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Effects of Local-Heating Stimulation on the Harmonic Structure of the Blood Pressure and Photoplethysmography Waveforms

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Abstract. Photoplethysmography (PPG) involves measuring an optic signal related to the arterial volumetric pulsations of blood, and has great potential in clinical applications due to its simplicity and noninvasiveness. In the present study, we aimed to verify if the induced vasodilation and increase in terminal blood supply by local heating stimulation (LH) could help to improve the correlation of harmonic components between radial BP and finger PPG waveforms. Trials were performed on male healthy volunteers (n=17) aged 25-31 years. LH was performed by placing a waterbag filled with 35^{o}C water around the lower arm. BP and PPG spectra were calculated from the averages of all of the pulses during the entire measurement period for the amplitude proportion. For the first three harmonics, the correlation coefficients for the regression lines between BP and PPG waveforms were significantly increased and decreased, respectively, following LH. The present result illustrated improved BP-PPG correlations of harmonic components following LH. It implies that an appropriate environmental temperature could improve the reconstruction of the BP waveform from noninvasive PPG measurements. The present frequency-domain analysis method could thus provide an alternative more-convenient method for acquiring the BP waveform, and hence bring new study directions for further applications such as in evaluating whole-body responses of the blood supply to various treatment strategies, the augmentation index calculation, and telemedicine.

Keywords: photoplethysmography, local heating, harmonic analysis

1. Introduction

Photoplethysmography (PPG) is an optical measurement technique used to monitor blood volume changes in microvascular beds of peripheral tissue, and also to monitor arterial pressure and compliance, with great potential in clinical applications due to its simplicity and non-invasiveness. Since the blood pressure (BP) inside an artery distends the vessel wall, changes in BP can be correlated with changes in the vessel volume and thus the PPG signal [1, 2].

The arterial stiffness is suggested to affect the propagation velocity of the pulse wave (PWV), and the wave reflection can be altered by changes in the perfusion condition of the peripheral vascular beds. Time-domain index based on arterial pulse-wave analysis, such as PWV and augmentation index, could thus help in establishing the extent of cardiovascular disease and in monitoring the effects of therapies [3].

However, time-domain waveforms can be distorted by various types of small perturbation, especially on the peak point (which leads to an erroneous PTT value) or the other parts of the pulsatile PPG waveform (which can lead to errors in calculating the pulse width) [1], [2]. It might limit practical applications of the time-domain PPG waveform index. Since the frequency ranges can be separated from the main components of the signal of interest, frequency-domain analysis can be less affected by some important types of interferences (e.g., motion artifacts and 50-/60-Hz noise) compared with time-domain analysis. For example, frequency-domain analysis has been applied to BPW to monitor the distribution function of the blood supply and to predict outcomes for important cardiovascular diseases [4], [5], and to the PPG signal to study autonomic nervous control of the peripheral circulation [6].

Nonpainful local heating (LH) evokes vasodilation that is mediated by neurogenic reflexes and locally released substances. The enhancement the blood circulation following LH may result in an increased metabolic rate and transport of metabolities and other essential biochemical compounds. Thermal hyperemia has been used to assess endothelial function, allowing the assessment of NO-dependent vasorelaxation reported as the amplitude of the second peak.

We previously demonstrated that an appropriate contact pressure could improve the reconstruction of the BP waveform (BPW) from noninvasive PPG measurements and frequency-component analysis [1]. In the present study, we aimed to verify if the induced vasodilation and increase in terminal blood supply by local heating stimulation (LH) could help to improve the correlation of harmonic components between radial BP and finger PPG waveforms. Such a technique might be useful in developing a new noninvasive index for monitoring the blood-flow condition at local vascular beds induced by LH or other types of treatment strategies that improve local blood supply.

2. Methods and Materials

2.1. Experimental Procedure

17 trials were performed on male healthy volunteers aged 25-31 years and without signs or symptoms of cardiovascular or neurological disease. The subjects were lightly clothed, supine, and were allowed to stabilize for at least 10 minutes before recording commenced. The subjects were enquired about their psychological condition to prevent the interference effect. The environmental temperature was within 23-25°C during the entire measuring period. All subjects gave their informed consent before experiments commenced, were asked to not take any medication for 3 days before experiments, and did not consume food at least 1 hour before each experiment. All subjects were non-smokers, and did not take coffee or drinks containing alcohol at least 1 day before experiments [1], [2].

The LH was applied by placing a waterbag filled with 2000-cc 35-37 °C water around the right lower arm, and ECG, PPG, LDF and BPW signal were measured simultaneously and noninvasively. ECG signals were measured by surface electrodes, and acquired by a preamplifier (lead II, RA-LL; 6600-series, Gould, USA). BPW was measured by a pressure transducer (Kyowa_KFG-2-120-D1-11). This device is linear within ±0.1% of the rated output and has a flat frequency response between 0-5 kHz. A 1.5-cm-wide plastic belt was used to hold the pressure sensor around the right wrist. LDF (MBF3, Moor Instruments, UK) was used for measuring the skin-surface MBF on the back of the right hand. The PPG signal from a 940-nm-wavelength infrared LED (QED233, Fairchild Optoelectronic) penetrating the finger tissue was acquired by a photodiode (L-SB1R9PD1D1, Para, Japan). When performing PPG measurements, subjects were instructed to put the right middle finger into a self-made measurement cavity that had a black inner wall to reduce interference from light leakage. A hand-shaped mold was placed under the palm to improve the positioning reproducibility of the hand and finger. A contact pressure was applied around the first knuckle of the finger using a 3-mm-thick sponge as a force cushion. The vertically applied pressure was precalibrated and monitored by a force gage (1000gw, OHBA SIKI, Japan) to be around 60 mmHg to improve the PPG measurement stability and to reduce user discomfort. The BP signal was connected to a preamplifier (UV-10, Sensotec), the PPG signal was connected to a self-made current-to-voltage converter circuit, and all signals were then connected to an analog-to-digital converter card (PCI-9111DG, Adlink Technology, Taiwan) operating at a sampling rate of 1024 Hz [1], [2].

For each experiment, we recorded a 3-minute baseline-data sequence (M0), applied local mild LH and recorded a 3-minute effect sequence (M1), and then recorded another 3-minute effect sequence right after stopping the stimulation (M2). Before and after the whole procedure, we measured fundamental physiological parameters of the subject, including HR, systolic BP (SBP), and diastolic BP (DBP) using a sphygmomanometer (MediGuard 150i, Rossmax). One thermistor was attached to monitor the contact temperature between the skin surface and the waterbag. The acceptable range for the temperature stability during the baseline period was a temperature variation of less than 1.0 °C.

2.2. Signal Analysis

For the LDF signals, the mean MBF (MMBF) was defined as their average values during each 3-minute data sequence. The PPG and BP signals were first passed through a digital 11th-order high-pass Chebyshev filter with a cut-off frequency of 0.01 Hz to eliminate the baseline drift. To determine each beat-to-beat waveform, the two neighboring minima of a signal helped to identify the cut points to define the pulse [2].

In harmonic analysis, the acquired BPW or PPG pulse [$x(t)$] can be represented by the following finite series:

$$x(t) = \frac{A_0}{2} + \{\sum_{n=1}^{k/2} A_n \cos n\omega t_s + \sum_{n=1}^{k/2} B_n \sin n\omega t_s\}$$

The Fourier coefficients (A_n and B_n) of the BPW pulse can be calculated by

$$A_n = \frac{2}{k}\sum_{s=0}^{k} x_s \cos n\omega t_s \quad (\text{for } n = 0, 1, ..., \frac{k}{2})$$

$$B_n = \frac{2}{k}\sum_{s=0}^{k} x_s \sin n\omega t_s \quad (\text{for } n = 0, 1, ..., \frac{k}{2})$$

where ω is the angular frequency and t_s is the sampling time interval. The amplitude (Amp_n) and phase angle (φ_n) of each harmonic can then be calculated by $Amp_n = \sqrt{A_n^2 + B_n^2}$ and $\varphi_n = \tan^{-1}(B/A)$, respectively.

BPW and PPG spectra were calculated from the averages of all of the pulses during the entire measurement period for the amplitude proportion (C_n) of the nth harmonic according to $Amp_n/Amp_0 \times 100\%$ for n=1 to 10, where Amp_n is the amplitude of the nth harmonic of the BPW and Amp_0 is the DC component of the pulse spectrum. Signal processing was performed with MATLAB. Differences were considered significant when $p<0.05$.

3. Results

The fundamental physiological parameters did not change significantly between before and after the LH ($p>0.2$ by two-tailed paired t-test). As shown in Fig.1, MMBF was significantly increased following LH, which illustrated prominent influences on local MBF supply.

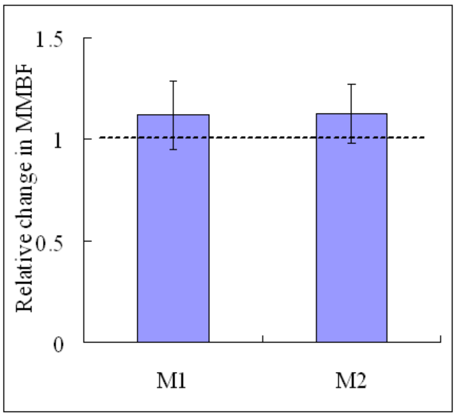

Fig. 1: Relative changes (defined as [M1 or M2 values] / [M0 value]) of MMBF following LH. Both $p<0.05$ compared with the baseline (M0) value by two-tailed t-test.

As listed in Table 1 and shown in Fig.2, the correlation coefficients of the regression line of the first three harmonic component (C_n, the amplitude rations) between BPW and PPG waveforms were improved (increased) following the present mild LH.

Table 1: Correlation coefficients (R^2) of the regression line of harmonic component (C_n) between BPW and PPG waveforms.

	M0	M1	M2
C1	0.72	0.92	0.86
C2	0.72	0.82	0.83
C3	0.51	0.60	0.52
C4	0.0049	0.02	0.0067
C5	0.14	0.0064	0.0232
C6	0.0087	0.2398	0.0657
C7	0.0003	0.2304	0.0017
C8	0.0672	0.4672	0.0794
C9	0.0378	0.2282	0.1326
C10	0.0917	0.2608	0.1281

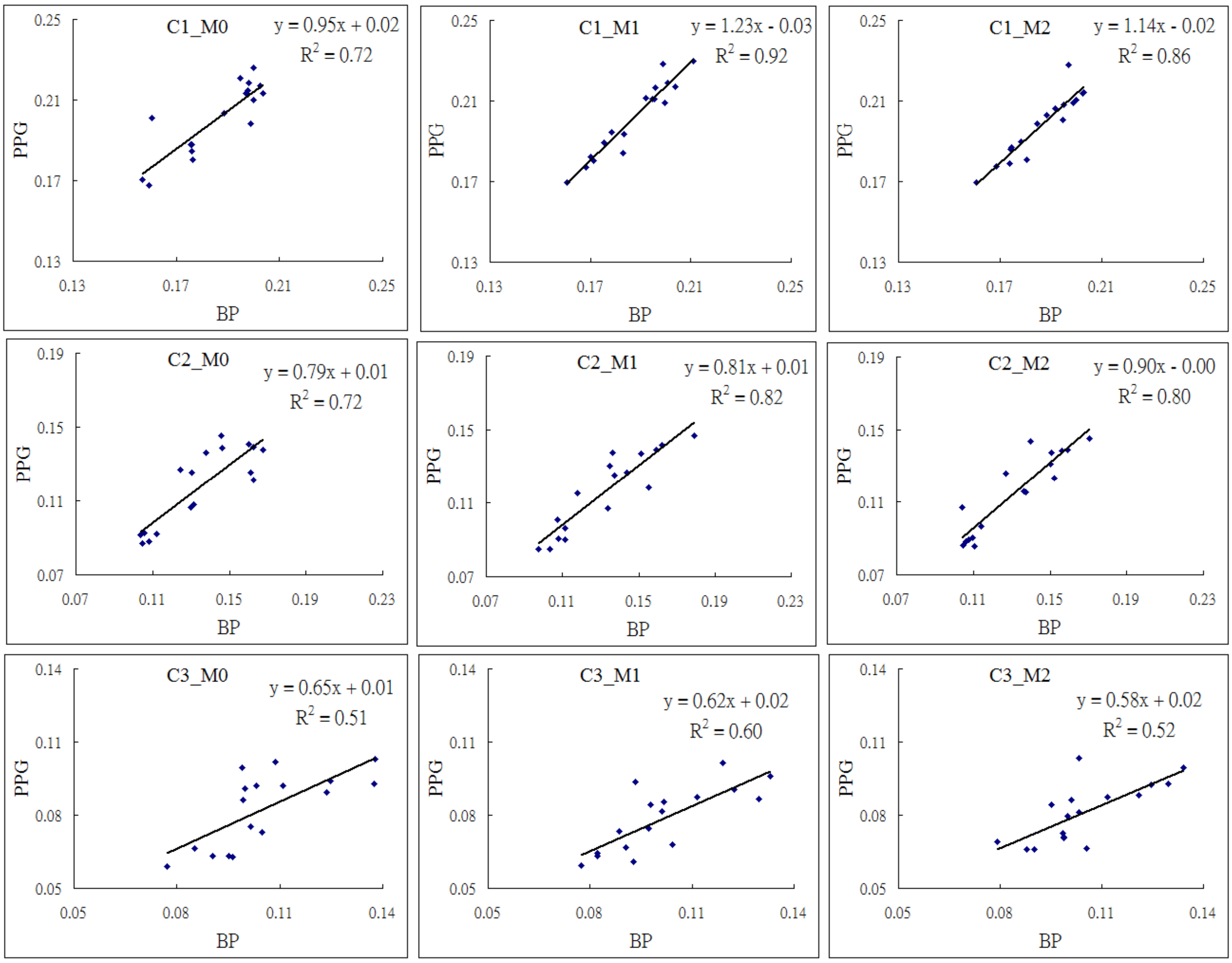

Fig. 2: Linear regression of the first three harmonic components (C_n, the amplitude rations) between BPW and PPG waveforms following LH.

4. Discussion

In summary, we have demonstrated that although the present LH was mild (in order to minimize interference of other physiological mechanisms to focus the discussion), harmonic-analysis index of BP and PPG waveforms, possible indicators of wave transmission, were significantly changed. Applying LH to the skin surface of the PPG measurement site had a prominent effect on the PPG waveform. The regression between the radial-artery BP and finger PPG waveforms was best in Group PS60, which implies that using an appropriate applied LH could improve the reconstruction of the BP waveform from noninvasive PPG measurements. Significant differences in LDF MMBF were noted, whereas absence of significant difference in fundamental physiological parameters illustrated no prominent induced whole-body effect following the present mild LH, which ensured local response and minimized the interference of other sensational effect induced by LH.

It is possible that the temperature rising can increase the blood flow supply in the underlying vascular beds of the finger. The pulsation of the local arteries was increased, and therefore the index of the PPG waveform can aid the monitoring of the change in the local microcirculatory condition. As blood fills the microvascular beds, it might enhance the resistance ability for the vessels against various external interfering factors on the coupling between the radial artery and the finger vessels, and hence produce a reliable transfer relation between finger PPG and radial-artery BP waveforms.

This preliminary study suggests that the responses of harmonic index of BP and PPG waveforms can be used to quantify the microcirculatory to LH, possibly due to providing more detailed information about the pulse transmission of each frequency components. Since blood supply is essential to the physiological function of local tissue, the present finding provides new insight into the cardiovascular responses to LH, and could have meanings in developing index to improve the resolving ability for the arterial elastic properties induced by LH, other forms of stimulation, or pathological factors.

The pulse waveform can vary between different sites along the arterial transmission. The BP pulse contour is often difficult to assess noninvasively, except for some specific sites such as the skin surface of the radial artery or the carotid artery. Compared with BP measurement, assessing PPG waveform is easier on many sites, such as the downstream site (the finger) of the radial artery. This advantage of PPG measurement may facilitate an easier and more user-friendly method to noninvasively evaluate the condition of arterial pulse transmission. Therefore the present finding could provide a new solution for the practical application of PPG measurement, and may be pertinent to monitoring of disease progression, evaluation of treatment efficacy, and to the medical-device development for application in point-of-care system or in telemedicine.

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