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Investigation of blood pulse PPG signal regulation on toe effect of body posture and lower limb height

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Abstract: Objective: To study the regulation of blood pulse volume via photoplethysmography (PPG) signal detected from toe, while the lower limb is passively raised in different height positions. Methods: Use a modified non-invasive PPG technique to detect the blood pulse signal on toe with infrared (IR) photo sensor. A protocol consisting of two postures, i.e., supine and 45° reclining, was designed to conduct laboratory trial in this study. During the period of performing the protocol of these postures, the lower limb was passively raised from the heights of 10 cm to 60 cm randomly and individually with sponge blocks underneath the foot. Results: In the supine posture, the higher the foot was passively raised, the more the blood PPG signal decreased. In the 45° reclining posture, the blood PPG signal increased at the beginning and then decreased in the foot height position from 10 cm to 60 cm. In both postures the normalized AC signal changes significantly while the normalized DC signal changes little. Conclusion: The toe PPG signals can obviously indicate the regulated blood volume change with the designated postural procedures due to the heart level position.

Key words: Photoplethysmography (PPG), Non-invasive, Body posture, Blood pulse volume signal, Lower limb
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INTRODUCTION

According to the estimate of the World Health Organization (WHO) and International Diabetes Foundation (IDF), there are currently 194 million diabetic patients worldwide and the number will be 330 million in 2025 (WHO, 2006). Approximately 15% of the total diabetic population (Boulton, 2000) will develop diabetic foot ulceration with some stage of blood vessels (London and Donnelly, 2000; Watkins, 2003; Vinik and Mehrabyan, 2004). The long term and severe diabetes could lead to amputation of lower limbs.

In order to reduce ulcerate caused by diabetes and other lower limb vascular diseases, we need to access lower limb peripheral vascular perfusion for physiologist and pathologist to understand clinical situation before the clinical symptome appeared and decrease the amputation rate (Donnelly *et al*., 2000; Cobb and Claremont, 2002). Pulse measurement for distal blood vessel is one of the common means, for instance, detection of lower limb vascular perfusion to keep foot from being damaged (Tripathi *et al*., 1989; Cooper and Hainsworth, 2002; Allen *et al*., 2005). In this study we present pulse amplitude derived from PPG signal to indicate the change of toe blood pulse volume utilizing modified PPG technique. The AC and DC components from the test toe in executing the protocol were captured. Analysis of the normalized AC, DC and the ratio of AC/DC (Cunningham *et al*., 1988; Allen and Murray, 2003) was processed to express the postures of foot raised passively in supine and 45° reclining.

METHODS

Subjects

The trials were conducted on 13 healthy subjects including 9 males and 4 females aged 20~30. The subjects were asked to refrain from caffeine, smoking, alcohol drinking and strenuous exercise within 4 h prior to the test. The subjects were recruited from students and staffs of Loughborough University, UK. All subjects gave their written informed consents.

Ambient conditions

The ambient temperature is (24±2) °C; the room noise ≤55 dB; the relative humidity is (50±15)%.

Equipment and software

The toe probes were Dolphin 3311V (Nellcor compatible) transmission mode pulse oximetry probes (Dolphin Medical, UK), with wavelength 905 nm, at approximately 2 mW optical power. The probe was used to detect the PPG signal from the subjects' second right toes. The PPG signal was sampled at 128 Hz and captured by PADD system (Dialog Devices Ltd., UK). The data were recorded by the developed program DISCO4FEET with LabView 7.1. The data were loaded to Matlab 6.5 and Microsoft Excel 2000 for data processing and analyzing.

Protocol

The subjects were requested to measure their systolic blood pressure (SBP), diastolic blood pressure (DBP) and heart rate via a digital blood pressure monitor (A&D Instruments Ltd., UK) just before the trial. The probe was attached to the subject's second toe and the temperature sensor (RS Components Ltd., UK) was also stuck on the subject's lower limb. The subject was asked to lie on a trial bed and relax 5 min. During the period of a successive trial, the right foot was passively raised onto a sponge block at a random height of 10~60 cm, and the left foot was kept still.

1. Supine posture

The subject's right foot was passively raised onto a sponge block at height of 10, 20, 30, 40, 50 and 60 cm respectively. The order of the height was random.

(1) The PPG signal was collected for 10 s in supine position (Zhang *et al*., 2004).

(2) After sponge blocks 10 cm to 60 cm height were gently added up below the subject's right foot, the subject was requested to relax for 5 s and the PPG signal was recorded 10 s.

(3) The sponge blocks were gently moved out and then the right foot was returned to the original supine position. After 5 s relaxation, the PPG signal was recorded 10 s again.

The above steps (1)~(3) were repeated 3 times.

Fig.1a shows a subject in supine position, the right foot was passively raised at test height position and the PPG signals were collected from the right toe.

The subject was asked to have a break for 5 min before the 45° reclining posture trial.

2. 45° reclining position

The subject was asked to recline on 45° sponge block. The operating procedures were the same as those for the supine posture trial.

Fig.1b shows a subject in the 45° reclining position with the foot passively raised to a test height and PPG signals were collected from the right toe.

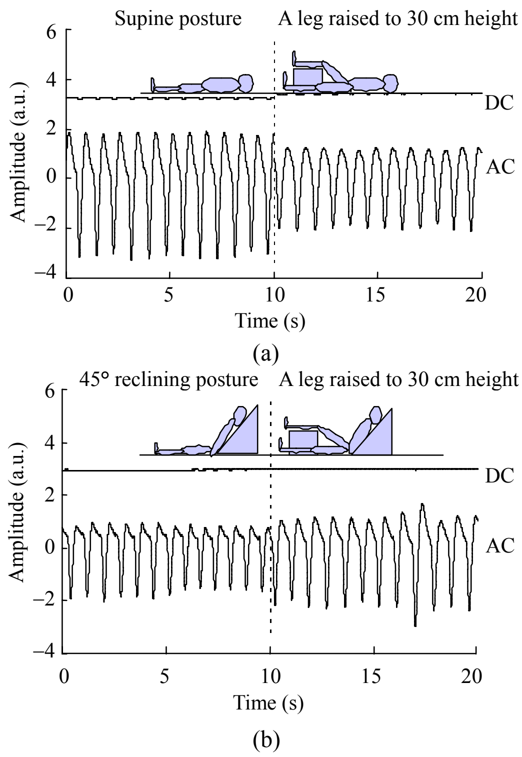

Fig.1 AC and DC signal from a subject with passive right leg raised to 30 cm height. (a) Supine posture; (b) 45° reclining posture

Data analysis

The digitised PPG AC and DC signals collected from the trial were analyzed using Matlab. The PPG AC amplitude can be defined in Fig.2 as the absolute value from the peak to the trough of the PPG wave, and the interval is defined as the absolute value between two wave troughs, called pulse-to-pulse interval (PPI).

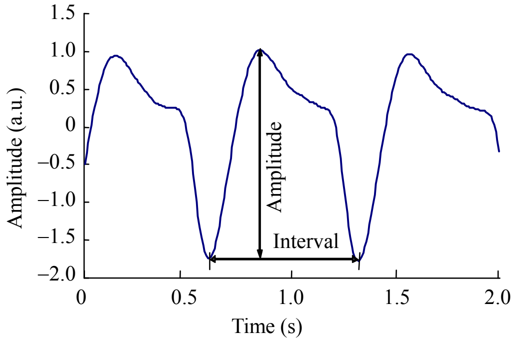

Fig.2 Typical photoplethysmographic AC signal

The pulse-to-pulse AC amplitude was first measured, from which the mean AC amplitude of each subject was calculated. The mean DC was calculated by averaging over each 10 s recording, as the DC signal was relatively constant over a short period. For individual postural trial height (10, 20, 30, 40, 50 and 60 cm), the mean value of the AC amplitude and the DC were calculated by averaging mean AC and DC over all the 13 subjects.

The mean AC and DC amplitudes for each leg raised period were then position normalized by dividing the mean values from the not-raised position.

RESULTS

The mean values and the standard deviation (SD) of normalized amplitude in the supine posture are shown in Table 1. The mean values for each height were different. The mean values of normalized AC and the ratio of AC/DC significantly decreased when the foot was passively raised to height of 10~60 cm. The lowest value of the ratio of AC/DC was only 0.30 and the normalized DC amplitude derived from the supine PPG signals indicated increasing tendency.

In the 45° reclining posture, the mean values and the SD of normalized AC and the ratio of AC/DC increase are listed in Table 2. The results showed these values increased first and then decreased when the right foot was passively raised to height of 10~60 cm. The normalized DC amplitude derived from the 45° reclining PPG signals also showed increases. The values of Table 1 and Table 2 are respectively plotted in Fig.3 and Fig.4.

Table 1 Normalized PPG amplitude and the standard deviation (SD) in the supine postural trial

Height (cm)	AC mean	SD (AC)	DC mean	SD (DC)	AC/DC mean	SD (AC/DC)
10	1.00	0.09	1.02	0.01	0.99	0.10
20	0.95	0.13	1.03	0.02	0.92	0.13
30	0.78	0.17	1.05	0.02	0.74	0.16
40	0.60	0.15	1.07	0.03	0.56	0.13
50	0.46	0.18	1.08	0.04	0.42	0.16
60	0.33	0.17	1.09	0.04	0.30	0.15

Table 2 Normalized PPG amplitude and the standard deviation (SD) in the 45° reclining postural trial

Height (cm)	AC mean	SD (AC)	DC mean	SD (DC)	AC/DC mean	SD (AC/DC)
10	1.04	0.12	1.02	0.02	1.02	0.13
20	1.15	0.15	1.04	0.03	1.10	0.16
30	1.15	0.23	1.06	0.03	1.06	0.22
40	1.10	0.28	1.08	0.04	1.00	0.27
50	1.02	0.35	1.10	0.04	0.92	0.35
60	0.84	0.26	1.12	0.04	0.73	0.23

Fig.3 shows that with supine position the normalized DC amplitude increased and the normalized AC amplitude decreased with increasing block height. The amplitude ratio of height 60 cm was only about 0.30.

Fig.4 shows that with 45° reclining position the normalized DC amplitude increased and the normalized AC amplitude increased from the height of 10~30 cm and decreased from the height of 30~60 cm. The curves of the normalized AC and the ratio show that the highest point is at the height of 30 cm.

DISCUSSION

When a foot is passively raised from low to high position, the venous blood in lower limb can return to the heart. Then the end-diastolic volume, the stroke

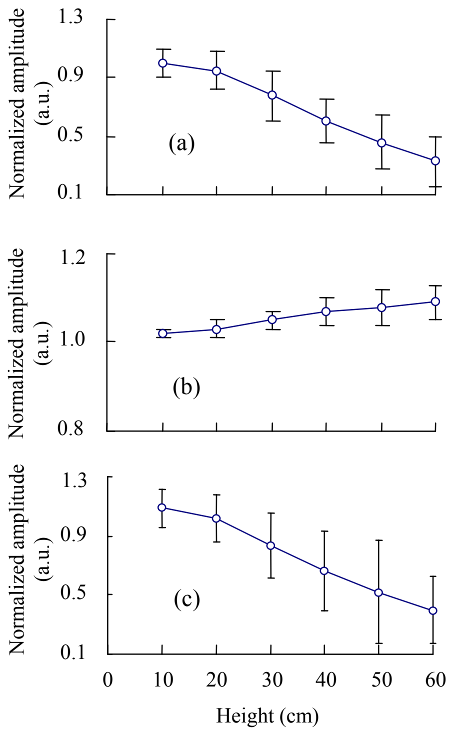

Fig.3 Peripheral vascular response of lower limb in supine posture. AC (a), DC (b) and AC/DC (c) normalized amplitude of PPG

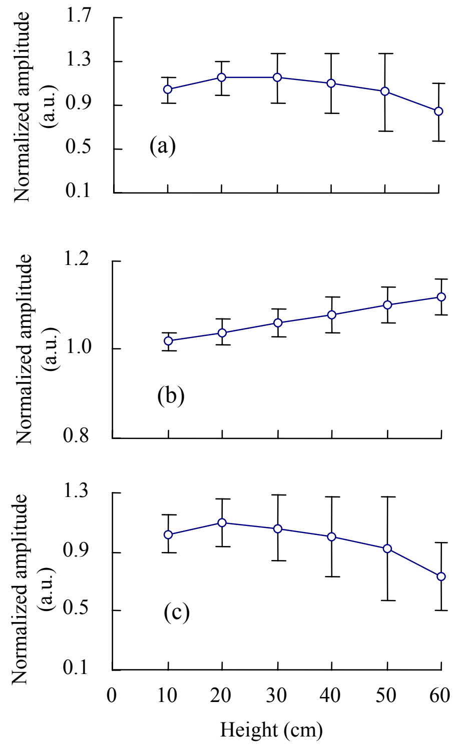

Fig.4 Peripheral vascular response of lower limb in 45° reclining posture. AC (a), DC (b) and AC/DC (c) normalized amplitude of PPG

volume and the cardiac output could be increased as well (Berne and Levy, 1998). The increase of the blood pressure could be easily observed. Baroreceptor reflex adjustment could also decrease the blood pressure trend to balance through sympathetic and parasympathetic systems to decrease cardiac rate and cardiac output. The central response could appear as the symptom in several heart beats (Fox, 2002), thus impacts the PPG signal after few seconds with foot raised.

The baroreceptor reflex can be activated whenever the relative height of the raised foot and the heart level are changed. In this study, the values of AC normalized amplitude and the ratio of AC/DC decreased with foot height increased from 10 cm to 60 cm in supine postural trial. In similar outcome from the 45° reclining postural trial, the values of normalized amplitude of AC and the ratio of AC/DC decreased in the position from 30 cm to 60 cm and increased in the position from 10 cm to 30 cm. The effect of blood pulse regulation with the postural changing in this study is in consistence with the theory of blood flow dynamics (Liu and Li, 1997).

CONCLUSION

The results from the supine and the 45° reclining postural trials showed identical regulation of lower limb blood perfusion. The critical point of changing tendency appears while the foot and heart are at the same level. When the blood volume of the peripheral vasculature or blood vessel in lower limb is blocked via either physiological or pathological stage, it will affect local blood circulation and even central blood circulation. Hence the blood pulse volume on the foot can be observed obviously.

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