INVESTIGATION OF PHOTOPLETHYSMMOGRAPHIC SIGNALS AND ARTERIAL BLOOD OXYGEN SATURATION VALUES (SpO_2) DURING BLOOD PRESSURE CUFF-INDUCED HYPOPERFUSION

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ABSTRACT
Photoplethysmography is a non-invasive electro-optical technique widely used in the study and monitoring of the pulsations associated with changes in blood volume in a peripheral vascular bed. Photoplethysmography is used in the estimation of arterial oxygen saturation (SpO_2) by pulse oximetry. A reflectance finger photoplethysmographic (PPG) probe and a multiplexed data acquisition system operating simultaneously at two wavelengths and incorporating an external lead II electrocardiogram (ECG) reference channel, and a commercial finger pulse oximeter has been developed. The aim of this study is to investigate the morphology and amplitude of PPG signals and its effect on pulse oximetry during blood pressure cuff-induced hypoperfusion. PPG signals and SpO_2s and standard ECG traces were obtained from 14 healthy volunteers and displayed on a personal computer. Measurable PPG signals at both infrared and red wavelengths were obtained from all induced pressures prior to full brachial occlusion. There are statistically significant differences between the ac PPGs in the low pressures (0 to 80 mmHg) than those in the upper pressures (90 to 150 mmHg) at both wavelengths. Both pulse oximeters showed gradual decrease of saturations during induced hypoperfusion which demonstrate the direct relation between blood volumes (PPG amplitudes), arterial vessel stenosis and blood oxygen saturation. The custom made pulse oximeter was found to be more sensitive to SpO_2 changes than the commercial pulse oximeter especially at high occluding pressures.

KEY WORDS
Photoplethysmography (PPG), arterial oxygen saturation (SpO_2), Blood pressure, Hypoperfusion

1. Introduction

Photoplethysmography is a non-invasive electro-optical technique widely used in the study and monitoring of the pulsations associated with changes in blood volume in a peripheral vascular bed [1-5, 7] . Photoplethysmography is based on the absorption properties of vascular tissue when it is transilluminated by light. The emitted light, which is made to traverse the skin, is reflected, absorbed and scattered in the tissues and blood. The modulated light which emerges is measured using a suitable photodetector. The photoplethysmographic (PPG) signal component is synchronous with the heart rate which is assumed to be related to the arterial blood volume pulse [6-7]. Also, the PPG pulse shapes are indicative of vessel compliance and cardiac performance. Photoplethysmography is used in the estimation of arterial oxygen saturation (SpO_2) by pulse oximetry. Pulse oximeters estimate arterial oxygen saturation non-invasively by shining light at two different wavelengths, red and near infrared, through vascular tissue [8]. Hence, the technique of pulse oximetry relies on the presence of adequate peripheral arterial pulsations, which are detected as photoplethysmographic (PPG) signals. When peripheral perfusion is poor, as in states of hypovolaemia, hypothermia, vasoconstriction, low cardiac output and low mean arterial pressure, pulse oximeter readings become unreliable or cease altogether [9,10]. The oxygenation readings become unreliable in these circumstances because conventional pulse oximeter sensors are usually placed on the most peripheral parts of the body such as the finger, where pulsatile flow is most vulnerable, as it is compromised by diversion of blood flow to more vital organs. Hence, pulse oximetry becomes unreliable in a significant group of patients at just the time when the measurement of blood oxygen saturation would be clinically of most value. Newly developed pulse oximetry technologies such as Masimo SET were designed to display accurately blood oxygen saturation values during motion artefact or during periods of hypoperfusion. However, there are only a few reports on the accuracy of pulse oximeters during hypoperfusion in a clinical setting [11]. This pilot study will investigate in detail the morphology and amplitude of the PPG signal and its effect on pulse oximetry under controlled vasoconstrictive studies.

2. Methods

2.1 Instrumentation

A reflectance finger PPG/SpO_2 probe was constructed comprising two infrared (IRED) and two red surface mount emitters and a surface mount photodetector (figure 1). The photodetector detected radiation back scattered by

the tissue from the infrared and red emitters and gave an output current proportional to the detected radiation intensity. A screened multicore cable carried the power to the infrared and red emitters in the probe from the main pulse oximetry processing unit and also the PPG signal currents from the photodetector (figure 1).

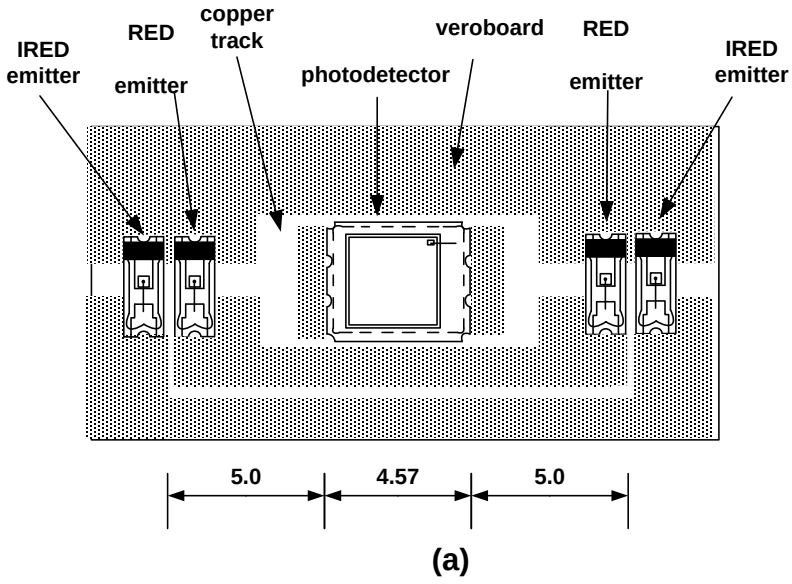

Figure 1: (a) Top view of the custom made finger PPG/SpO_2 probe showing the layout of the surface mount components (IRED and RED emitters and photodetector) mounted on a veroboard; (b) Photograph of the Reflectance finger Probe

The infrared and red emitters used were ceramic chip surface mount types (dimensions of each: 3.2 mm x 1.27 mm) with peak emission wavelengths at 880 nm and 655 nm, respectively (ELCOS GmbH). The photodetector was a surface mount silicon PhotoPinDiode on a ceramic contact base (dimensions: 4.57 mm x 3.81 mm) (ELCOS GmbH). The photodetector was mounted between the red and infrared emitters to detect radiation intensity back scattered by the tissue (figure 1).

An electrically isolated, time-multiplexed PPG processing system [12, 13] was used to detect and pre-process simultaneously the red and infrared ac and dc PPG output signals. Blood oxygen saturation values were also obtained using a commercial transmittance finger pulse oximeter (Diascope 2 VISMO; S&W Medico Teknik, Albertslund, Denmark). Lead II ECG signals were also recorded using a commercial ECG machine (Diascope 2 VISMO; S&W Medico Teknik, Albertslund, Denmark). PPG traces (obtained at red and infrared wavelengths) from the custom made finger pulse oximeter, SpO_2 traces from the commercial pulse oximeter and ECG signals were digitised at a sampling rate of 100 Hz by a 16-bit data acquisition card (National Instruments Corporation, Austin, Texas). The signals were furthered analysed by the *Virtual Instrument (VI)* implemented in *LabView* [12]. All acquired signals were also saved in spreadsheet format for further post processing analysis.

2.2 Software

The digitised signals were analysed offline in Matlab 6.5 using the available filter design and signal processing toolboxes. A band-pass Finite Impulse Response (FIR) filter and an adaptive threshold algorithm were implemented for the peak detection of the infrared and the red PPG signals. The peak detection threshold was obtained by convolving the absolute value of the filtered PPG signal with a square window and multiplying by a constant (0.00615). This constant was found empirically to give the best detection results. The filter was designed using the Equiripple method. At the sampling frequency of 100 Hz the filter order was 550. The lower and the upper cut-off frequencies of the band-pass filter were chosen to be 0.5 Hz and 2.3 Hz respectively. These cut-off frequencies were selected so that the filtered signal mainly consists of the fundamental component of the ac PPG signal, as its frequency varies between approximately 1 Hz to 2 Hz.

2.3 Measurement

The institutional Ethics Committee of City University approved this study, and all subjects gave written consent for participation prior to the study. Fourteen healthy male volunteers, mean age, ± SD (28 ± 5.2) who had not been taking any regular medication and were free of cardiovascular or chronic pulmonary diseases or other significant medical problems participated in this study.

All measurements were performed in a control lab facility. The lab temperature was maintained constant during all measurements. Volunteers were told to rest comfortably and quietly in the supine position in an examination table for three minutes to obtain a stable

haemodynamic period. Left and right arm blood pressures using a sphygmomanometer were taken prior to the signal acquisition. The cuff of the sphygmomanometer was then placed on the left arm at the level of the brachial artery. The custom made reflectance finger PPG/SpO_2 probe was placed on the index finger of the left hand and the commercial transmittance finger pulse oximeter was placed on the ring finger of the same hand. The volunteer was also connected to an ECG machine. Hypoperfusion was induced by gradually occluding the brachial artery using the sphygmomanometer at increments of 10 mmHg (10-15 seconds per pressure increment). During the gradual hypoperfusion process all parameters (ECG, custom made PPG/SpO_2 probe, commercial SpO_2 probe) were monitored and recorded continuously. In the event the volunteer felt uncomfortable, the process was stopped.

there was any significant difference between the mean PPG amplitudes at all induced pressures. A value of $p < 0.05$ was considered statistically significant. The SpO_2 values between the two pulse oximeters during the period of hypoperfusion were also compared.

3. Results

Measurable finger ac PPG traces at both wavelengths were obtained in all volunteers in all pressures taken prior to complete arterial occlusion where the finger PPG signals ceased due to no blood flow to the finger. Figure 2 depicts typical ac infrared PPG traces, at all pressure increments, from one volunteer.

Table 1 gives the mean ± SD of the ac PPG amplitudes at

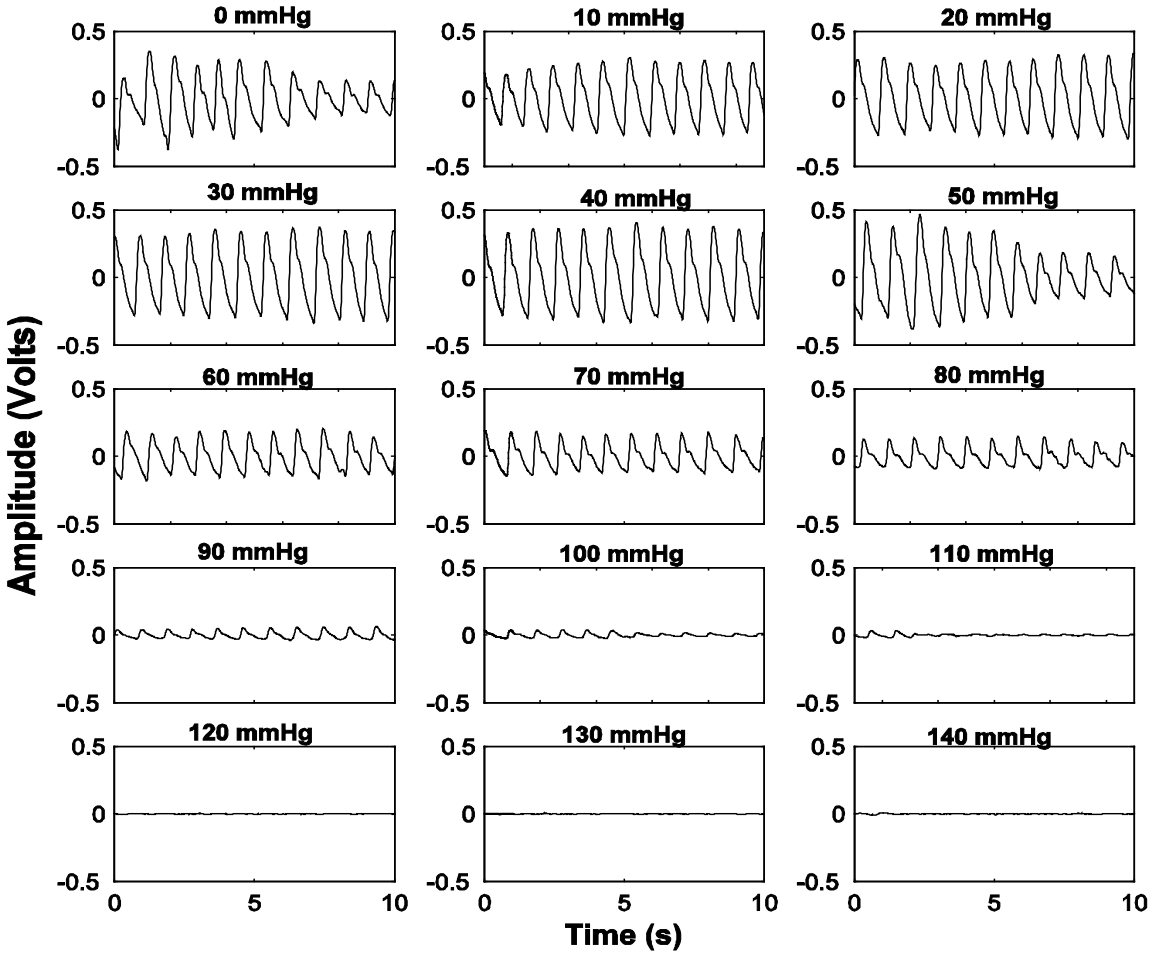

Figure 2: Infrared ac PPG signals at various pressure increments (0 to 140mmHg)

2.4 Data Analysis and Statistics

The amplitudes of the finger ac PPG signals (red and infrared) for all fourteen volunteers were measured during the hypoperfusion process, and the means and standard deviations (SD) calculated. A Kruskal-Wallis One Way Analysis of Variance (ANOVA) was performed to see if

both wavelengths at the different pressure increments.

Due to volunteer variability PPG signals at high pressures were not possible to obtain in all participants (see Table 1).

Table 1: Mean ± SD of ac PPG amplitudes (V) at two wavelengths at all pressure induced increments. Number of volunteers (n) is fourteen for all measurements unless stated differently

Induced pressure (mmHg)	Mean Infrared ac PPG Amplitudes (V)	Mean Red ac PPG Amplitudes (V)
0	0.441	0.287
10	0.457	0.287
20	0.518	0.336
30	0.518	0.348
40	0.478	0.340
50	0.479	0.342
60	0.401	0.310
70	0.317	0.252
80	0.248	0.120
90	0.151	0.120
100	0.075	0.056
110	0.032	0.024
120	0.012	0.009
130	0.007 (n=13)	0.007 (n=13)
140	0.005 (n=11)	0.005 (n=11)
150	0.004 (n= 3)	0.004 (n=3)

To see if there was any significant difference between the mean PPG amplitudes at all induced pressures, a Kruskal-Wallis One Way Analysis of Variance on Ranks was performed. The results of the test show that there are statistically significant differences between the ac PPGs in the low pressures (0 to 80 mmHg) than those in the upper pressures (90 to 150 mmHg) at both wavelengths.

The SpO_2 values from both pulse oximeters were observed during the hypoperfused period. Figure 3 clearly demonstrates the behaviour of the two pulse oximeters during induced hypoperfusion. As it was expected the SpO_2 values decreased gradually as the cuff pressure increased. With the systematic occlusion of the brachial artery the volume of blood reaching the finger was decreased and that was obvious from the changes in the amplitude of the ac PPG signal from the custom made finger probe. The custom SpO_2 probe was found to be much more sensitive to changes in SpO_2 than the commercial finger pulse oximeter and this is clearly visible in Figure 3. This is because most commercial pulse oximeters include time averaging to maintain a signal well after the peak pressure in the cuff has been reached. Also, commercial pulse oximeters such as the one used in this study include time averaging in their algorithms to minimise the influence of transit noise on data or low amplitude pulsations.

Figure 3 demonstrates clearly that the commercial pulse oximeter failed to give any saturation values after the release of the cuff for approximately 100 seconds, where the custom made probe was able to estimate SpO_2 immediately after the cuff was released. This is again possibly due to the averaging algorithms within the commercial pulse oximeter.

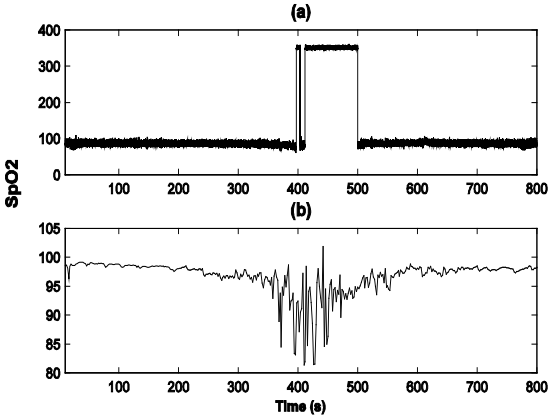

Figure 3: Blood oxygen saturation traces during hypoperfusion. Gradual hypoperfusion started from 0 to 140 mmHg (time 0 to 400 seconds). After full occlusion the cuff was released gradually down to 0 mmHg (time 420 to 800 seconds).

4. Discussion and Conclusion

Finger PPG signals with large amplitudes and high signal-to-noise ratios were measured in the majority of induced pressures prior to complete occlusion of the brachial artery in all volunteers. During hypoperfusion the amplitude of the PPG signals were decreased gradually to the point that were not visible at all on the screen of the computer. The mean PPGs at low pressures (0 to 80 mmHg) found to be statistically significant with the mean PPGs at the upper pressures (90 to 150 mmHg) at both wavelengths.

The decrease in the amplitude of the PPG signals correlated well with the decrease in blood oxygen saturation. This is in full agreement with the physiological phenomenon that suggests that during arterial vessel stenosis the volume of blood decreases with a direct effect on SpO_2 values measured at a vascular site downstream from the stenosis. The custom finger pulse oximetry was found to be more sensitive to SpO_2 changes during induced hypoperfusion when compared with the commercial pulse oximetry. Signal averaging might be one of the reasons that affected the slow response of the commercial pulse oximetry. Additional clinical studies, in a group of patients with peripheral vascular disease, are suggested to investigate such a phenomenon further.

References

[1] A. V. J. Challoner, Photoelectric plethysmography for estimating cutaneous blood flow (Academic Press, New York, 1997).

[2] J. C. Dorlas and J. A. Nijboer, Photo-electric plethysmography as a monitoring device in anaesthesia.

Application and Interpretation, British Journal of Anaesthesia, 57, 1985, 524-530.

[3] J. L. Higgins and A. Fronek, Photoplethysmographic Evaluation of the Relationship Between Skin Reflectance and Blood Volume, Journal of Biomedical Engineering, 8, 1986, 130-136.

[4] L. G. Lindberg and P. A. Oberg, Photoplethysmography Part 2: Influence of light source wavelength, Medical & Biological Engineering & Computing, 29, 1991, 48-54.

[5] J. A. Nijboer, J. C. Dorlas and H. F. Mahieu, Photoelectric plethysmography-some fundamental aspects of the reflection and transmission method, Clin. Phys. Physiol. Meas. 2, 1981, 205-215.

[6] Y. Mendelson and B. D. Ochs, Noninvasive pulse oximetry utilizing skin reflectance photoplethysmography, IEEE Transactions on Biomedical Engineering, 35, 1988, 798-805.

[7] V. C. Roberts, Photoplethysmography - fundamental aspects of the optical properties of blood in motion Trans. Inst. M. C., 4, 1982, 101-106.

[8] J Webster, Design of Pulse Oximeters (Bristol: Institute of Physics Publishing, 1997).

[9] D. G. Clayton, R. K. Webb, A. C. Ralston, D. Duthie and W. B. Runciman, A comparison of the performance of 20 pulse oximeters under conditions of poor perfusion, Anaesthesia 46, 1991, 3-10.

[10] D. L. Reich, A. Imcenko, C. A. Bodian, J. Kraidin, J. B. Hofman, M. Deperio, S. N. Konstadt, T. Kurki and J. B. Eisenkraft, Predictors of Pulse Oximetry Data Failure, Anesthesiology, 84, 1996, 859-864.

[11] K. Irita, Y. Kai, K. Akiyoshi et al., Performance evaluation of a new pulse oximeter during mild hypothermic cardiopulmonary bypass, Anesth Analg., 96, 2003, 11-14.

[12] P. A. Kyriacou, S. Powell, R. M. Langford and D. P. Jones, Esophageal Pulse Oximetry Utilizing Reflectance Photoplethysmography, IEEE Transactions of Biomedical Engineering, 49(11), 2002, 1360-1368.

[13] P. A. Kyriacou, Pulse Oximetry in the oesophagus, Physiological Measurement, 27, 2006, R1-R35.