Measurement 42 (2009) 1001–1005

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

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

P.A. Kyriacou [a,*], K. Shafqat [a], S.K. Pal [b]

[a] School of Engineering and Mathematical Sciences, City University, London EC1V 0HB, UK
[b] St. Andrew's Centre for Plastic Surgery & Burns, Broomfield Hospital, Chelmsford, Essex CM1 7ET, UK

ARTICLE INFO

Article history:
Received 27 March 2008
Received in revised form 9 February 2009
Accepted 28 February 2009
Available online 9 March 2009

Keywords:
Photoplethysmography
Pulse oximetry
Perfusion

ABSTRACT

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_2s 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.

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

* Corresponding author. Tel.: +44 207040 8131.
E-mail addresses: P.Kyriacou@city.ac.uk (P.A. Kyriacou), K.Shafqat@city.ac.uk (K. Shafqat), Sandip.Pal@meht.nhs.uk (S.K. Pal).

0263-2241/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.measurement.2009.02.005

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/SpO_2 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, 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* [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/SpO_2 probe was placed on the index finger (second finger) of the left hand and the commercial transmittance finger pulse oximeter was placed on the

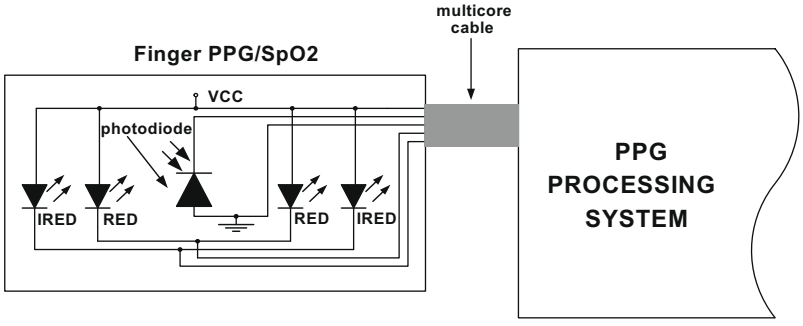

Fig. 1. Block diagram of the finger PPG/SpO_2 probe connected to the PPG processing system.