Accuracy of Reflectance Photoplethysmography on detecting Cuff-Induced Vascular Occlusions

T. Y. Abay, *Graduate Student Member*, P. A. Kyriacou, *Senior IEEE Member*

***Abstract*— Photoplethysmography (PPG) is a noninvasive optical technique, which can also be used to derive important parameters other than arterial oxygen saturation (SpO_2). In this work, the accuracy of the technique on detecting changes in blood perfusion during different levels of vascular occlusions has been explored. A dual-wavelength, reflectance PPG probe was applied on the left forearm of 10 healthy volunteers and raw PPG signals were acquired by a research PPG processing system. The raw PPG signals were separated into pulsatile AC and continuous DC PPG components. The signals were used to estimate SpO_2 and changes in concentration of oxygenated, deoxygenated, and total haemoglobin. Different levels of occlusions, from 20 mmHg to total occlusion were induced by a pressure-cuff on the left arm. The system was able to indicate all the occlusions. In particular, the haemoglobin concentration changes estimated from PPG were in high agreement with Near Infrared Spectroscopy measurements**.

I. Introduction

Photoplethysmography (PPG) is a noninvasive optical technique in which light is applied to the tissue and the backscattered and reflected light is detected by a photodetector. The signal produced by the photodetector is commonly known as Photoplethysmograph [1] [2]. This trace is composed by two main components: pulsatile AC and continuous DC. The AC component represents the pulsatile nature of arteries and it is synchronous with the cardiac cycle [1] [2]. The AC component is widely used in PPG applications for estimation of physiological information such as heart rate and Pulse Transit Time [1] [3]. The DC component is a slow frequency signal (~ 0.01 – 0.5 Hz) and contains information about the general absorption of light in the tissue and its modulation can be used for indication of respiration and regulatory vascular mechanisms [1] [2].

Photoplethysmography is at the base of pulse oximetry, where light at two different wavelengths (red and infrared) is shone in tissue for the non-invasive estimation of arterial oxygen saturation (SpO_2). The technique uses the ratio of AC and DC PPG components at both wavelengths and it applies empirical curves for the estimation of SpO_2 [2]. Pulse Oximetry revolutionized the clinical application of optical techniques and it is widely used in anaesthesia and in emergency medicine [2].

The technique is inexpensive and relative simple, and its potentials have been attracting increasing interests for new applications such as calculation of cardiovascular parameters and imaging [4] [5] .

Near Infrared Spectroscopy (NIRS) is another non-invasive optical technique used for the assessment of perfusion in tissues [6]. The technique allows the estimation of changes in deoxygenated, oxygenated, and total haemoglobin in tissue by applying the Modified Beer Lambert Law (MBLL) [6] [7]. Since its discovery, NIRS has been increasingly attracting interest in physiological monitoring due to its ability to track and distinguish changes in tissue blood perfusion [6] [7]. The technique is widely applied in research such as in cerebral perfusion monitoring, splanchnic perfusion, surgery, sport medicine, trauma and imaging (fNIRS) [6] [7].

NIRS shares several characteristics with pulse oximetry: both modalities use light to collect physiological information and light at a minimum of two wavelengths is sequentially applied to the tissue. However, NIRS differs from pulse oximetry in the processing of the signals, the wavelengths adopted, the large separation distance between light emitter and detector(s), and consequent penetration depth.

In a previous publication, the authors introduced the feasibility of using PPG signals to estimate changes in oxygenated ($\Delta[HbO_2]$), deoxygenated ($\Delta[HHb]$) and total haemoglobin ($\Delta[tHb]$) as achieved in NIRS [8]. The results showed good agreement between the two techniques during venous and total occlusion on healthy volunteers [8]. In this work, the authors investigate more rigorously the correlation in detecting changes in blood perfusion, during different levels of occlusions, between the two techniques, NIRS and PPG.

II. Material and Methods

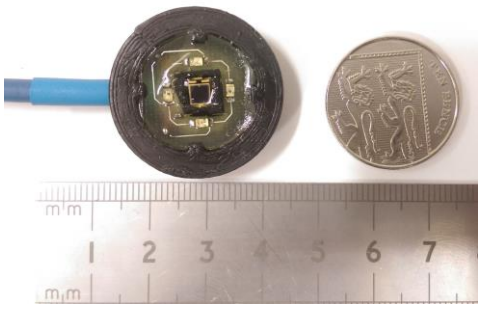
A. PPG Processing System and Reflectance Probe

For this study, raw photoplethysmographic signals were acquired on the forearm of healthy volunteers by a research photoplethysmographic system and a reflectance PPG probe. The PPG processing system was designed by the Biomedical Engineering Group at City University London and it allows the continuous acquisition of dual channel, dual wavelength raw PPG signals [9]. The system was previously described in detail and it was designed to drive PPG sensors comprising Light Emitting Diodes (LED) and a photodiode [9]. The PPG system mainly comprises a power board, a current source board, a transimpedance board, and core

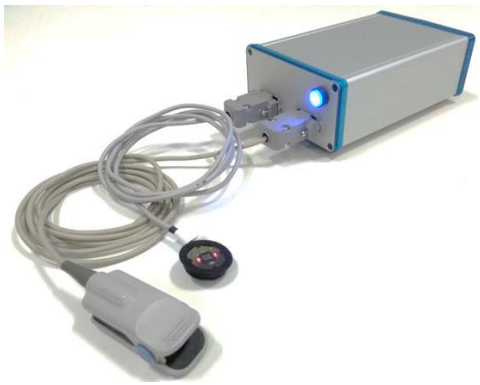
Research supported by the Barts and The London NHS Trust (Barts Charity Grant: 832/1716).

T. Y. Abay is with the School of Mathematics, Computer Sciences & Engineering, City University London, London, UK (Tel: +44 020 7040 3878, email: Tomas.Ysehak-Abay.1@city.ac.uk).

P. A. Kyriacou is with the School of Mathematics, Computer Sciences & Engineering, City University London, London, UK (Tel: +44 020 7040 8131, email: p.kyriacou@city.ac.uk).



(a)



(b)

Figure 1: Reflectance PPG probe and PPG processing system. (a) Reflectance PPG probe with optical components (LEDs and photodiode) and black case. (b) PPG processing system used in the study.

board. The current source provides the current to the Light Emitting Diodes in the sensor. Current produced by a photodiode is converted into voltage by the transimpedance amplifiers [9]. The light switching into two different wavelengths is achieved by multiplexers, while the separation of the detected signal in the respective wavelengths is performed by demultiplexers [9]. The light ON/OFF switching and dark period cycles are carried at a frequency of approximately 1200 Hz. The core board controls the multiplex-demultiplex cycle using microcontroller technology, and provides connection to a National Instruments Data Acquisition System [9].

A reflectance PPG probe, driven by the processing system, was designed for acquisition of raw PPG signals from the forearm. The probe was developed using printed circuit board (PCB) technology. The light sources placed on the board were two red (R) and two infrared (IR) surface mount LEDs. The KP-2012SRC-PRV and KP-2012SF4C (Kingbright, Taipei, Taiwan) had respectively a peak emission wavelength of 660 and 880. A surface mount photodiode (TEMD5010X01, Vishay Semiconductors) with an active area of 7.5 mm^2 detects the backscattered light from the tissue. The photodiode and LEDS were mounted at 5 mm center-to-center distance in order to optimize PPG signal quality [10]. The PCB was enclosed in a black case to cover from ambient light interference. The case was manufactured in Polylactic Plastic by 3D printing technology. The optical components were covered by clear medical epoxy. Fig. 1 shows the reflectance PPG probe and processing system adopted in this study.

B. Investigation Protocol

Ten (10) healthy volunteers (6 males and 4 females, mean age: 32 ± 7.82) were recruited for the investigation. Ethical approval was gained from the Senate Research Ethics Committee at City University London. Subjects with a history of cardiovascular diseases were excluded from the study. The volunteers were seated in a comfortable chair, with their arms rested on a table. Blood pressure was measured prior to the start of the investigation. The left arm was rested on a pillow in order to avoid vascular compression. A blood pressure cuff was placed around the volunteer's upper left arm and connected to a sphygmomanometer. The reflectance PPG sensor was placed above the brachioradialis and it was attached by means of double-sided clear medical tape. A commercial NIRS sensor (NIRO 200NX, Hamamatsu Photonics, Japan) was attached above the same muscle, proximal to the cuff. The NIRS sensors had an emitter-detector separation distance of 4 cm and peak emission wavelengths at 735, 810 and 850 nm.

The investigation protocol consisted of seven vascular occlusions at different pressures. The occlusions pressures were 20, 40, 60, 80, and 100 mmHg, followed by occlusions at the systolic pressure and total occlusion (20 mmHg exceeding the volunteer's systolic pressure). The occlusions were induced by manually inflating and deflating the cuff; while the pressures levels were monitored from the sphygmomanometer. Each occlusion lasted for one minute and it was followed by one-minute recovery. The measurement stopped once all physiological parameters returned to baseline levels.

Two Data Acquisition Cards (Pcle 6321, National Instruments, U.S.A) were used for the digitization of the physiological signals. A Virtual Instrument (VI) was designed on LabVIEW (National Instruments, U.S.A) for the acquisition and real time display of the signals. The VI was also used for saving the raw PPG signals and the signals from the NIRS monitor on a text file. The signals were acquired at a sampling frequency of 400 Hz. Post-acquisition analysis was performed on Matlab2013.

C. Data Analysis

The raw PPG signals were used to estimate the Ratio of Ratio as showed in (1). The ratio R was directly correlated to arterial oxygen saturation, SpO_2, by the empirical equation in (2).

$$R = \frac{AC_R/DC_R}{AC_{IR}/DC_{IR}} \quad (1)$$

$$SpO_2 = 110 - 25R \quad (2)$$

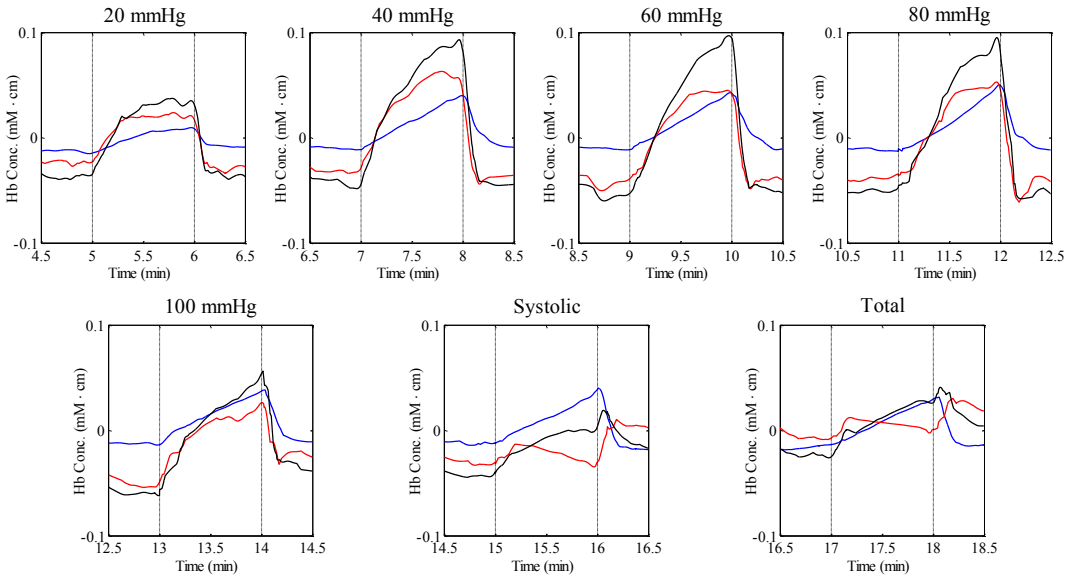


Figure 2: Mean changes in oxygenated, deoxygenated, and total haemoglobin estimated from PPG signals for all the volunteers. Each subplot represents the occlusion steps of the protocol. Vertical dotted lines indicate the inflation and deflation of the cuff. Red trace: oxygenated haemoglobin; blue trace: deoxygenated haemoglobin; black trace: total haemoglobin.

Where AC_R and AC_{IR} are respectively the AC PPG components at red (660 nm) and infrared (880 nm) wavelengths; and DC_R and DC_{IR} are the DC PPG components at the same two wavelengths. The AC and DC PPG components were separated from the raw signal by applying a zero-phase band-pass digital filter (band-pass frequencies: 0.5-5 Hz) and a zero-phase low-pass digital filter (cut-off frequency: 0.1 Hz). The SpO_2 was estimated throughout the signal by a three-second rolling-window.

In addition to SpO_2, the DC PPG components were used to estimate $\Delta[HbO_2]$, $\Delta[HHb]$, and $\Delta[tHb]$ by applying the Modified Beer-Lambert law (MBLL). Its generic application to dual-wavelength PPG signals is showed in (3) and (4).

$$\Delta A_R = \ln\left(\frac{DC_{0_R}}{DC_R}\right) = \left([\Delta HbO_2]\cdot\alpha_{R_{HbO_2}} + [\Delta HHb]\cdot\alpha_{R_{HHb}}\right)\cdot d \qquad (3)$$

$$\Delta A_{IR} = \ln\left(\frac{DC_{0_{IR}}}{DC_{IR}}\right) = \left([\Delta HbO_2]\cdot\alpha_{IR_{HbO_2}} + [\Delta HHb]\cdot\alpha_{IR_{HHb}}\right)\cdot d \qquad (4)$$

Where A_R and A_R are the attenuation changes at the two wavelengths, DC_0 and DC are respectively the DC levels at the start of the measurement and during the entire measurement, ΔHbO_2 and ΔHHb are respectively the changes in oxygenated and deoxygenated haemoglobin concentrations, α are the extinction coefficients of the two haemoglobins at the different wavelengths, and d is the optical pathlength. However, the full pathlength was not determined; therefore, we opted to represent the concentration changes as relative concentration changes in mM·cm. The solution of the linear system in (3) and (4), assuming an unknown pathlength d is presented in (5) and (6).

$$\Delta[HbO_2] = \frac{A_R\cdot\alpha_{IR_{HHb}} - A_{IR}\cdot\alpha_{R_{HHb}}}{\left(\alpha_{R_{HbO_2}}\cdot\alpha_{IR_{HHb}} - \alpha_{IR_{HbO_2}}\cdot\alpha_{R_{HHb}}\right)} \qquad (5)$$

$$\Delta[HHb] = \frac{A_{IR}\cdot\alpha_{R_{HbO_2}} - A_R\cdot\alpha_{IR_{HbO_2}}}{\left(\alpha_{R_{HbO_2}}\cdot\alpha_{IR_{HHb}} - \alpha_{IR_{HbO_2}}\cdot\alpha_{R_{HHb}}\right)} \qquad (6)$$

The $\Delta[tHb]$ were calculated as the sum of $\Delta[HHb]$ and $\Delta[HbO_2]$. The same parameters (haemoglobin concentration changes) were acquired from the commercial NIRS monitor. Spearman's correlation coefficient r^2 was used to find correlation between the same haemoglobin concentration changes during the protocol.

III. Results

Fig. 2 shows the mean changes in relative concentrations of haemoglobin calculated from PPG signals, for all the volunteers investigated. The PPG system was able to track the changes in perfusion caused by different degrees of occlusions. In particular, during small occlusions such as 20 and 40 mmHg, the system detected the small blood perfusion changes. The occlusions created different levels of venous engorgement in the forearm. The accumulation of venous blood can be noticed by the increases of deoxygenated haemoglobin and total haemoglobin (blue and black traces respectively). At occlusions between 20 and 80 mmHg, a gradual increase in total haemoglobin can be observed at each occlusions, reaching maximum levels at 60-80 mmHg (i.e. veins occlusion pressure). Total haemoglobin can be used to express changes in total blood volume changes. Thus, its gradual increase during different levels of venous occlusions represents correctly the gradual build-up of venous blood in the forearm. At occlusions pressures >80 mmHg, the arterial branches began to occlude

TABLE 1: SPEARMAN'S CORRELATION COEFFICIENTS OF HAEMOGLOBIN CONCENTRATIONS, ESTIMATED BY PPG AND NIRS, DURING DIFFERENT OCCLUSIONS.

	HHb	**HbO_2**	**tHb**
Occlusion	$r^2(p)$	$r^2(p)$	$r^2(p)$
20	0.959 (p<0.001)	0.933 (p<0.001)	0.960 (p<0.001)
40	0.998 (p<0.001)	0.916 (p<0.001)	0.961 (p<0.001)
60	0.991 (p<0.001)	0.959 (p<0.001)	0.990 (p<0.001)
80	0.992 (p<0.001)	0.931 (p<0.001)	0.969 (p<0.001)
100	0.998 (p<0.001)	0.828 (p<0.001)	0.954 (p<0.001)
Systolic	0.989 (p<0.001)	0.645 (p<0.001)	0.812 (p<0.001)
Total	0.998 (p<0.001)	0.357 (p<0.001)	0.874 (p<0.001)

as well, with a consequent decrease of venous engorgement. When occlusions reached the systolic and total pressure, a drop in oxygenated haemoglobin (red trace) was observed, indicating the total occlusion of oxygen delivery to the tissue.

The changes in relative concentrations of haemoglobin estimated from PPG signals were in agreement with the same parameters estimated from NIRS. Table 1 shows the correlation coefficients determined between the haemoglobin concentrations estimated by both techniques. Deoxygenated and total haemoglobin showed high correlation with their respective NIRS-measured parameters. However, Oxygenated haemoglobin presented a poor correlation during total occlusions. This may be due to a not sufficient recovery time following the previous occlusion (systolic pressure).

The system estimated SpO_2 from the measurement area by applying (1) and (2) as in conventional pulse oximetry. Fig. 3 shows the mean values (±SD) for all the volunteers during the protocol. At the occlusion pressure of 20 mmHg, the SpO_2 values did not significantly drop from baseline. However, at occlusions between 40-80 mmHg, the SpO_2 started to decrease, until significant desaturations were observed at higher occlusions. Shafique et al. previously reported significant drops in SpO_2 from fingers only for higher occlusions (>75 mmHg) [11].

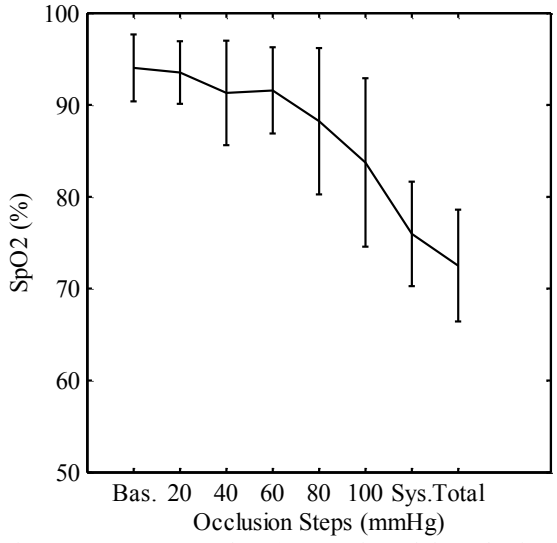


Figure 3: Mean SpO_2 values (±SD) estimated from the forearm at different occlusions in the protocol.

IV. CONCLUSIONS

This preliminary work investigated the correlation between reflectance photoplethysmography and NIRS measurements during different degrees of occlusions on the forearm. The two techniques presented high correlations during all the occlusions and our results suggest that the SpO_2 from the forearm may be a more sensitive location to cuff-induced occlusions, when compared to fingers. More studies on large groups of volunteers are needed in order to investigate these correlations further.

REFERENCES

[1] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiological Measurements,* vol. 28, pp. R1-R39, 2007.

[2] P. A. Kyriacou, "Pulse oximetry in the oesophagus," *Physiological Measurement,* vol. 27, no. 1, pp. R1-R35, 2006.

[3] K. Shelley, "Photoplethysmography: Beyond the Calculation of Arterial Oxygen Saturation and Heart Rate," *Anaesthesia & Analgesia,* vol. 105, no. 6, pp. S31 - S36, 2007.

[4] A. A. Alian and K. H. Shelley, "Photoplethysmography: Analysis of the Pulse Oximeter Waveform," in *Monitoring Technologies in Acute Care Environments*, Springer New York, 2014, pp. 165-178.

[5] J. R. Estepp, E. B. Blackford and C. M. Meier, "Recovering pulse rate during motion artifact with a multi-imager array for non-contact imaging photoplethysmography," in *2014 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, San Diego, CA, USA, 2014.

[6] A. Pellicer and M. del Carmen Bravo, "Near-infrared spectroscopy: A methodology - focused review," *Seminar in Fetal & Neonatal Medicine,* vol. 16, no. 2011, pp. 42-49, 2011.

[7] J. M. Murkin and M. Arango, "Near-infrared spectroscopy as an index of brain and tissue oxygenation," *British Journal of Anaesthesia,* vol. 103, no. Suppl. 1, pp. i3-i13, 2009.

[8] T. Y. Abay and P. A. Kyriacou, "Reflectance Photoplethysmography as Non-invasive Monitoring of Tissue Blood Perfusion (Accepted for publication)," *IEEE Trans. on Biomedical Engineering,* to be published.

[9] V. Rybynok, J. M. May, K. Budidha and P. A. Kyriacou, "Design and Development of a novel Multi-channel Photoplethysmographic Research System," in *IEEE Point-of-Care Healthcare Technologies*, Bangalore, India, 2013.

[10] K. Budidha and P. A. Kyriacou, "The human ear canal: investigation of its sutability for monitoring photoplethysmographs and arterial oxygen saturation," *Physiological Measurement,* vol. 35, pp. 111-128, 2014.

[11] M. Shafique, P. A. Kyriacou and S. K. Pal, "investigation of photoplethysmographic signals and blood oxygen saturation values on healthy volunteers during cuff-induced hypoperfusion using a multimode PPG/SpO2 sensor," *Medical and Biological Engineering and Computing,* vol. 50, p. 575 583, 2012.