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Investigation of pulse oximeter failure rates during artificial hypoperfusion utilising a custom made multimode pulse oximetery sensor

M. Shafique, P. A. Kyriacou, Senior Member, IEEE and S K Pal

***Abstract*—Pulse oximetry utilises the technique of photoplethysmography (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. In order to investigate further the threshold where pulse oximetry fails to produce accurate SpO_2 values, we have developed a custom made multimode finger pulse oximetry probe that operates in conventional, reflectance and transmittance mode independently and also in a combined mode called transreflectance. Experiments on twenty healthy volunteers undergoing induced artificial hypoperfusion utilising a brachial blood pressure cuff were performed in order to investigate the possible threshold of failure to accurately estimate SpO_2 values from all pulse oximetry modes. The results suggest that the transreflectance pulse oximeter endures more in estimating accurately SpO_2 values when compared with the other two custom made pulse oximeters and a commercial finger pulse oximeter.**

***Index Terms*—Photoplethysmography, transreflectance, peripheral hypoperfusion, pulse oximetry.**

I. Introduction

PULSE oximeter is one of the most commonly used patient monitors both in and out of the operating room [8]. Because of its ability to quickly detect hypoxaemia, it has become a standard of care during anaesthesia as well as in the recovery room and intensive care unit [9]. Pulse oximetry is based on two basic principles. First, the light absorbance of oxyhaemoglobin and deoxyhaemoglobin is different at red and infrared wavelengths. Second, the absorbance at these two wavelengths has a pulsatile component attributed to the cardiac pulsations [4]. The technique of detecting these pulsatile components is called photoplethysmography, which 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 on the same side (reflectance mode) [3]. 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 [5]. 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 [10]. From the ratios of these amplitudes, and the corresponding DC photoplethysmographic components, arterial blood oxygen saturation is estimated. Hence, the technique of pulse oximetry relies on the presence of adequate peripheral arterial pulsations, which are detected as photoplethysmographic (PPG) signals [3]. The accuracy of commercially available pulse oximeters in critically ill patients has been investigated in several studies [1]. Compared with the Gold standard (multiwavelength CO oximeter) of measuring arterial oxygen saturation (SaO_2), the accuracy of pulse oximeters becomes extremely unreliable when SaO_2 falls to 80% or less [2]. Moreover, slow reaction time of the transmittance mode PPG has also been reported in low peripheral perfusion [7]. In order to overcome some of the limitations of the commercial transmittance or reflectance pulse oximeters that appear in cases of poor PPG pulsations, a new multimode photoplethysmography processing system [6] was developed and a pilot study was conducted to assess its performance in acquiring meaningful and reliable photoplethysmographic signals [7]. The purpose of this study was to investigate in detail the threshold where pulse oximetry fails to produce accurate SpO_2 values. In order to compare the reliability of the custom made multimode pulse oximeter, SpO_2 values have also been recorded from a commercial pulse oximeter.

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II. Material and Methods

A. PPG processing and data acquisition system

Figure 1 shows the block diagram of the custom made multimode PPG probe described earlier [6]. The system is designed to enable simultaneous operation of the reflectance, transmittance and transreflectance pulse oximeters [6]. The outputs from the multimode pulse oximeter probe (which consists of both reflectance and transmittance photodiodes and the red and infrared LEDs) are connected to the respective reflectance and transmittance PPG processing systems. For the transreflectance PPG processing system the outputs of both reflectance and transmittance transimpedance amplifiers (I-V Converter) are summed together using a summing amplifier. All three voltage outputs representing the three modes follow an identical process. In each PPG processing system, the mixed voltage output of the I-V converter is connected to a demultiplexer in order to separate the red and infrared PPG

signals for each mode. The PPG signals are then filtered into their respective red and infrared AC and DC PPGs using 2nd order Butterworth band-pass (pass-band frequency, 0.5 Hz to 10 Hz) and low-pass filters (cut-off frequency, 0.5 Hz). The red and infrared AC PPG signals are then amplified using an inverting amplifier with a gain of 30. The red and infrared AC and DC PPGs from all three modes and the SpO_2 values from a commercial pulse oximeter are then digitised using a 16-bit data acquisition card (DAQPad-6015, National Instruments Corporation, Austin, TX, USA). A virtual instrument was implemented in LabVIEW to record and display all PPG signals.

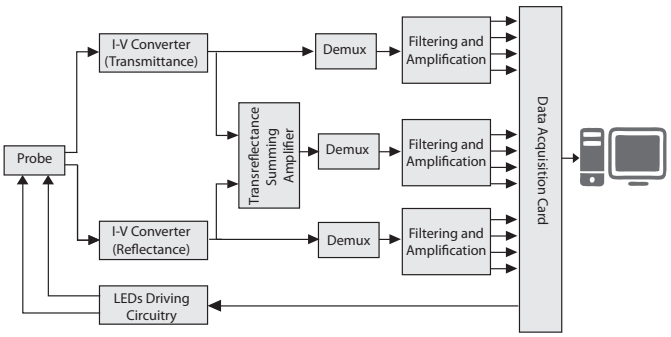

Figure 1. Block diagram of the custom made multimode pulse oximetry system [6].

B. Measurements

The study was approved by the Senate Research Ethics Committee of City University London and permission was given to conduct the experiments in twenty volunteers. Non-smoking healthy volunteers 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 two hours before the experiment. Most (all but one) of the volunteers that took part in the study were males with ages ranging between 19 to 40 years with the mean and standard deviation of 24.2 and 5.8 respectively (see Table I).

Prior to the acquisition of signals, the heart rate, systolic and diastolic blood pressure of each subject was recorded using an automatic blood pressure monitor device (HEM-907, Omron Healthcare, Hoofddorp, The Netherlands). A sphygmomanometer (Rudolf Riester GmbH, Bruckstr, Jungingen, Germany) blood pressure cuff was then wrapped around the right arm in order to constrain blood flow in the brachial artery. The custom made multimode PPG probe was placed on the index finger of the same arm. A two wave, transmittance commercial finger pulse oximeter (Nellcor N-200 Pulse oximeter, Nellcor Inc, Hayward, California U.S.A) was also placed on the middle finger of the same hand enabling continuous measurements of oxygen saturation values. Artificial hypoperfusion was then induced by gradually occluding the brachial artery using the sphygmomanometer. The pressure was exerted in increments of 15 mmHg and PPG signals were recorded from all three modes for a period of 30 seconds at each pressure increment. 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 seconds.

Table I
Biometric detail of the volunteers that took part in the study.

Volunteer	Sex	Age	Weight (kg)	B.P (mmHg)	Heart Rate (bpm)
1	M	21	85	138/84	74
2	M	20	70	132/74	74
3	M	35	82	140/75	80
4	M	19	70	130/65	65
5	M	19	72	130/68	83
6	M	20	69	145/82	78
7	M	21	55	125/55	75
8	M	21	70	120/66	67
9	M	22	60	107/52	62
10	M	20	84	137/86	69
11	M	21	80	125/52	85
12	M	31	80	135/78	75
13	M	30	62	121/65	74
14	F	28	88	115/85	83
15	M	40	87	130/91	75
16	M	24	71	134/80	100
17	M	21	74	110/60	65
18	M	23	60	124/82	69
19	M	25	80	135/82	66
20	M	22	65	130/65	72

Oxygen saturation values were computed using a programme developed in Matlab. When the code was run, the data of the AC PPG signal at a specific pressure for the period of 30 seconds was selected. A peak detection algorithm was used to detect peaks of the infrared and red AC PPG signals. Mean PPG peak values were calculated by taking the mean of all the detected peaks during that period (approximately 10 seconds). The same algorithm was used (bypassing the step of peak detection) to calculate the mean values of the red and infrared DC PPG signals for the same period of time. These values were then used in the formula shown below in order to calculate the ratio-of-ratios (R);

$$R = \frac{AC_{red}}{DC_{red}} \; / \; \frac{AC_{ired}}{DC_{ired}}$$

The SpO_2 values were then calculated using an empirically calibrated equation [10] given below;

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

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 seconds, 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).

III. Results

Figure 2 depicts all the AC PPG signals plotted against all induced cuff-pressures acquired from a randomly selected volunteer. Each vertical tick on the x-axis shows the increments

of 15 mmHg cuff-pressure exerted on the brachial artery for every 30 seconds time interval.

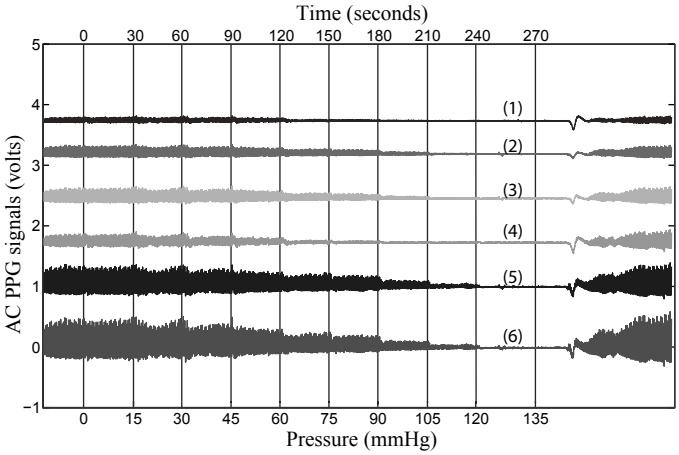

Figure 2. Red and infrared AC PPG signals from one volunteer, plotted versus the brachial pressure induced with the steps of 15 mmHg after each 30 seconds. Traces 6, 5 and 4 represent transreflectance, transmittance and reflectance infrared AC PPG signals, whereas 3, 2 and 1 indicate transreflectance transmittance and reflectance red AC PPG signals.

As can be seen, all the signals are gradually affected by the increase of pressure but the PPG amplitudes are mostly influenced when the pressure was increased above 75 mmHg. It is noticeable that after 75 mmHg, the amplitudes decrease rapidly and decay down as the pressure reaches the systolic pressure of the subject. This was also evident in all the AC signals acquired from all volunteers. Amongst the three infrared signals (4, 5 and 6), the bottom two (5 and 6 in Figure 2), transreflectance, and transmittance infrared PPGs lasted longer than the other PPG signals. The same applies to the top three red PPGs (1, 2 and 3 in Figure 2). The infrared PPG amplitudes of the reflectance (4) were smaller than the transmittance (5) and the transreflectance infrared PPG signals (6) at all pressure values, however, the transreflectance PPG signals (6) were larger in amplitude when compared with the other two modes at all occlusion pressures. The reflectance red PPG signal (1) was also lower in amplitude than the red AC PPG signals acquired from the transmittance (2) and transreflectance (3) modes.

The SpO_2 values from the reflectance, transmittance, and transreflectance modes were calculated (at all pressures). SpO_2 values were successfully estimated from 19 volunteers, with one failure which was attributable to a technical fault. The range of calculated SpO_2 values at 0 mmHg (i.e. no pressure was exerted) from all modes was from 97% to 100% (as expected at this pressure since all volunteers where healthy and well perfused), which shows reasonable agreement between the reflectance, transmittance and transreflectance PPG systems. Table II shows the mean SpO_2 values at each brachial pressure for "n" volunteers. The mean SpO_2 values (Table II) for each mode showed that the oxygen saturation values produced by the transreflectance mode remained higher than those of the reflectance, and the transmittance modes. The SpO_2 values at brachial pressures between 15 mmHg to 75 mmHg fell in the range of 85 to 100%. As the pressure was increased the mean SpO_2 values decreased by approximately 1% from one pressure to another.

Table II
Mean of the means SpO_2 values at each pressure from the reflectance (Ref), transmittance (Tr), transreflectance (TrR) and commercial (Comm) pulse oximeters. Every entry in the Table represents mean SpO_2 value from "n" volunteers at each pressure.

n	Cuff pressure (mmHg)	Ref (%)	Tr (%)	TrR (%)	Comm (%)
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**
	S. Dev.	**6.91**	**3.77**	**3.29**	**2.38**

All custom made pulse oximetry modes including the commercial pulse oximetry performed reasonably well in estimating accurate SpO_2 values in the range of cuff pressures from 0 to 75 mmHg. When the pressure increased further, there was noticeable misbehaviour amongst the different modes. This misbehaviour is translated in the inaccurate estimation of SpO_2 values or the complete failure in estimating a saturation values at a particular pressure. This is possibly due to the degradation of the PPG signals at such pressures. Table III summarises the number of complete failures amongst all pulse oximeters in the range of pressures from 75 mmHg to 135 mmHg.

Table III
Number of failures in estimating SpO_2 values by the custom made reflectance (Ref failures), transmittance (Tr failures), transreflectance (TrR failures) and commercial (Com failures) pulse oximeters. "n" represents the number of volunteers at each respective brachial pressure. There was no failure between 0 to 75 mmHg.

n	Cuff pressure (mmHg)	Ref failures	Tr failures	TrR failures	Com failures
19	75	0	0	0	0
19	90	1	0	0	3
19	105	6	0	0	2
18	120	10	3	0	5
11	135	8	4	3	7
	Total Failures	**25**	**7**	**3**	**17**

A pair t-test was preformed to compare the mean of means SpO_2 values of reflectance, transmittance, transreflectance, and commercial pulse oximeter. The results from this test are shown in Table IV.

Table IV
Results of the paired t-test, comparing reflectance, transmittance, transreflectance and commercial pulse oximeter SpO2 values.

	Transmittance	Transreflectance	Commercial
Reflectance	<0.05	<0.05	<0.05
Transmittance		<0.05	<0.05
Transreflectance			NS

IV. Conclusions

In this investigation the multimode SpO_2 sensor and a commercial pulse oximeter sensor were tested under conditions of poor peripheral perfusion emulated by gradually occluding the brachial artery while estimating blood oxygen saturation values from the fingers of the same arm. The results from these tests showed that the reflectance pulse oximeter is most easily compromised when compared with the transmittance and the transreflectance pulse oximeters and this was evident by the estimated SpO_2 values. Also, the reflectance pulse oximeter failed (25 times) more times when compared to the other modes. The transmittance pulse oximeter failed to estimate SpO_2 values in 7 volunteers. The transreflectance mode endured the most at high occlusion pressures and managed to estimate SpO_2 values with certain accuracy and consistency even when the other modes struggled or completely failed. When the number of failures to estimate SpO_2 values of the custom made system was compared with the commercial pulse oximeter it was observed that the commercial transmittance pulse oximeter failed in 17 volunteers, whereas the transreflectance pulse oximeter failed only in 3 volunteers. The results of this study suggest that the transreflectance pulse oximeter might be more reliable in the estimation of blood oxygen saturation in cases of compromised peripheral perfusion. Further studies in the clinical setting need to take place in order to test this hypothesis in more real conditions of hypoperfusion.

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