the signal from

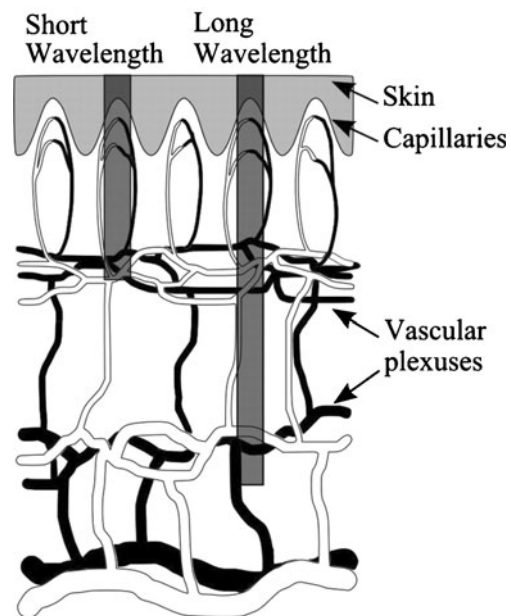


Fig. 1 The subepidermal vascular arrangement and the penetration depth of light of different wavelengths

infrared light with a large penetration depth compared to that from green light with a small penetration depth because the light irradiation volume is larger in infrared light than in green light. The skin perfusion also changes with environment. That is, if the skin is either cooled or heated, the skin perfusion varies with AC and DC components. Especially in the case of a large blood volume, the blood absorption increases and the signal decreases. In the reflected type, the influence is weaker with the green light compared to infrared light because the change in light irradiation volume is smaller. Thus, we investigated the PPG signal changes with environment using two different wavelengths and examined the signals based on AC and DC components.

Experimental setup

PPG involves the use of a light source, detector, amplifier, and power source. Both signals from green and infrared lights were obtained simultaneously. The green light-emitting diode (LED) (NSCG100A Nichiya, peak wavelength 525 nm, half intensity angle $\pm 60^\circ$) and infrared LED (SFH412, OSRAM, peak wavelength 880 nm, half intensity angle $\pm 60^\circ$) were used as light sources. The optical intensity was compensated by spectroscope (epp2000-vis100, Tokyo Instruments) and the optical densities of both wavelengths were the same. The detectors had a maximum sensitivity of 560 nm (S9067-01, Hamamatsu) and 880 nm (PA1101W, Stanley) for green and infrared LEDs, respectively. Both detectors had a half intensity angle of $\pm 70^\circ$. We measured the PPG signal without filtering to obtain the DC component. The signal was then band-pass filtered and amplified to obtain the AC component.

The green and infrared PPG sensors were attached to the index finger of the non-dominant hand. Simultaneously, we monitored the ECG (Bioview2000, NEC) with the II lead. Furthermore, skin temperature was measured using a thermocouple sensor (HPD1121 digital thermometer, Anritsu Electronics) on the ring finger and the skin blood flow was measured using a laser Doppler flowmeter (780 nm LD, ALF21D, Advance) on the middle finger for reference. All signals were sampled at 1,024 Hz and A/D-converted.

The cooling and heating for local heat stress was made using a small precision isothermal bath (FR-004, Tokyo Grass Kikai) and portable cooling unit (NCL-107, Nisshin Rika). The temperature for cold and hot exposures was set at 10°C and 45°C, respectively (Fig. 2).

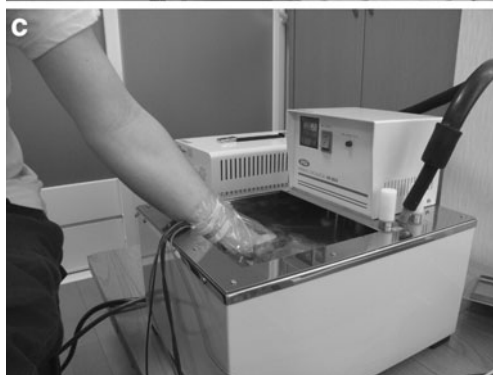
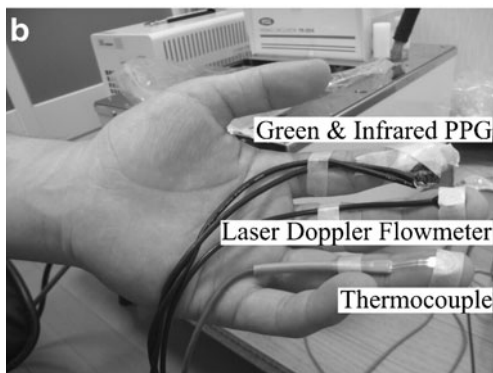
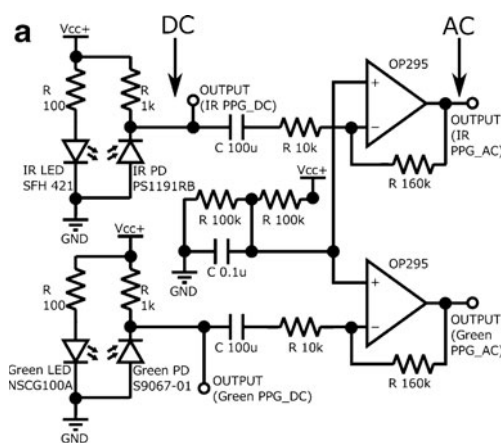


Fig. 2 **a** Measurement circuit, **b** measurement site, **c** measurement view

Subjects

Twelve young healthy subjects aged 23.6 ± 1.5 years without any indication of peripheral circulatory failure were recruited to participate in the experiment. This study was approved by the ethics committee of Chiba University School of Engineering. Written informed consent was obtained from all subjects after the experimental procedure was explained to them.

Protocol

In our preliminary experiments, we found that the skin temperature and skin blood flow increased or decreased gradually to new steady-state conditions. Most subjects reached the new steady-state condition after about 20 min. Furthermore, the skin temperature did not reach the temperature of the isothermal bath and most subjects showed skin temperatures of 20°C and 38°C with cold and hot exposure, respectively. Measurements were recorded at the new steady-state condition with skin temperatures of 20°C and 38°C.

For the cold exposure, the subject sat on a chair and immersed the hand into the isothermal bath at 10°C. After immersion, the skin temperature reached the new steady-state condition in 23.8 ± 8.2 min and the measurements were recorded in 1 min. For the hot exposure, the subject sat on a chair and immersed the hand into the isothermal bath at 45°C. After immersion the skin temperature reached the new steady-state condition in 20.7 ± 7.3 min and the measurements were recorded in 1 min.

Evaluation

Correlation coefficient The PPG signal represents volume changes based on the heartbeat. The pulse rate obtained by PPG in normal subjects should be the same as the heart rate obtained by ECG. Thus, the interval of the PPG signal was calculated and the compared heart rate was based on the R–R interval. The pulse rate was defined as the maximum points of the pulse signal of the first and second waves. The heart rate was defined as the interval of the R wave.

The pulse rate and heart rate are distributed as normal and linear regressed. Thus, the Pearson product-moment correlation coefficient was used. The correlation coefficient was defined as shown in Eq. 1 and 1'.

$$r(x, y) = \frac{C(x, y)}{\sigma(x)\sigma(y)} \quad (1)$$

$$C(x, y) = \frac{1}{N} \sum_{k=1}^N (x_k - \bar{x})(y_k - \bar{y}) \quad (1')$$

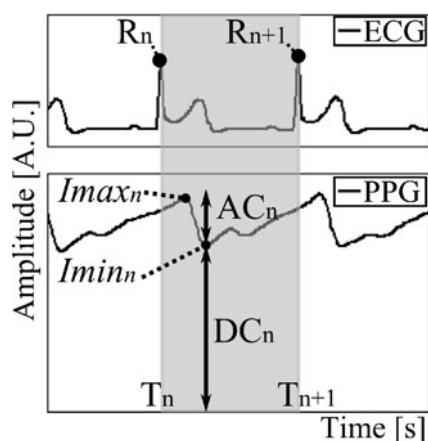


Fig. 3 AC and DC components in PPG signals

where x is the heart rate and y is the pulse rate. $\bar{x}$ and $\bar{y}$ are average of the heart rate and the pulse rate, respectively. C is the variance-covariance, σ is the standard deviation, and N is number of heart and pulse rate.

Component ratio The PPG signal contains AC and DC components. In this study, the AC and DC components as well as the component ratio were evaluated. AC component defines as the heartbeat-related signal from the arterial blood flow, and DC component includes reflected and scattered light component from the tissue. AC and DC components are total amount of reflected and scattered light from the skin. Thus Component ratio (CR) defines as a pulsatile component on the optical path.

In Fig. 3, AC is defined as the difference between the maximum (I_{max}) and minimum (I_{min}) optical densities. The DC component is defined as the minimum point of PPG

signal (I_{min}). I_{max} and I_{min} are found between two R waves in ECG. The component ratio was defined as shown in Eq. 2:

$$CR_n = \frac{AC_n}{AC_n + DC_n} = \frac{I_{max_n} - I_{min_n}}{I_{max_n}} \quad (2)$$

Finally, the averages of AC, DC, and CR were calculated. All data were statistically analyzed by Student's t -test.

Results

Typical examples of PPG signals in the normal environment (a) and at cold (b) and hot exposures (c) are shown in Fig. 4. The upper figures show the signal detected without filtering, which represents the DC component of the PPG signal. The middle and lower figures show the AC component of the PPG signal after band-passing of 0.7–10 Hz. With the cold and hot exposures, the amplitudes of pulse signals decreased, but we still acquired visible signals. Specifically, we could obtain the visible green signal with cold exposure, which the previous green LED displayed as a signal of lesser amplitude. Additionally, the maximum peak with cold exposure was unclear for the infrared signal as compared to the green one.

Table 1 lists the correlation coefficients between the pulse rate and heart rate, AC and DC components, and component ratio for cold and hot exposure and normal room temperature for green and infrared signals. The pulse rates were highly correlated with heart rates, showing correlation coefficients of more than 0.9 for all environments, except the infrared light with cold exposure. The correlation for infrared light with cold exposure was significantly lower (0.731) compared to that of the other environments ($P < 0.05$).

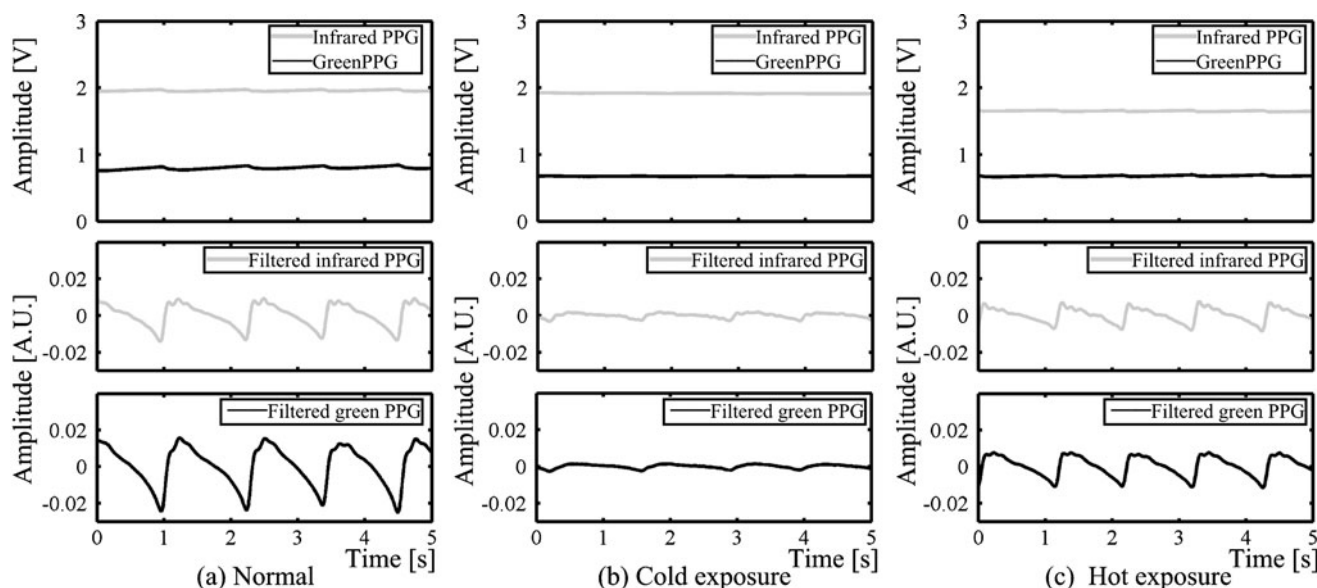


Fig. 4 Typical examples of PPG signals with cold and hot exposures and the normal environment

Table 1 Results of the current study

	Green PPG		IR PPG	
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
(a) Cold exposure (Below 20°C)				
	Below 20°C	Normal temperature	Below 20°C	Normal temperature
Correlation coefficient	0.934 $\pm$ 0.081	0.983 $\pm$ 0.020	0.731 $\pm$ 0.266*	0.977 $\pm$ 0.022
AC [mV]	5.91 $\pm$ 3.24*	44.63 $\pm$ 14.78	5.60 $\pm$ 1.84*	47.24 $\pm$ 19.44
DC [V]	0.671 $\pm$ 0.091	0.663 $\pm$ 0.082	1.852 $\pm$ 0.158	1.852 $\pm$ 0.173
CR	0.009 $\pm$ 0.004*	0.062 $\pm$ 0.014	0.003 $\pm$ 0.001*	0.025 $\pm$ 0.010
(b) Heat exposure (Over 38°C)				
	Over 38°C	Normal temperature	Over 38°C	Normal temperature
Correlation coefficient	0.988 $\pm$ 0.016	0.988 $\pm$ 0.010	0.903 $\pm$ 0.145	0.981 $\pm$ 0.028
AC [mV]	30.97 $\pm$ 9.15*	40.73 $\pm$ 7.83	17.83 $\pm$ 7.36*	38.99 $\pm$ 12.43
DC [V]	0.685 $\pm$ 0.085	0.703 $\pm$ 0.130	1.713 $\pm$ 0.254*	1.848 $\pm$ 0.246
CR	0.043 $\pm$ 0.010	0.056 $\pm$ 0.013	0.010 $\pm$ 0.004*	0.021 $\pm$ 0.009

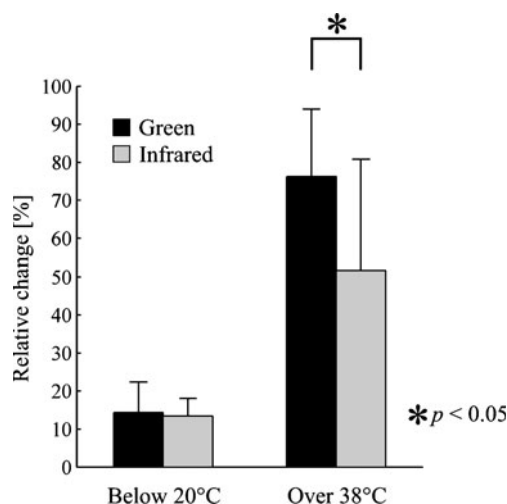
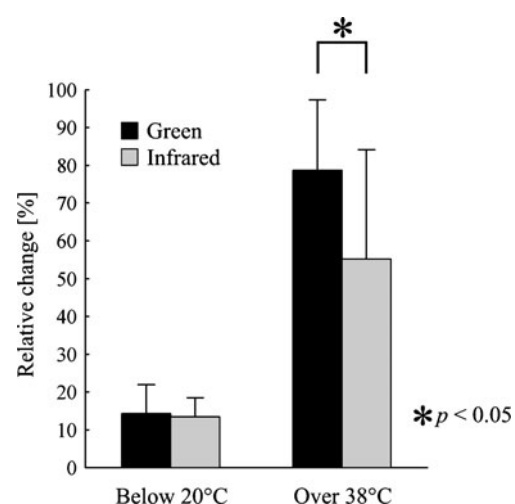
* $P < 0.05$

The AC components obtained from green and infrared light decreased with cold exposure compared to the signals obtained at the normal temperature; they also decreased with hot exposure, albeit to a lesser extent. With cold exposure, the AC component declined to 14% and 13% for green and infrared light, respectively, whereas the AC components with hot exposure were 76% and 52% for green and infrared light, respectively. Figure 5 depicts the relative changes in AC components with hot exposure; the decrease for green light was significantly smaller than that observed with infrared light ($P < 0.05$).

For the DC component, small changes were observed between green and infrared light with cold exposure. With hot exposure, the signal for infrared light was 93% of that observed at the normal temperature. Only the infrared

signal showed a significant reduction of the DC component with hot exposure ($P < 0.05$).

The component ratio (CR) is presented in Fig. 6. The CR of the green light PPG was more than twice that of the infrared PPG at normal temperature, and more than threefold greater with cold and hot exposure. Furthermore, the change in CR was significant with cold exposure, showing signals of 14% and 13% for green and infrared light, respectively. The CR with hot exposure was relatively small compared to that with cold exposure, showing 79% and 55% for green and infrared light, respectively. However, the change in CR for infrared light was significantly greater than that for green light ($P < 0.05$). The CR represents the ratio of the AC component in the detected signal; the green light showed the larger CR in all environments.

**Fig. 5** Relative changes in the AC component**Fig. 6** Relative changes in the component ratio (CR)

Discussion

Generally, the transmitted-type of PPG with infrared light has been used in monitoring the pulse rate and the measurement site has been limited to the peripheral. In recent years, the reflected-type PPG has become popular for the purpose of the prevention of lifestyle-related diseases and for the evaluation of postoperative exercise. Furthermore, green light has been used as a light source [6]. Green light is absorbed by the blood vessels and has a small penetration depth. Thus, green light does not suit the reflected type PPG. Nevertheless, our results suggest a benefit in using reflected green light PPG because it can detect the pulse rate with a high degree of precision in two different environments.

The penetration depth of light is dependent on its wavelength [5]. The shorter wavelength of green light means that it will not reach deeper tissues, and thus reflected green light PPG would include less information from various non-pulsatile media than infrared PPG [6]. The reflection and scattering from deeper tissue produce a much more complex signal. This means that reflected infrared will not contain a simple PPG signal and that reflected green light PPG is affected by noise to a much lesser extent. In particular, the PPG signal amplitude is very low for skin temperatures below 20°C. Most likely, noise based on non-pulsatile media strongly influences the correlation coefficients.

The interpretation of PPG signal changes in different environments is rather complicated. With cold exposure, the AC components of each green and infrared light decreased significantly, but the DC components were almost similar in amplitude. The changes in AC components were caused by the vasoconstriction upon cold exposure but the total irradiation volume did not change. With hot exposure, the AC components of each green and infrared light decreased, and the DC component of green light did not change, whereas the DC component of infrared light decreased (Table 1). The irradiation volume including the blood vessel

should be larger with hot exposure than that at normal temperature. Thus, the absorption of infrared light increased. Furthermore, the optical pass was influenced by the noise from the non-pulsatile media. Nevertheless, the CR values for green light were always larger than those of the infrared. Therefore, reflected green light may be a good candidate for wearable PPG.

Conclusions

We investigated the utility of reflected green light PPG in comparison with reflected infrared PPG and ECG. The results indicated that the difference in wavelength affects the CR, and that the CR affects the correlation coefficients of the heart rate and pulse rate, especially at skin temperatures above 38°C. These results suggest that reflected green light PPG has an advantage over reflected infrared PPG.

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