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Pilot investigation of photoplethysmographic signals and blood oxygen saturation values during blood pressure cuff-induced hypoperfusion

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A B S T R A C T

Photoplethysmography (PPG) is a non-invasive electro-optical technique widely used in the monitoring of the pulsations associated with changes in blood volume in a peripheral vascular bed. The technique is based on the absorption properties of vascular tissue when it is transilluminated by light. Photoplethysmography is also used in the estimation of arterial blood oxygen saturation (SpO_2) by pulse oximetry where the technique relies on the presence of adequate peripheral arterial pulsations. The aim of this study was to investigate (14 healthy volunteers) the effect of pressure cuff-induced hypoperfusion on PPG signals and SpO_2 s using a custom made finger blood oxygen saturation PPG/ SpO_2 sensor and a commercial finger pulse oximeter. PPG signals with high signal-to-noise ratios were obtained from all induced pressures prior to full brachial occlusion. An Analysis of Variance (ANOVA) on ranks showed that there are statistically significant differences ($p < 0.05$) between the PPGs in the low pressures (0–80 mmHg) than those in the upper pressures (90–150 mmHg). 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.

Keywords:

Photoplethysmography

Pulse oximetry

Perfusion

1. Introduction

Photoplethysmography is a non-invasive optical technique widely used in the study and monitoring of the pulsations associated with changes in blood volume in a peripheral vascular bed [1–8]. Photoplethysmography is used in the estimation of arterial blood oxygen saturation (SpO_2) by pulse oximetry. Pulse oximeters estimate arterial oxygen saturation by shining light at two different wavelengths, red and infrared, through vascular tissue. In this method, the pulsatile photoplethysmographic (ac PPG) signal associated with cardiac contraction is assumed to be attributable solely to the arterial blood component. The

amplitudes of the red and infrared ac PPG signals are sensitive to changes in arterial oxygen saturation because of differences in the light absorption of oxygenated and deoxygenated haemoglobin at these two wavelengths. From the ratios of these amplitudes, and the corresponding dc photoplethysmographic components, arterial blood oxygen saturation (SpO_2) is estimated. Hence, the technique of pulse oximetry relies on the presence of adequate peripheral arterial pulsations, which are detected as photoplethysmographic (PPG) signals [9].

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 [10,11]. The oxygenation readings become unreliable in these circumstances because conventional pulse oximeter sensors are usually placed on the most peripheral parts of the body

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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 [12]. 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 custom made reflectance finger PPG/SpO₂ probe was developed utilising two surface mount infrared (IREDs) and two red (REDS) emitting diodes and a surface mount silicon diode photodetector (Fig. 1). The photodetector detected radiation back scattered by the tissue from both infrared and red emitters and gave an output current proportional to the detected radiation level. A screened multicore cable carried the power to the IREDs and REDs in the probe from the main PPG processing unit and also the detected PPG signals from the photodetector.

2.1.1. Optical components

The IRED and RED emitters used were ceramic chip surface mount types (dimensions of each: 3.2 mm × 1.27 mm) with peak emission wavelengths at 880 and 655 nm, respectively (ELCOS GmbH). The photodetector was a surface mount silicon PhotoPinDiode (dimensions: 4.57 mm × 3.81 mm) which had the positive side on the front and the negative side on a ceramic contact base (ELCOS GmbH).

2.1.2. Mechanical construction of the finger PPG probe

The photodetector was mounted between the emitters to detect radiation back scattered by the tissue from both IRED and RED emitters and gave an output current proportional to the detected radiation level. The distance between the emitters and the photodetector was 5 mm (Fig. 2a). The

emitter and photodiode chips were mounted on the copper side (Fig. 2a) of an epoxy glass copper clad single sided eurocard (dimensions: 20 mm × 10 mm × 1.6 mm). Fig. 2b shows a close-up photograph of the complete design of the reflectance finger probe.

An electrically isolated, time-multiplexed PPG processing system [13,14] 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 signals (obtained at red and infrared wavelengths) from the custom made finger pulse oximeter, SpO₂ 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 further analysed by the *Virtual Instrument* (VI) implemented in *LabView* [13]. All acquired signals were also saved in spreadsheet format for further post processing analysis. The digitised signals were analysed offline in *Matlab* 6.5 using the available filter design and signal processing toolboxes.

2.2. 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 from cardiovascular or chronic pulmonary diseases or other significant medical problems participated in this study.

All measurements were performed in a control laboratory facility. Volunteers were told to rest comfortably and quietly in the supine position on 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/SpO₂ probe was placed on the index finger (second finger) of the left hand and the commercial transmittance finger pulse oximeter was placed on the

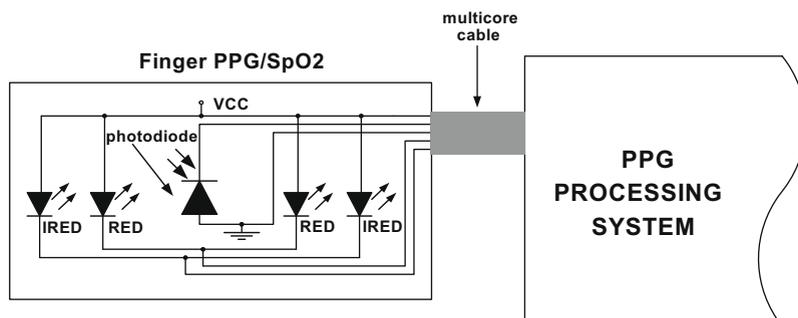
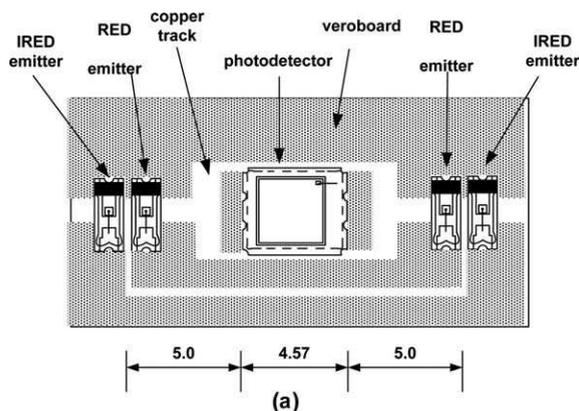
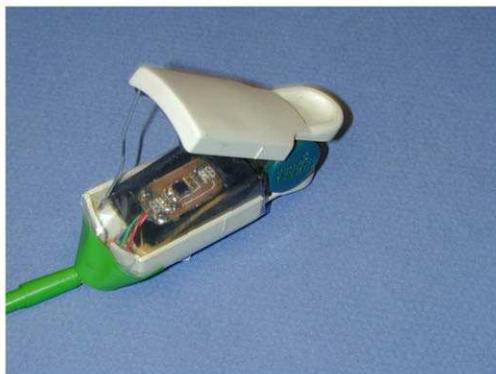


Fig. 1. Block diagram of the finger PPG/SpO₂ probe connected to the PPG processing system.



* All measurements are in mm



(b)

Fig. 2. (a) Top view of the custom made finger PPG/SpO₂ 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.

third finger of the same hand. The volunteer was also connected to an ECG machine. Hypoperfusion was induced by gradually occluding the brachial artery (just above the systolic pressure of each volunteer) using the sphygmomanometer at increments of 10 mmHg (10–15 seconds per pressure increment). During the gradual hypoperfusion process all variables (ECG, custom made PPG/SpO₂ probe, commercial SpO₂ probe) were monitored and recorded continuously. In the event the volunteer felt uncomfortable, the experiment was stopped.

2.3. 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 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 SpO₂ 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 at all pressures recorded prior to complete arterial occlusion where the finger PPG signals ceased due to no blood flow to the finger. Fig. 3 depicts typical ac infrared PPG traces, at all pressure increments, from one volunteer.

Fig. 4 gives the mean \pm SD of the ac PPG amplitudes at the different pressure increments. 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 (0–80 mmHg) than those in the upper pressures (90–150 mmHg) at both wavelengths.

The SpO₂ values from both pulse oximeters were observed during the hypoperfused period. Fig. 5 clearly demonstrates the behaviour of the two pulse oximeters during induced hypoperfusion. As it was expected the SpO₂ values obtained from both the commercial and custom made finger pulse oximeters decreased gradually as the cuff pressure increased. The systematic occlusion of the brachial artery caused the volume of blood reaching the finger to decrease which was obvious from the changes in the amplitude of the ac PPG signal obtained from the custom made finger probe. The custom made SpO₂ probe was found to be much more sensitive to changes in SpO₂ than the commercial finger pulse oximeter and this is clearly visible in Fig. 5. 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.

4. Discussion

Although generally reliable, pulse oximeters have been reported to fail and many of their physiological and technical limitations have been described [15]. Some of these limitations are due to interference as many substances in blood can interfere optically with pulse oximetry. This interference generally takes the form of false absorbers, or components besides deoxyhaemoglobin or oxyhaemoglobin that will absorb light within the red and near-infrared wavelengths used in pulse oximetry. Other limitations are due to signal artefact which is one of the most common problems of pulse oximeters. Signal artefact results from false sources of signal or from a low signal-to-noise ratio. False signal can arise from detection of non-transmitted light (ambient sources or optical shunt) or from non-arterial sources of alternating signal. A low signal-to-noise ratio results from inadequate signal complicated by an excess of physiological or technical noise. Apart from the physiological and technical limitations of pulse oximeters described briefly above, commercial pulse oximeters have been also reported to fail in patients with compromised

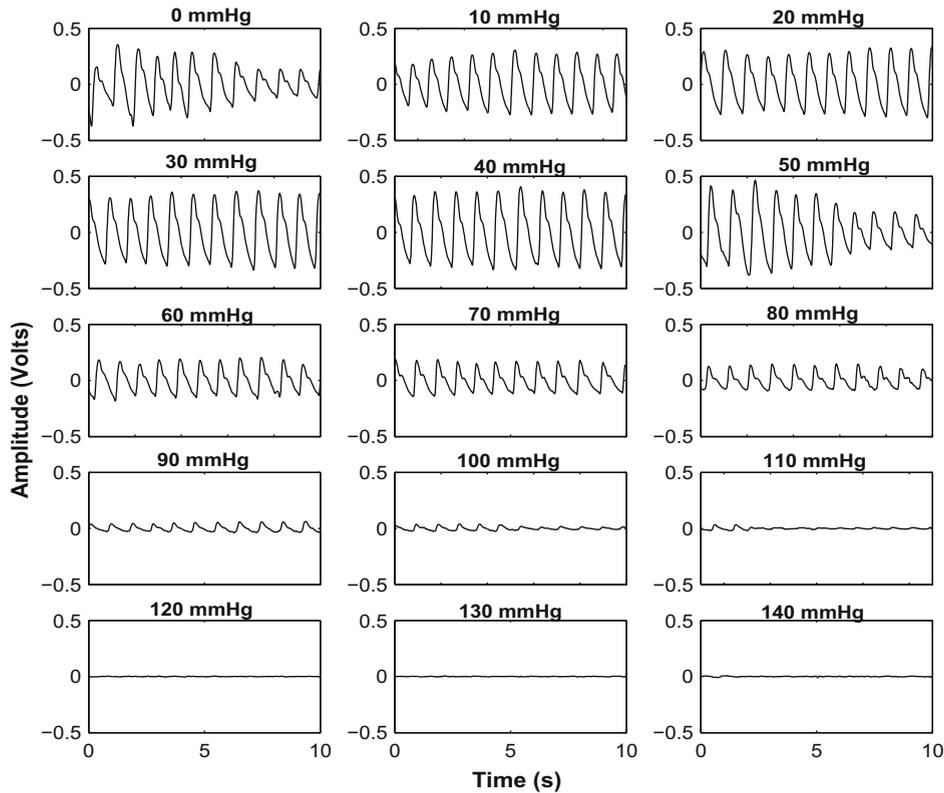


Fig. 3. Infrared ac PPG signals at various pressure increments (0–140 mmHg).

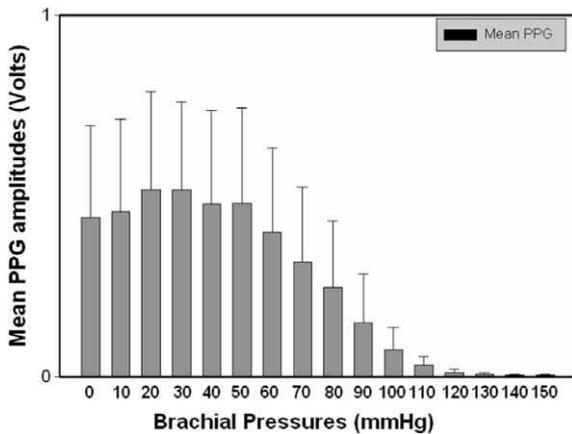


Fig. 4. Mean (\pm SD) ac infrared PPG amplitudes at different brachial occlusion pressures.

peripheral perfusion [11]. Pulse oximetry is a pulse dependent technique, any significant reduction in the amplitude of the pulsatile component of the photoplethysmographic signal can lead to dubious values for blood oxygen saturation (SpO_2) or complete failure. Hence, pulse oximeters require adequate peripheral perfusion to operate accurately. As described in the introduction when peripheral perfusion is poor, oxygenation readings become unreliable or cease. Such clinical situations occur, for example, after prolonged

operations, especially hypothermic cardiopulmonary bypass surgery. The problem arises because conventional pulse oximetry sensors must be attached to the most peripheral parts of the body, such as finger, ear or toe, where pulsatile flow is most easily compromised.

There have been many studies comparing the accuracy of commercial pulse oximeters [16]. However, the focus of these studies was solely on SpO_2 and therefore do not include an appreciation of PPG signals. There has been no attempt thus far to investigate the behaviour of the PPG signal both in amplitude and morphology as the SpO_2 values change. The limitations of these studies provided the stimulation for this pilot study where a custom made PPG processing system has been developed in order to enable the investigation of the PPG signals at both wavelengths during blood pressure cuff-induced hypoperfusion. The developed custom made PPG processing system enable the access to all raw signals (ac and dc PPG signals at both wavelengths), something that it is not possible with commercial pulse oximeters. Also, the custom-built system did not apply and high order filtering or any averaging on the acquired PPG signals, therefore enabling a true real time acquisition.

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 where they were not visible at all on the screen

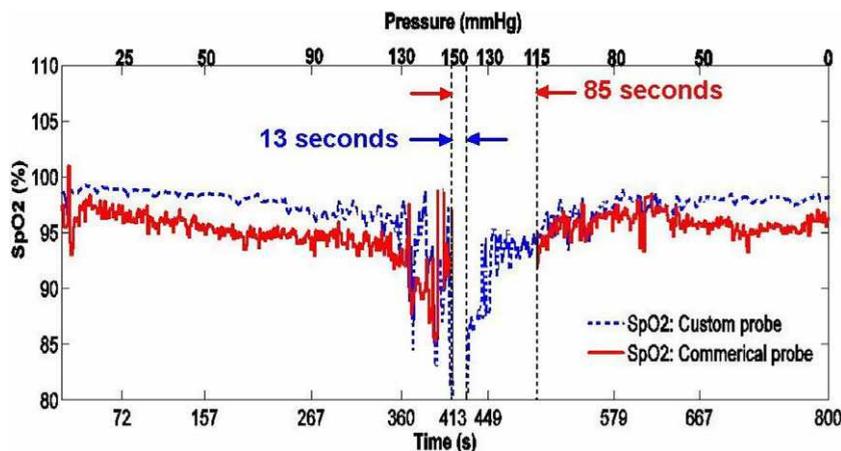


Fig. 5. Blood oxygen saturation traces during blood pressure cuff induced hypoperfusion. Gradual cuff-induced hypoperfusion started from 0 to 140 mmHg (time 0–400 s). After full arterial occlusion the cuff was released gradually down to 0 mmHg (time 420–800 s).

of the computer. The mean PPGs at low pressures (0–80 mmHg) were found to be statistically significant with the mean PPGs at the upper pressures (90–150 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 SpO₂ values measured at a vascular site downstream from the stenosis.

5. Conclusion

A new PPG/SpO₂ reflectance probe and the corresponding processing system have been successfully developed to investigate in detail the morphology and amplitude of the PPG signal and its effect on pulse oximetry under controlled vasoconstrictive studies. The custom finger pulse oximetry was found to be more sensitive to SpO₂ changes during induced hypoperfusion when compared with the commercial pulse oximetry. Additional clinical studies, in a group of patients with peripheral vascular disease, are suggested to investigate such a phenomenon further.

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