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Investigation of photoplethysmographic signals and blood oxygen saturation values on healthy volunteers during cuff-induced hypoperfusion using a multimode PPG/SpO_2 sensor

M. Shafique · P. A. Kyriacou · S. K. Pal

Abstract Photoplethysmography (PPG) is a technique widely used to monitor volumetric blood changes induced by cardiac pulsations. Pulse oximetry uses the technique of PPG to estimate arterial oxygen saturation values (SpO_2). In poorly perfused tissues, SpO_2 readings may be compromised due to the poor quality of the PPG signals. A multimode finger PPG probe that operates simultaneously in reflectance, transmittance and a combined mode called "transreflectance" was developed, in an effort to improve the quality of the PPG signals in states of hypoperfusion. Experiments on 20 volunteers were conducted to evaluate the performance of the multimode PPG sensor and compare the results with a commercial transmittance pulse oximeter. A brachial blood pressure cuff was used to induce artificial hypoperfusion. Results showed that the amplitude of the transreflectance AC PPG signals were significantly different ($p < 0.05$) than the AC PPG signals obtained from the other two conventional PPG sensors (reflectance and transmittance). At induced brachial pressures between 90 and 135 mmHg, the reflectance finger pulse oximeter failed 25 times (failure rate 42.2 %) to estimate SpO_2 values, whereas the transmittance pulse oximeter failed 8 times (failure rate 15.5 %). The transreflectance pulse oximeter failed only 3 times (failure rate 6.8 %) and the commercial pulse oximeter failed 17 times (failure rate 29.4 %).

Keywords Photoplethysmography · Pulse oximetry · Perfusion · Transreflectance · Vasoconstriction

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1 Introduction

Photoplethysmography (PPG) 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 [5]. It is based on the absorption properties of vascular tissue when it is transilluminated by light. It is possible for the tissue to be directly transilluminated where the light source is on one side of the tissue and the detector on the other side (transmittance mode) or where the light source and the photodetector can be positioned side by side (reflectance mode).

The intensity of the light that reaches the photodetector in either reflectance or transmittance mode is measured and the variations in the photodetector current are assumed to be related to blood volume changes underneath the probe [1]. These variations are amplified and recorded as the photoplethysmographic signal, used in the estimation of arterial oxygen saturation (SpO_2) by pulse oximetry. Pulse oximeters estimate arterial oxygen saturation non-invasively by illuminating vascular tissue with red light and near-infrared radiation. 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 [13]. The arterial blood oxygen saturation may be estimated from the ratios of these amplitudes, normalised by dividing by the total detected intensity (the DC signal). Hence, the technique of pulse oximetry relies on the presence of an adequate peripheral arterial pulse [10].

When peripheral perfusion is poor, as in states of hypovolaemia, hypothermia, vasoconstriction, low cardiac output and low mean arterial pressure [2], pulse oximeter readings become unreliable or cease altogether [8, 11]. The oxygen saturation readings become unreliable in these circumstances because conventional pulse oximeter sensors are usually placed at the most peripheral parts of the body such as the finger, where pulsatile flow is most vulnerable [5]. Delay in the estimation of SpO_2 by transmittance pulse oximeters has also been reported [9] in cases of low peripheral perfusion.

The aim of this study was to investigate a new multimode PPG sensor, which can contribute towards the overcoming of the current limitations of pulse oximeters especially during conditions of poor peripheral perfusion. A multimode finger photoplethysmographic sensor capable of operating simultaneously as a reflectance and transmittance PPG sensor has been proposed. The hypothesis is that such a sensor will "harvest" both the light transmitted and reflected from the vascular bed and therefore, enhance its performance in cases of poor peripheral perfusion.

2 Methods

2.1 Multimode finger PPG probe

A PPG finger probe that operates simultaneously in transmittance and reflectance mode has been designed and developed. Four LEDs were used, two for each wavelengths (red and infrared). The probe was developed in such a way that the red and infrared LEDs are never on at the same time. When the red or infrared LED was on, transmitted or backscattered light was detected by two photodiodes. The first photodiode was placed opposite the LEDs (transmittance mode) and the second photodiode was placed adjacent to the LEDs (reflectance mode). A diagram outlining the principle of operation of the multimode PPG finger probe is shown in Fig. 1.

2.1.1 Optical components

Surface mount ceramic type infrared and red LEDs (CR 10 IRK, PerkinElmer, Inc., USA) with peak emission wavelength at 950 and 660 nm, respectively, were used. The dimensions of each LED were 3.20 mm × 2.00 mm × 0.50 mm. Two infrared and two red LEDs were used for the maximum illumination of the tissue. Each pair of LEDs was mounted on the diagonal corners of a printed circuit board (Fig. 1). All LEDs were driven by the LED driving circuitry (described below) providing 20 mA to each LED. Two ceramic chip-based surface mount photodiodes (CFD 10 DLF, PerkinElmer, Inc., USA) (dimension 4.6 mm × 3.8 mm × 2 mm) were used. The first photodiode was used to detect the reflected light and the other to detect the transmitted light.

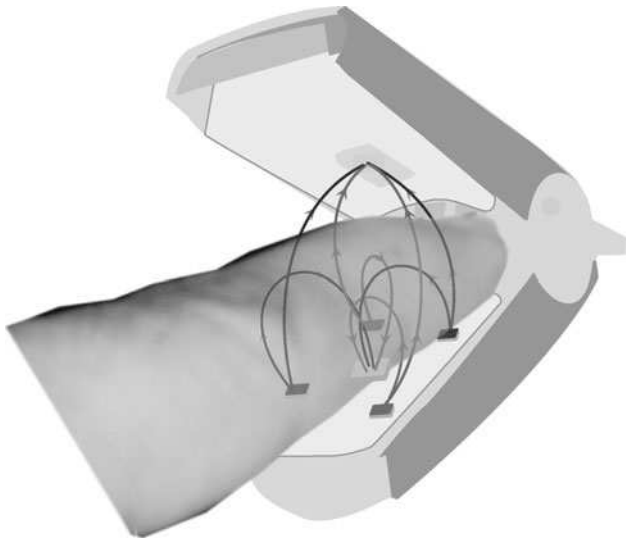

Fig. 1 Diagram of the multimode photoplethysmographic finger probe identifying the configuration (placement) of all optical devices (LEDs and photodiodes)

2.1.2 Mechanical construction of the multimode finger PPG probe

Two printed circuit boards (PCBs) were developed to house all optical components. The copper tracks were hand-etched using an eraser polivit. Low-temperature (230 °C) soldering was used to connect the surface mount components to the copper tracks of the boards. The first PCB (dimensions 14.4 mm × 13 mm × 1 mm) represented the reflectance site and comprised the two red and two infrared LEDs and one photodiode. The photodiode was mounted between the red and infrared LEDs to detect back scattered radiation by the tissue from both infrared and red LEDs. The distance between the LEDs and the photodiode was 5 mm (Fig. 1). The second PCB (6 mm × 7 mm × 1 mm) comprised of one photodiode used to detect the transmitted light. Both PCBs were housed in a conventional finger clip pulse oximeter probe with the reflectance PCB placed on the lower part of the clip and the transmittance PCB on the upper part of the clip. An eight-core screened cable was used to connect all optical components to the main PPG processing system.

2.2 Multimode PPG processing system

Two independent but electronically identical photoplethysmographic systems were developed for processing the signals from the transmittance and the reflectance PPG probes. A transreflectance PPG system (combining the transmittance and the reflectance signals into one signal) was also developed. A block diagram of the developed system is shown in Fig. 2. The various stages comprising the PPG processing systems are described below.

The LEDs were driven by a constant current source, which consists of a JFET-input operational amplifier and two NPN and two N-logic mosfets transistors (2N3904 and 2N7000, Fairchild Semiconductor Corporation, Portland, USA). Both LEDs (red and infrared) were multiplexed using the National Instrument LabVIEW software which turned the red and infrared LEDs "on" and "off" at a frequency of 500 Hz. The output current from the two photodiodes was converted into voltage using two identical differential transimpedance amplifiers. The outputs from the reflectance and transmittance transimpedance amplifiers were fed into a summing amplifier to make the transreflectance signal. The mixed output of the transimpedance amplifiers was a time-multiplexed mixed signal containing both red and infrared PPG signals, which needed to be separated. This was accomplished using a demultiplexer (MC14051, ON Semiconductor, Arizona, USA). In order to eliminate the high-frequency (500 Hz) switching noise from the demultiplexer the red and infrared PPG signals were filtered. Also, the red and infrared PPG signals were split into their corresponding AC and DC PPG components using band-pass (with a cut-off frequency of 0.5–10 Hz) and low-pass (with a cut-off frequency of 0.5 Hz) filters. The red and infrared AC PPG signals were further amplified before digitisation.

2.3 Software control and data analysis

Twelve analogue output signals (six AC and six DC PPG signals at both wavelengths, for each of the three modes) and an output signal from a commercial finger transmittance pulse oximeter (Nellcor N-200 Pulse oximeter, Nellcor Inc, Hayward, CA, USA) were connected to a National instrument 16-bit data acquisition card (DAQPad-6015, National Instruments Inc., USA). The digitised signals were further analysed by a virtual instrument (VI) implemented in LabVIEW on a personal computer. The VI was able to (1) control the LEDs driving circuitry by sending multiplexed signals to turn the LEDs on and off an analogue signal to power-up the LEDs. (2) Perform the acquisition of all signals and (3) process, store and display the acquired data.

Matlab version R2007b (3 Apple Hill Drive Natick, MA, USA) was also used for the offline signal analysis. A peak detection algorithm was implemented to detect the maxima and the minima of all the acquired AC PPG signals of the reflectance, transmittance, and transreflectance modes. Oxygen saturation values were also computed using an algorithm developed in Matlab. The mean (every 10 s) AC and DC PPG amplitudes were used to calculate the ratio-of-ratios (R);

$$R = \frac{\mathrm{AC_{red}}}{\mathrm{DC_{red}}} \Big/ \frac{\mathrm{AC_{ired}}}{\mathrm{DC_{ired}}}.$$

The SpO_2 values were then calculated using an empirically calibrated equation [13] given below:

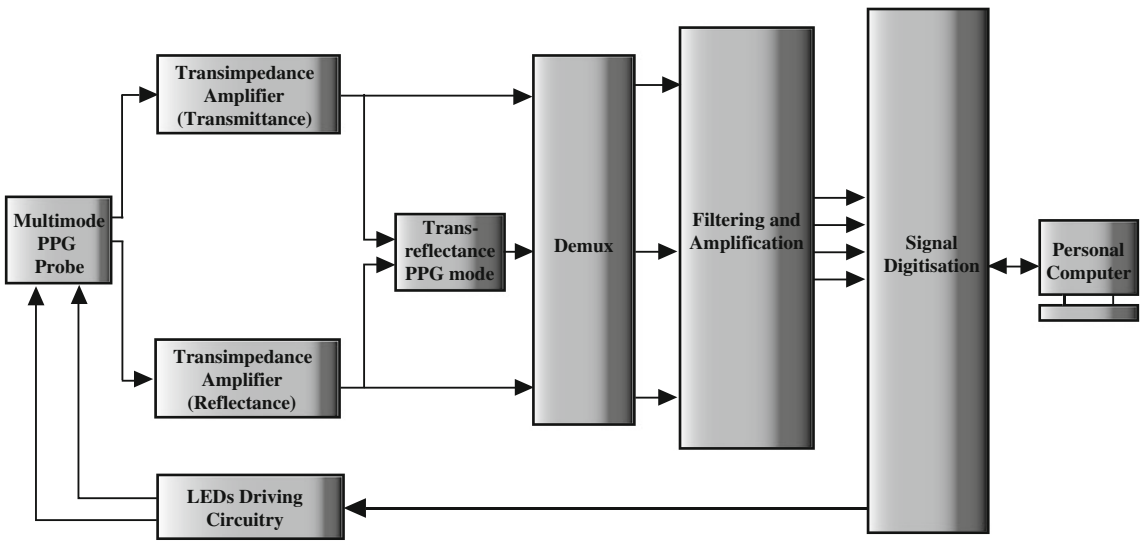

Fig. 2 Block diagram of the new multimode PPG processing system

$$SpO_2 = 110 - 25(R)$$

This was repeated for all the data, therefore enabling the computation of SpO_2 values at all pressures. Before calculating the mean value of the AC PPGs for the chosen segment of 10 s, the morphology of the PPGs was carefully observed. During these segments some PPG traces failed to be categorized as normal PPGs (both in amplitude and morphology) due to the high induced pressure and were then considered as inadequate signals for SpO_2 estimation. Failure was also considered when no form of pulsation was visible on the screen of the computer (especially at very high induced pressures).

2.4 Measurements

The study was approved by the Senate Research Ethics Committee of City University London, and permission was given to conduct experiments on 20 volunteers. Non-smoking healthy volunteers (19 male and 1 female) were recruited and each volunteer signed a consent form prior to the experiment. The subjects were asked to abstain from eating, drinking and exercise for at least 2 h before the experiment. The ages of the volunteers range from 19 to 40 years with the mean and standard deviation of 24.15 and 5.76, respectively.

At the start of the experiment, the subject was told to sit comfortably on a chair. Heart rate, systolic and diastolic blood pressure, of each subject was monitored using an automatic blood pressure monitor device (HEM-907, Omron Healthcare, Hoofddorp, The Netherlands) prior to the acquisition of PPG signals. A sphygmomanometer (Rudolf Riester GmbH, Jungingen, Germany) blood pressure cuff was then wrapped around the brachial artery of the right arm. The custom-made multimode PPG probe was then placed at the index finger of the same arm. A two-wave, transmittance commercial finger pulse oximeter (Nellcor N-200 Pulse oximeter, Nellcor Inc, Hayward, CA, USA) was also placed on the middle finger of the same hand enabling continuous measurements of oxygen saturation values. PPG recordings commenced prior to any occlusion. Artificial hypoperfusion was then induced by gradually occluding the brachial artery using the sphygmomanometer. The pressure was exerted with increments of 15 mmHg and PPG signals were recorded from all three modes for a period of 30 s. Once the exerted pressure reached close to the systolic blood pressure, measured prior to the experiment, the pressure of the sphygmomanometer cuff was released and the PPGs were recorded for a further period of 30 s.

3 Results

3.1 Results from the AC PPG amplitude analysis

Figure 3 depicts all the AC PPG signals plotted against all induced cuff-pressures from one volunteer. Each vertical tick on the *x*-axis corresponds to a specific cuff pressure. It can be seen that the amplitudes of all signals are gradually affected by the increase of pressure, and this is more noticeable after 75 mmHg (approximately mid-systolic pressure). After this occluding pressure the PPG amplitudes decreased rapidly and decayed as the pressure reached the systolic pressure of the subject. This was evident in all the AC PPG signals acquired from all 20

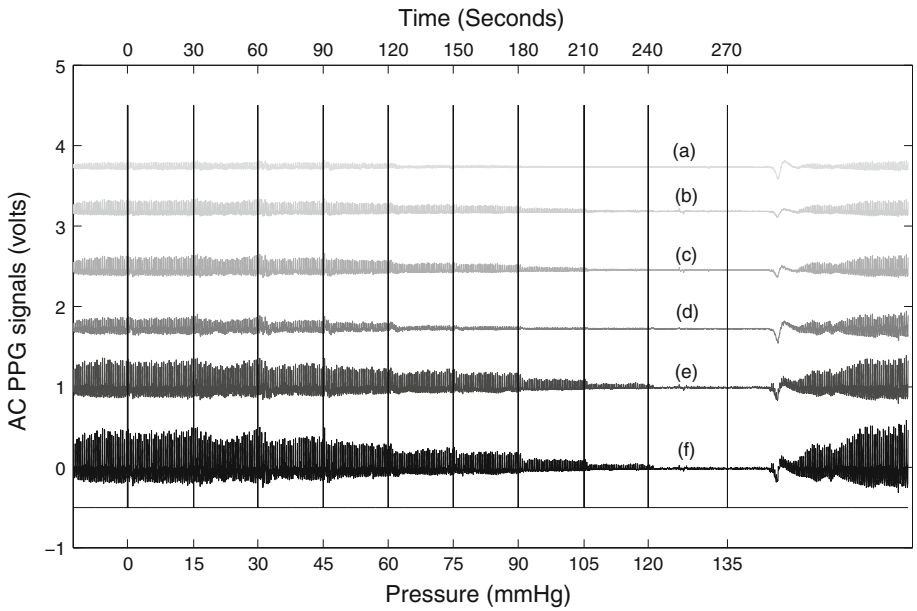

Fig. 3 Red and infrared AC PPG signals from one volunteer, plotted versus the brachial pressure induced at steps of 15 mmHg after each 30 s. Traces *a*, *b* and *c* indicate reflectance, transmittance and transreflectance red AC PPG signals, whereas traces *d*, *e* and *f* represent reflectance, transmittance and transreflectance infrared AC PPG signals

volunteers. Amongst the three infrared AC PPG signals, the bottom two (Fig. 3e, f) representing the transreflectance, and transmittance infrared PPGs, endured more than the other PPG signals. The same applies to the top three red PPGs (see Fig. 3). The infrared AC PPG amplitudes from the reflectance (3d) mode were smaller than the transmittance (3e) mode and the transreflectance mode (3f) at all pressure values. The transreflectance infrared AC PPG signals (3f) were larger in amplitude when compared with the other two modes at all occlusion pressures. The reflectance red AC PPG amplitudes (3a) were also lower in amplitude than the red AC PPG signals acquired from the transmittance (3b) and transreflectance (3c) modes.

The mean AC red and infrared reflectance, transmittance and transreflectance PPG amplitudes at each pressure from all volunteers are shown in Table 1. The systolic pressure of some of the volunteers was at 120 mmHg; therefore, the cuff pressure was not raised to 135 mmHg in those volunteers; hence no PPG signals were recorded ($n = 11$). It can be seen in Table 1 that at all pressures, both the red and infrared transreflectance mean AC PPG values are greater than those of the corresponding values acquired from the transmittance and reflectance PPG systems.

Figure 4 depicts AC infrared PPG signals (10 s) from all monitoring modalities at three different pressures (15, 90, 105 mmHg). All modalities provided PPG signals of good quality and large amplitudes with some exception to the reflectance PPG amplitudes which are much smaller than the other two modes (transmission and transreflectance) especially at higher pressures.

Figure 5 shows a bar chart of the mean (±SD) of the means infrared AC PPG amplitudes at all occlusion pressures. It can be seen that the mean transmittance PPG amplitudes are greater than the reflectance PPG amplitudes at all pressures. Furthermore, at all occlusion pressures, the mean transreflectance PPG amplitudes are greater than those recorded from the other two modes.

To see if there was any statistically significant difference between the mean AC PPG amplitudes at different pressures, pair t tests were performed on the mean infrared AC PPG amplitudes from the reflectance, transmittance and transreflectance PPG modes. The results from the reflectance mode are shown in Table 2. The p value of <0.05 was considered to be significant which increases with the increase in pressure. It can be noticed that the p value decreases substantially as the pressure was raised above 75 mmHg which suggests that the chances of infrared AC PPG values at 75 mmHg and above to be equal to the infrared AC PPG values at 60 mmHg and below are substantially smaller. Physiologically, it implies that the arterial blood volume decreases considerably after the brachial pressure was raised to 75 mmHg.

The results of the t tests performed on the transmittance and transreflectance mean infrared AC PPG values were found to be similar to the t test results from the reflectance infrared AC PPG values discussed above.

To compare the three mean AC PPG values for any significant difference single-factor analysis of variance (ANOVA) was used. The differences between the mean AC PPG values were statistically significant; $F(2, 27) = 4.034$, $p < 0.05$ with MS = 0.0312.

3.2 Results from the SpO_2 analysis

Blood oxygen saturation values from the reflectance, transmittance and transreflectance modes were calculated

Table 1 Mean of the means red AC PPG values obtained from the reflectance, transmittance and transreflectance modes at all pressures

Pressure (mmHg)	Volunteers (n)	Reflectance (V)		Transmittance (V)		Transreflectance (V)	
		AC mean PPG		AC mean PPG		AC mean PPG	
		Red	Ired	Red	Ired	Red	Ired
0	20	0.084	0.247	0.162	0.450	0.221	0.662
15	20	0.087	0.257	0.166	0.464	0.230	0.679
30	20	0.071	0.196	0.145	0.408	0.210	0.583
45	20	0.053	0.138	0.115	0.315	0.145	0.471
60	20	0.046	0.104	0.102	0.259	0.128	0.362
75	20	0.032	0.071	0.069	0.174	0.099	0.238
90	20	0.023	0.048	0.037	0.102	0.051	0.140
105	20	0.025	0.055	0.035	0.095	0.044	0.120
120	19	0.016	0.036	0.026	0.073	0.041	0.103
135	11	0.011	0.025	0.014	0.046	0.020	0.062
Mean		0.045	0.118	0.087	0.241	0.119	0.342
SD		0.028	0.088	0.059	0.166	0.080	0.242

Each entry in the respective columns represents men value of n volunteer

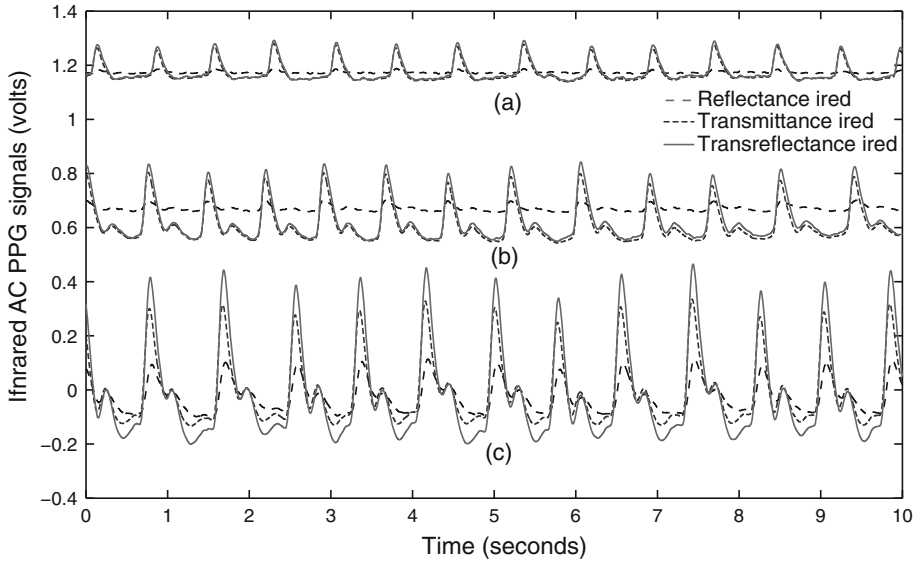

Fig. 4 Infrared AC PPG signals at three different pressures for the duration of 10 s. The traces *a*, *b* and *c* show PPG signals at 105, 90, and 15 mmHg, respectively

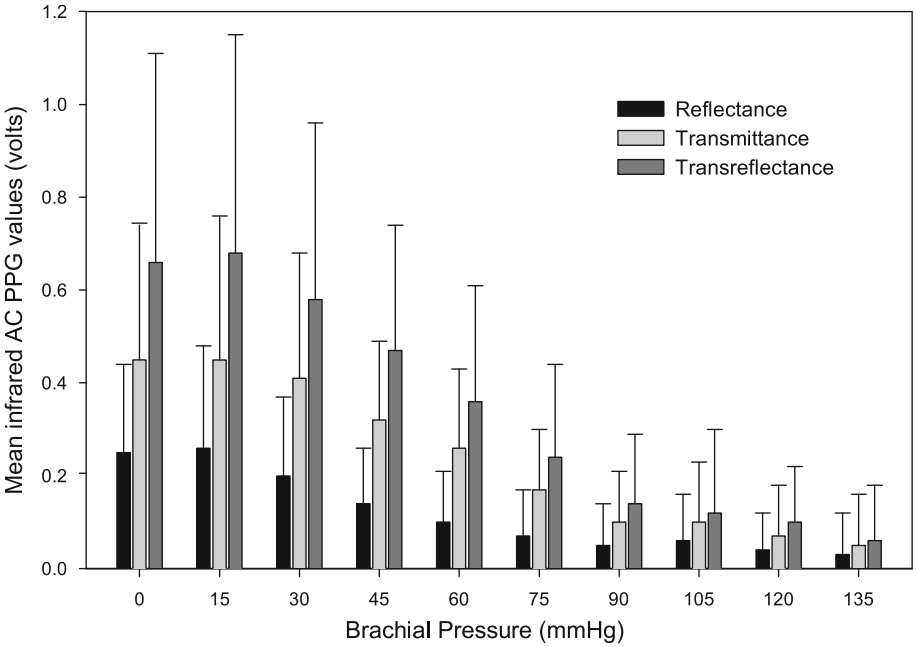

Fig. 5 Mean (±SD) of infrared reflectance, transmittance and transreflectance infrared AC PPG signals

Table 2 Results from the paired t-test performed on the reflectance infrared AC PPG values at different pressures

	15 *p*	30 *p*	45 *p*	60 *p*	75 *p*	90 *p*	105 *p*	120 *p*	135 *p*
0	0.741	0.142	**0.006**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**
15		0.181	**0.009**	**0.003**	**0.0008**	**<0.05**	**<0.05**	**<0.05**	**<0.05**
30			**0.018**	**0.001**	**0.0002**	**<0.05**	**<0.05**	**<0.05**	**<0.05**
45				**0.017**	**0.0003**	**$9.4 \times e^{-5}$**	**<0.05**	**<0.05**	**<0.05**
60					**$4 \times e^{-6}$**	**$5.7 \times e^{-5}$**	**$4.8 \times e^{-5}$**	**<0.05**	**<0.05**
75						**$9.8 \times e^{-3}$**	**0.015**	**<0.05**	**<0.05**
90							0.852	0.739	0.487
105								0.788	0.505
120									0.675

(at all pressures) using the previously mentioned algorithm (see Sect. 2.3).

The range of estimated SpO_2 values when the cuff pressure was at 0 mmHg from all modes was from 96 to 100.2 %. The mean SpO_2 values for each mode showed that the transreflectance SpO_2 values remained higher than that of the reflectance and the transmittance oxygen saturation values. At cuff pressures from 15 to 75 mmHg, most of SpO_2 values were in the range of 90–100 %. Table 3 shows the mean SpO_2 values from all sensors including the commercial pulse oximetry at all induced pressures.

At 90 mmHg cuff pressure, the reflectance SpO_2 value of subject no. 19 failed, which means that the reflectance PPG system was unable to detect reliable PPG waveform and hence failed to estimate a meaningful SpO_2 value. Also, most of the SpO_2 values from the reflectance PPG system at 90 mmHg were too low to be considered as the true representation of the arterial oxygen saturation (Table 3). Compared with the reflectance SpO_2 values, the transmittance, and transreflectance SpO_2 values were mostly >90 %. Nine, out of 19 transreflectance SpO_2 values were greater or equal to 95 %, which may show a true representation of the arterial oxygen saturation. Moreover, many of the transreflectance SpO_2 values were greater than that of the reflectance and transmittance SpO_2 values.

At 105 mmHg, in 6 out of 19 volunteers, the reflectance PPG system was unable to detect any meaningful PPG signal and therefore failed to accurately estimate SpO_2 values. SpO_2 values of six volunteers were below 85 % which is not accurate for healthy volunteers (Table 3). The transmittance PPG system performed well as compared with the reflectance PPG system at 105 mmHg cuff pressure. Four SpO_2 values were <85 %. Many of the transreflectance SpO_2 values were higher than the corresponding reflectance, and transmittance SpO_2 values and therefore can be considered as more reliable at this pressure. The mean values also reflect the performance of the three modes at 105 mmHg pressure.

At 120 mmHg, the reflectance PPG sensor failed in nine volunteers and most of the SpO_2 values cannot be considered as the accurate representation of the actual arterial oxygen saturation. There were three failures of the transmittance PPG sensor and five failures from the commercial pulse oximeter. There was no failure by the transreflectance PPG sensor at this high brachial pressure. The mean values also showed higher SpO_2 values of the transreflectance PPG sensor (Table 3).

As stated in the measurements section, for each volunteer the brachial pressure was raised to just below their systolic pressure. There were 11 volunteers whose systolic pressure was around 135 mmHg. The reflectance PPG sensor failed in nine volunteers in estimating of reliable SpO_2 values. In five volunteers, the transmittance PPG sensor was unable to produce any accurate SpO_2 value and only a few values may be considered as accurate, whereas the transreflectance PPG sensor produced reliable SpO_2 values (with three failures) for more volunteers as compared with the other two modes (Table 3). The commercial pulse oximeter failed in seven volunteers to produce SpO_2 values.

The failure rates ((no. of failures to estimate SpO_2 values × 100)/(total number of volunteers × total number of increments in brachial pressures)) of the four pulse oximeters (reflectance, transmittance, transreflectance and commercial) to estimate SpO_2 values from all volunteers at higher cuff pressures (above 75 mmHg) are given in Table 4. It can be seen that at 90 mmHg, the failure rates of the reflectance and commercial pulse oximeters were 5.7 and 15.8 %, respectively. At the same pressure, transmittance and transreflectance pulse oximeters did not fail to estimate SpO_2 values at any volunteer (failure rate 0 %). At 120 mmHg, the transmittance pulse

Table 3 Mean of the means SpO_2 values at each pressure. Every entry in the table represents mean SpO_2 value from all volunteers at each pressure

n	Cuff pressure (mmHg)	Reflectance (%)	Transmittance (%)	Transreflectance (%)	Commercial (%)
19	0	96.3	96.4	98.2	99.1
19	15	96.0	95.5	97.7	98.8
19	30	94.3	94.9	96.7	98.6
19	45	92.4	94.0	96.2	98.3
19	60	91.2	93.4	95.8	97.6
19	75	86.3	91.7	95.4	97.1
19	90	84.8	91.7	94.5	96.6
19	105	83.3	88.4	91.1	95
18	120	81.4	86	90.6	97
11	135	77.4	86.3	88	91.1
Mean		88.0	91.8	94.5	96.9
SD		6.91	3.77	3.29	2.38

Table 4 Failure rates of reflectance (Ref), transmittance (Tr), transrelectance(TrR) and the commercial (Comm) pulse oximeters to estimate SpO_2 values at cuff-pressure between 90 and 135 mmHg for *n* volunteers

n	Cuff pressure (mmHg)	Ref (%)	Tr (%)	TrR (%)	Comm (%)
19	90	5.7	0	0	15.8
19	105	31.5	0	0	10.5
18	120	50	16.6	0	27.7
11	135	81.8	45.5	27.2	63.6
Mean		42.2	15.5	6.8	29.4

oximeter failed in three volunteers (failure rate 16.6 %). At the same brachial pressure the reflectance and the commercial pulse oximeters performed poorly (failure rate 50 %). No failure was observed in any volunteer during this pressure from the transreflectance pulse oximeter. As the brachial pressure was raised to 135 mmHg, out of 11 volunteers the reflectance and the commercial pulse oximeter failed in 9 volunteers (failure rate 81.8 %) and 7 volunteers (failure rate 63.6 %), respectively. The transmittance pulse oximeter performed better than the reflectance and commercial pulse oximeter with a failure rate of 45.5 %. At this pressure, the transreflectance pulse oximeter performed relatively better than the other modes and only failed in three volunteers. The mean failure rates were calculated for each pulse oximeter mode which suggests that the transreflectance pulse oximeter was the most reliable with least failures to estimate SpO_2 value (Table 4).

4 Discussion

Poor perfusion is the main cause of failure to obtain a satisfactory PPG signal [3]. A pulse oximeter can only function if it can detect a modulation in transmitted or reflected light. Thus if perfusion is poor and pulse amplitude is small it will be prone to error or completely unable to estimate SpO_2 reading [3].

In this experiment, three custom-made PPG/SpO_2 sensors were used to investigate PPG and SpO_2 values under conditions of poor peripheral perfusion emulated by gradually occluding the brachial artery artificiality, while estimating blood oxygen saturation values from the fingers of the same arm using a commercial pulse oximeter. The results from this pilot investigation showed that the reflectance probe is most easily compromised when compared with the transmittance and the transreflectance modes and this was evident by the amplitude of the PPG signals and the estimated SpO_2 values. The transreflectance probe endured the most at high occlusion pressures and estimated SpO_2 values with certain accuracy and consistency even when the other modes failed. When the transreflectance pulse oximeter was compared with the commercial pulse oximeter it was found that the commercial transmittance pulse oximeter failed in 17 volunteers, whereas the transreflectance failed in only 3 volunteers. Analysis of the PPG waveforms showed that when the brachial pressure was increased, the blood volume gradually decreased and this noticeable decrease was very clear up to 60 mmHg. However, when the pressure was raised to 75 mmHg (around mid-systolic pressure) the PPGs from all modes experienced a sudden decrease in amplitude which suggests a sudden decrease in the arterial blood volume at the finger.

Apart from PPG signals being used in estimation of the SpO_2 values, these volumetric changes in the finger PPG signal appear as an information source for several indirect measurement methods [4, 7, 12]. In a previous study [6], a moderate correlation ($r = 0.54$) was found between fingertip PPG waveform variability (PPGV) and systemic vascular resistance (SVR). The use of a multimode finger PPG probe in such a study may help establish a better link between the PPGV and SVR. The proposed multimode finger PPG/SpO_2 sensor has proven to enable the further understanding of the behaviour of PPGs in cases of poor peripheral perfusion and the knowledge generated from such study will enable the optimisation in the hardware design and the signal analysis of the PPGs to develop more accurate and more robust pulse oximeters which will perform better in these difficult physiological cases. Clearly the opportunity to compare (PPGs and SpO_2s) the three modes (reflectance, transmittance and transreflectance) simultaneously along with SpO_2 values from a commercial transmittance finger pulse oximetry provided useful information and once more confirmed the behaviour of these modes under such conditions.

In conclusion, the multimode PPG/SpO_2 system enabled the detailed investigation of PPG signals and SpO_2 values under conditions of artificial hypoperfusion. The transreflectance mode performed better that the other modes (transmission and reflection) and the commercial pulse oximeter and therefore such mode could be used in in cases of poor peripheral perfusion.

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