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Photoplethysmographic signals and blood oxygen saturation values during artificial hypothermia in healthy volunteers

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Abstract

Pulse oximetry utilizes the technique of photoplethysmography to estimate arterial oxygen saturation (SpO₂) values. During hypothermia, the amplitude of the photoplethysmograph (PPG) is compromised which can lead to inaccurate estimation of SpO₂. A new multimode PPG/pulse oximeter sensor was developed to investigate the behaviour of PPGs during conditions of induced hypothermia (hand immersed in an ice bath). PPG measurements from 20 volunteers were conducted and SpO₂ values were estimated at all stages of the experiment. Good quality PPG signals were observed from the majority of the volunteers at almost all hand temperatures. At low temperature ranges, from 13 to 21 °C, the failure rate to estimate SpO₂ values from the multimode transreflectance PPG sensor was 2.4% as compared to the commercial pulse oximeter with a failure rate of 70%.

Keywords: photoplethysmography, pulse oximetry, hypothermia

(Some figures may appear in colour only in the online journal)

1. Introduction

Pulse oximetry has widely been used to determine arterial oxygen saturation non-invasively. It works by illuminating vascular tissue (finger, ear, etc) using red and near infrared light (Kyriacou *et al* 1999). The light can be detected on the same side (reflectance mode) or on the other side (transmittance mode) of the tissue by a photodetector. The output from the photodetector is converted into a voltage and then further processed producing the signal known as the photoplethysmographic signal (PPG) (Kyriacou *et al* 2001). The signal can be divided into a pulsatile (ac) and a relatively constant (dc) PPG component. Arterial oxygen saturation (SpO₂) is then calculated using the ratios of ac and dc components of the red and infrared PPG signals $\left(\frac{\left(\frac{ac}{dc}\right)_{red}}{\left(\frac{ac}{dc}\right)_{ired}}\right)$ and by using a calibration curve (Webster 2003).

Despite its popularity, pulse oximetry has the disadvantage of inaccuracies when used in patients suffering from conditions of low peripheral perfusion, which can be caused by hypothermia (Al Khudhairi *et al* 1990, Pälve and Vuori 1989). Poor tissue perfusion may severely compromise the PPG signals, both in quality and amplitude and therefore make the estimation of SpO₂ impossible (Goldman *et al* 2000). There is also a lack of understanding of exactly at what minimum body/skin temperature does the PPG signal and pulse oximeter readings become unreliable. Not enough studies have been conducted to determine the temperature threshold above which the PPG signal and SpO₂ values can be considered accurate. Most of the pulse oximeters also display the PPG signal, which itself contains a wealth of information (Shelley 2007) related to vascular assessment (Allen 2007), autonomic function (Avolio 2002) and respiration (Waksman *et al* 2010). During hypothermia, the quality of the PPG signal acquired from the periphery (finger, toe or ear lobe) deteriorates significantly (AlKhudhairi *et al* 1990, Pälve and Vuori 1989). Since the main function of commercial pulse oximeters is considered to be the estimation of SpO₂ values rather than displaying the actual PPG waveform, the pulse oximeter shuts off the PPG waveform from the display completely during any failure to estimate SpO₂ values. Therefore, even though the clinician might be interested to observe the PPG waveform for the above-mentioned conditions, this is not available and is due to the fact that the pulse oximetry probe is not able to acquire good quality PPG signals at low temperatures.

The aim of this study was to investigate PPG signals and arterial oxygen saturation values during induced hypothermia, by immersing the hand in an ice bath using a new multimode PPG/pulse oximetry probe. The multimode finger pulse oximetry probe (documented earlier (Shafique *et al* 2009)) enables the simultaneous monitoring of reflectance and transmittance finger PPGs plus it combines (adds) the signals from both modes resulting in a new mode called 'transreflectance'. Such technology will enable the comprehensive mapping of PPGs during conditions of hand hypothermia. The output from such study will provide new knowledge on the threshold of the failure of pulse oximeters during cases of hypothermia plus will identify which one of the three modes has the capability of producing the most reliable PPGs which will enable the accurate estimations of SpO₂.

2. Materials and methods

The experimental set-up used in this study is shown in the block diagram in figure 1. In this experiment, the multimode PPG finger probe and a thermocouple sensor were placed on the index finger of volunteers (figure 1). A commercial finger pulse oximeter probe was also attached to the middle finger of the volunteer.

2.1. Multimode finger PPG probe and the processing system

The design and construction of the multimode finger PPG probe and the development of the PPG processing system has been previously described by Shafique *et al* (2009). The PPG finger probe operates simultaneously in transmittance and reflectance modes. Four LEDs were used, two for each wavelengths (red and infrared). The geometrical configuration of the optical components is shown in figure 2. Two red LEDs were placed in diagonal corners opposite to each other, whereas the two infrared LEDs were placed on the other diagonal corners of the printed circuit board (PCB) of the reflectance mode detector. The probe was developed in such a way that the red and infrared LEDs were 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 to the LEDs (transmittance mode) and the second photodiode

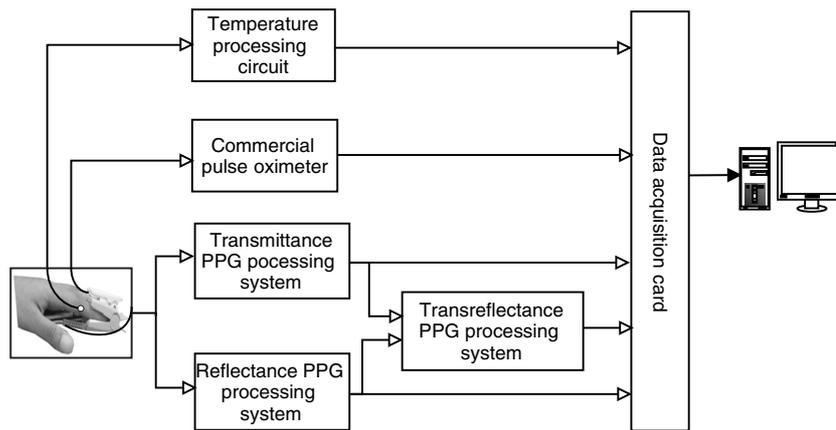


Figure 1. Block diagram of the set-up used for the experiments on volunteers under hypothermia using an ice bath.

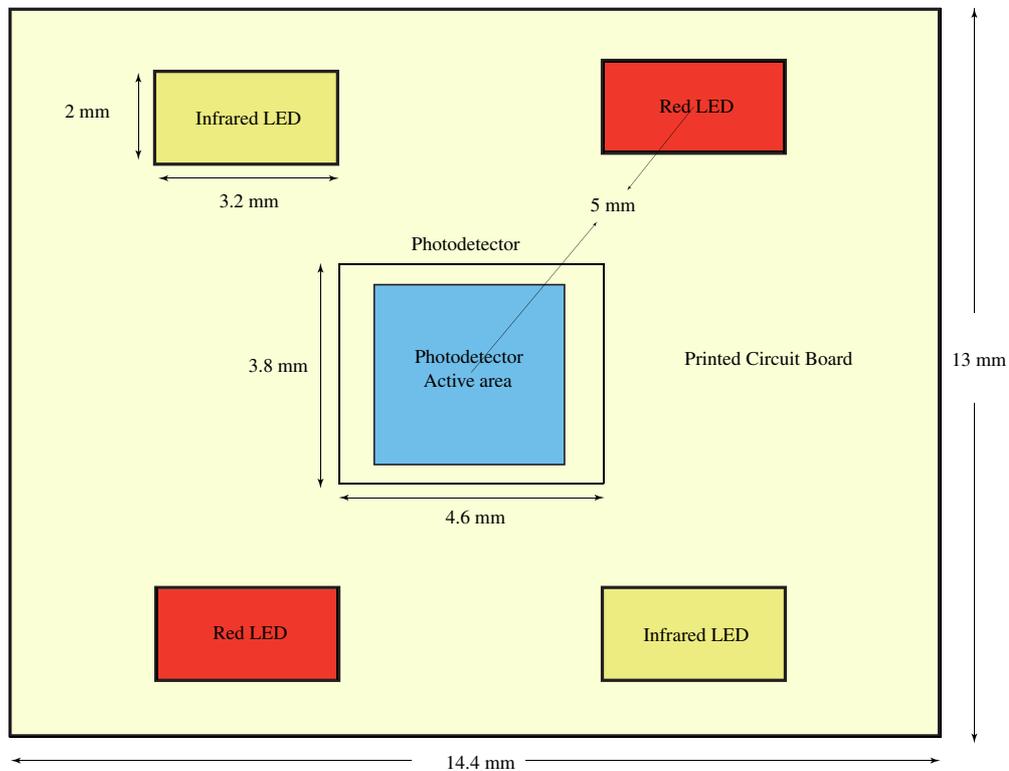


Figure 2. Structural view of the reflectance PPG sensor.

was placed in the middle of the four LEDs (reflectance mode). The distance between the LEDs and the photodiode for the reflectance mode was 5 mm (Shafique *et al* 2010) as shown in figure 2.

Two independent but electronically identical photoplethysmographic systems were developed for processing the signals from the transmittance and the reflectance PPG probes.

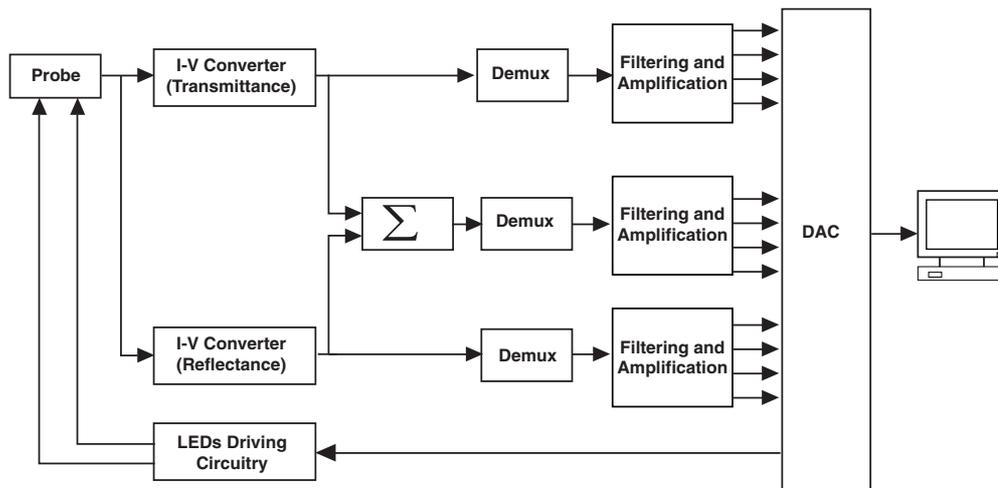


Figure 3. Block diagram of the multimode PPG processing system (Adapted from Shafique *et al* 2009).

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 figure 3.

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 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 by using two identical differential transimpedance amplifiers. The outputs from the reflectance and transmittance transimpedance amplifiers were fed into a summing amplifier to generate 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 by 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 a low-pass (with a cut-off frequency of 0.5 Hz) filters. The red and infrared ac PPG signals were further amplified before digitization.

2.2. Temperature sensor

In order to continuously record temperature from the finger, a temperature processing circuit was developed. A type K thermocouple was used as temperature sensor. Since the output of the thermocouple was not linear, a thermocouple amplifier (AD595CQ, Analog Devices) was used to produce a linear voltage output with sensitivity of $10 \text{ mV } ^\circ\text{C}^{-1}$. The AD595CQ is a complete instrumentation amplifier and thermocouple cold junction compensator on a monolithic chip. It combines an ice-point reference with a pre-calibrated amplifier to produce a high level, low impedance, $10 \text{ mV } ^\circ\text{C}^{-1}$ output directly from the thermocouple signal.

Figure 4 shows the schematic diagram of the temperature processing circuit. The thermocouple was connected to the two differential inputs of the linearizer (AD595CQ)

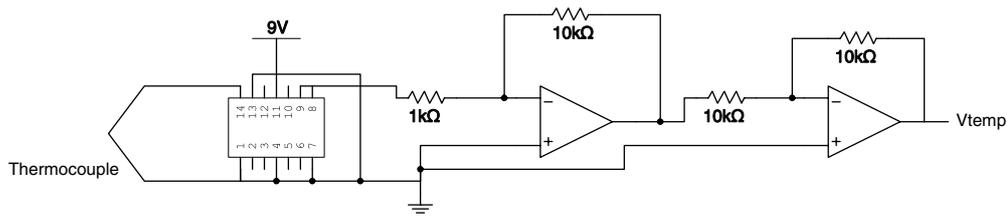


Figure 4. Schematic diagram of temperature processing circuit.

integrated circuit (IC). Since the output amplitude of the linearizer was too low, an inverting amplifier with a gain of 10 was used to amplify the voltage level. The voltage (V_{temp}) was then inverted using a unity gain inverting amplifier before feeding it into the DAQcard.

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), temperature signal from the thermocouple and an output signal from a commercial finger transmittance pulse oximeter (Nellcor N-200 Pulse oximeter, Nellcor Inc, Hayward, California USA) were connected to a National instrument 16-bit data acquisition card (DAQPad- 6015, National Instruments Inc., USA). The digitized signals were further analysed by a virtual instrument (VI) implemented in LabVIEW on a personal computer.

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 of all the acquired ac PPG signals of the reflectance, transmittance and transreflectance modes. A point was considered as a peak if it had two lower points on both sides. A difference (threshold) was set between the lower points and the peak to avoid any false detection such as the detection of diacrotic notch. Since the amplitude of the PPG signal from different volunteers was different, therefore a different threshold level was chosen for each PPG signal. 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);

$$R = \frac{ac_{red}}{dc_{red}} \bigg/ \frac{ac_{ired}}{dc_{ired}}.$$

The SpO_2 values were then calculated using the empirically calibrated equation (Webster 2003) given below;

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

This was repeated for all the data, therefore enabling the computation of SpO_2 values at all temperatures. Before calculating the mean value of the ac PPGs for the chosen segment of 10 s, the shape of the PPGs was carefully observed. During these segments some PPG traces failed to be categorized as normal PPG signals due to the low temperature 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 low temperatures) (Shafique *et al* 2012).

3. Volunteers and measurements

The study was approved by the Senate Research Ethics Committee of the City University London, and permission was given to conduct the study with 20 volunteers. Non-smoking

healthy volunteers were recruited. A written information sheet was provided. Signed consent was sought from each volunteer prior to their participation. The mean (\pm S.D) age of the volunteers was 24 (\pm 5.7) years, the mean (\pm S.D) systolic and diastolic blood pressure was 128 (\pm 9.8) and 72.3 (\pm 12), respectively. The mean (\pm S.D) heart rate of the volunteers was 74.5 (\pm 8.8), and the mean (\pm S.D) time volunteers immersed their hand in the ice bath was 88.8 (\pm 33.6) s.

PPGs and temperature signals were acquired from 20 healthy volunteers at the Biomedical Engineering Research Laboratory, School of Engineering and Mathematical Sciences, City University London. The subjects were asked to abstain from eating, drinking and exercise for at least two hours before the experiment. 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. The subjects were asked to place their hand into a bucket of iced water until the skin temperature of the hand dropped to a comfortably tolerable temperature. The hand was then removed from the iced water and the custom-made multimode finger PPG probe was placed on the index finger of the cold hand and PPG signals from all three modes were collected simultaneously. Meanwhile, the skin temperature was also recorded by attaching (using electrical tape) the thermocouple (figure 1) on the finger adjacent to the multimode finger probe. SpO₂ values from the commercial pulse oximeter were also recorded by placing the commercial probe on the middle finger of the volunteer. The signals (reflectance, transmittance and transreflectance PPG signals, and commercial pulse oximeter, and thermocouple sensor) were recorded until the temperature readings reached a steady state level.

4. Results

Good quality PPG signals were obtained from all volunteers at the majority of the recorded temperatures with some deterioration in the amplitude of the PPGs at very low temperatures. Three sets of PPG signals were recorded from the reflectance, transmittance and transreflectance PPG system, each set consisting of four PPG signals (infrared ac and dc, and red ac and dc signals). Analogue signals from the commercial pulse oximeter representing SpO₂ values and temperature values from the thermocouple were also recorded successfully. Figures 5 and 6 show a sample of the three red and infrared ac PPG signals, respectively, obtained from the transreflectance, transmittance and reflectance PPG systems for the period of 10 s in one volunteer at 28 °C. Both of these figures show good quality ac PPG signals from all three modes obtained from the developed PPG system.

4.1. Amplitude of the ac PPG signals

The red and infrared ac PPG signals from the reflectance, transmittance and transreflectance modes, and the simultaneously acquired temperature signal from the index finger of a randomly selected volunteer are shown in figure 7. The y-axis on the left-side represents amplitude of the ac PPG signals, whereas the y-axis on the right-side shows temperature values (in °C). As can be seen, all the signals are affected by the low temperature at the start and as the temperature increases, the amplitudes of the ac PPG signals increase gradually. It is notable that after a certain temperature (around 27 °C), the amplitudes of the ac PPG signals do not increase and retain a steady state level. This was also noted in all the ac PPG signals acquired from the other volunteers. Amongst the three infrared signals, the amplitude of the bottom two (figure 7), transreflectance and transmittance infrared ac PPGs are greater than the reflectance

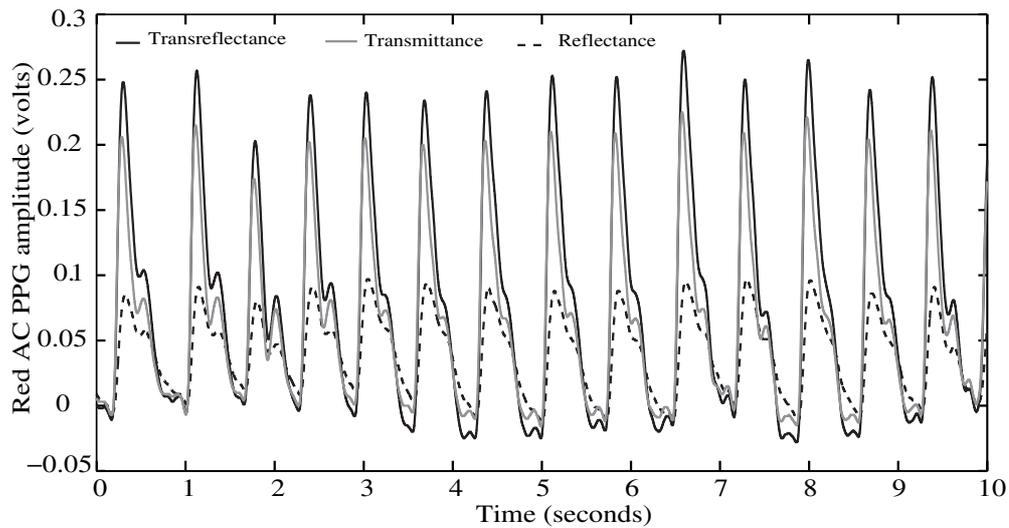


Figure 5. A segment of 10 s of red ac PPG signals of a randomly selected volunteer, recorded simultaneously from the reflectance, transmittance and transreflectance custom made PPG system at 28 °C.

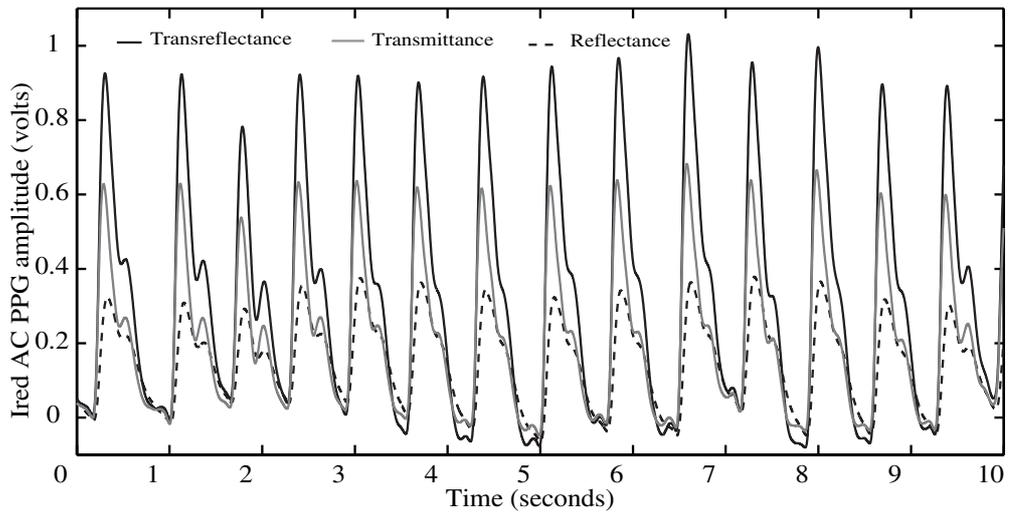


Figure 6. A segment of 10 s of infrared ac PPG signals of a randomly selected volunteer, recorded simultaneously from the reflectance, transmittance and transreflectance custom made PPG system at 28 °C.

infrared ac PPG amplitude at all temperature values. The same applies to the top three red ac PPG signals (figure 7). The ac PPG amplitudes from the reflectance mode were smaller than the transmittance and transreflectance red ac PPG signals. The transreflectance red ac PPG signals were larger in amplitude when compared with the other two modes at all temperature values.

The percentage of failures from the reflectance and transmittance PPG sensors to detect red ac PPG signals were 9.8% and 3.4%, respectively, at different temperatures (ranges from 13 to 35 °C) in all 20 volunteers. The transreflectance failure to detect red ac PPG signals

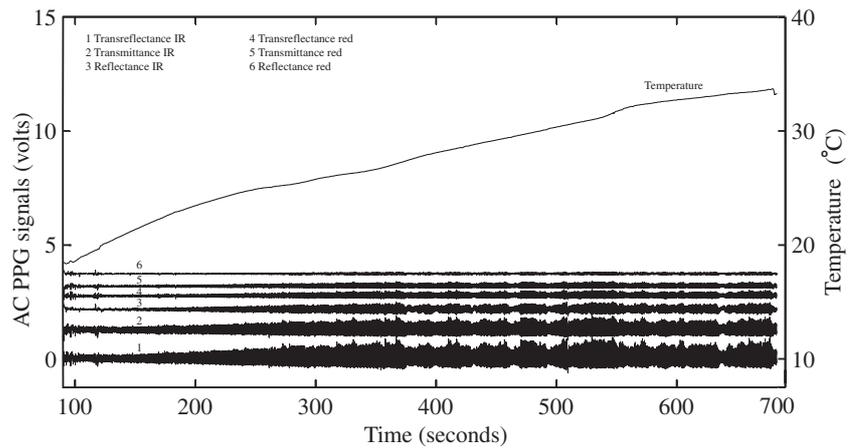


Figure 7. Red and infrared ac PPG signals (y-axis on the left side), and temperature (y-axis on the right side) signals recorded simultaneously from a randomly selected volunteer.

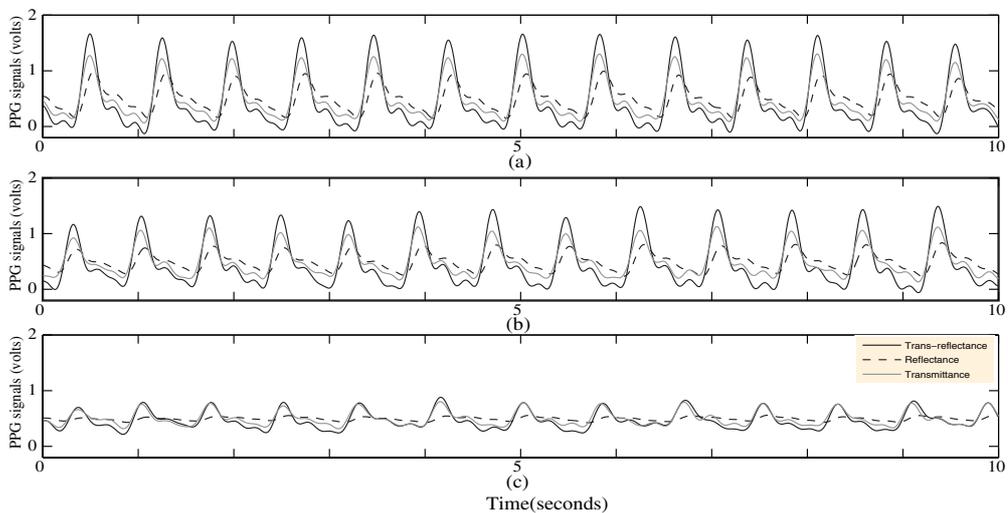


Figure 8. 10 s samples of infrared PPG signals recorded from the hand at a skin temperature of (a) 24 °C, (b) 20 °C and (c) 16 °C.

was 0.43%. There were some occasions when all three PPG sensors failed to detect infrared ac PPG signals. These percentages of failures were 2.1% for the reflectance, 2.5% for the transmittance and 0.42% for the transreflectance PPG sensors.

Figure 8 depicts infrared ac PPG signals (for ten s) recorded from the ‘cold’ index finger of a volunteer at three different temperatures. The set of traces (c) shows ac PPGs from the three modes at 16 °C and similarly the sets (b), and (a) show ac PPGs from the three different modes at temperatures 20 and 24 °C respectively (figure 8). Clearly, the transreflectance PPG signals have the larger amplitude than the reflectance and transmittance modes at 20 and 24 °C. At 16 °C, the amplitude of the reflectance ac PPG signal is smaller than the transmittance and transreflectance ac PPG signals. However, the transreflectance ac PPG signal is slightly bigger in amplitude than the transmittance infrared ac PPG signal.

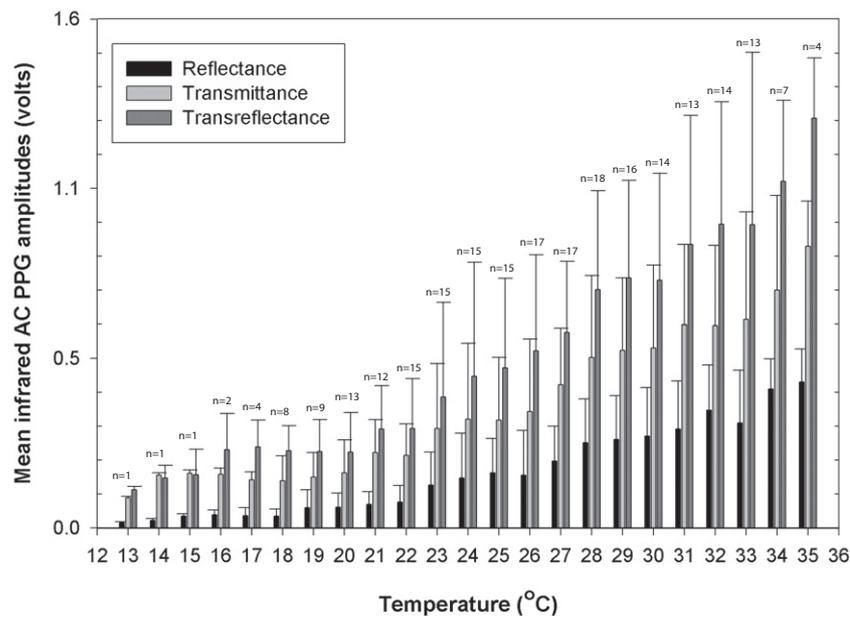


Figure 9. Mean (\pm SD) of infrared reflectance, transmittance and transreflectance ac PPG signals.

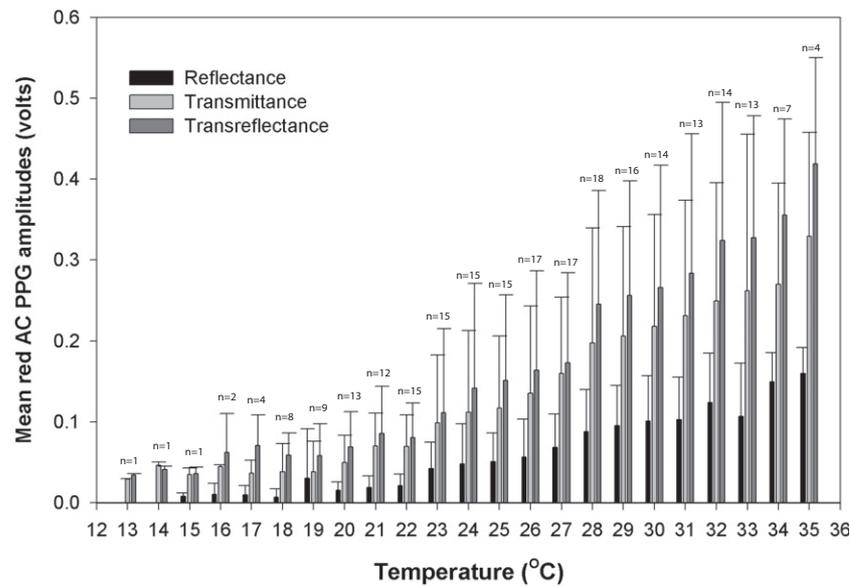


Figure 10. Mean (\pm SD) of red reflectance, transmittance and transreflectance ac PPG signals.

Figures 9 and 10 show bar charts of the means (\pm SD) of the means infrared and red ac PPG amplitudes respectively at each temperature from all volunteers. Each respective bar is the mean of the mean peak ac PPG value from 'n' volunteer at each temperature. When the hand was taken out from the ice bath and the temperature sensor was placed on the finger, different temperature values were observed initially for different volunteers. The initial temperature

Table 1. *P*-values from the pair *t*-test performed on the infrared ac PPG values from the reflectance, transmittance and transreflectance modes at each temperature.

Temperature (°C)	Ref versus Tr	Ref versus TrR	Tr versus TrR
16	0.020	0.213	0.456
17	0.005	0.009	0.056
18	0.002	<0.001	0.014
19	0.012	0.002	0.088
20	0.001	<0.001	0.002
21	<0.001	<0.001	0.001
22	<0.001	<0.001	0.093
23	0.005	0.001	0.002
24	0.015	<0.001	0.001
25	0.007	<0.001	<0.001
26	0.004	<0.001	0.042
27	<0.001	<0.001	0.034
28	0.001	<0.001	0.027
29	<0.001	<0.001	0.033
30	<0.001	<0.001	<0.001
31	<0.001	<0.001	0.114
32	<0.001	<0.001	0.017
33	0.018	0.005	0.174
34	0.047	<0.001	0.007
35	0.001	<0.001	0.006

values of 13, 14 and 15 °C were observed only for one volunteer ($n = 1$); hence, the PPG values of only one volunteer were recorded at these temperatures. It can be seen that the mean transmittance PPG amplitudes were greater than the reflectance PPG amplitudes at all temperatures. There is no sudden increase in the mean ac PPG amplitudes up-to 20 °C; however, steady increase in the mean ac PPG amplitudes was observed after 21 °C. Furthermore, at all temperatures, the mean transreflectance PPG amplitudes were greater than those recorded for the other two modes (figure 9). The reflectance finger PPG probe failed to detect any red ac PPG pulses at temperatures of 13 and 14 °C (figure 10), whereas transmittance and transreflectance red ac PPG signals were detected successfully at those temperatures.

To see if there was any statistically significant difference between the mean ac PPG amplitudes at all temperatures, pair *t*-tests were performed on the mean infrared ac PPG amplitudes from the reflectance, transmittance and transreflectance PPG systems. The mean ac PPG value at one temperature was compared with the mean ac PPG value at the following temperature. The *p*-value <0.05 was considered to be statistically significant. The statistical comparison of reflectance ac PPG values at temperature values from 16 to 26 °C showed that there were just a few significant *p*-values, whereas the statistical comparison of reflectance ac PPG values at temperature from 27 to 35 °C, most *p*-values were found significant. This implies that the reflectance infrared ac PPG amplitudes became distinctively greater after 27 °C. The pair *t*-test results from the transmittance and transreflectance infrared ac PPG values were found consistent with the results from the reflectance infrared ac PPG values.

To see if there was any significant difference between the two modes at one temperature, pair *t*-tests were performed on the pair of the mean reflectance and transreflectance, transmittance and transreflectance, and reflectance and transreflectance infrared ac PPG values. Table 1 shows the results of the *t*-test. A significant difference (the *p*-values shown as bold) between the mean reflectance and transmittance infrared ac PPG values at all temperatures was observed.

Table 2. Mean SpO₂ values at different temperatures from n volunteers estimated from the reflectance (Ref), transmittance (Tr), transreflectance (TrR) and commercial (Com) pulse oximeters.

n	Temp (°C)	Ref % (\pm SD)	Tr % (\pm SD)	TrR % (\pm SD)	Com % (\pm SD)
1	13.0	F	109.7 (0)	96.2 (0)	F
1	14.0	F	109.6 (0)	96.4 (0)	100.2 (0)
1	15.0	109.9 (0)	109.8 (0)	99.2 (0)	100.2 (0)
2	16.0	F	F	95.5 (0)	F
4	17.0	93.0 (4.2)	99.8 (2.4)	100.0 (6.9)	100.5 (0.4)
8	18.0	95.8 (1.7)	96.1 (3.9)	98.8 (2.9)	99.9 (0.6)
9	19.0	91.7 (10.9)	97.7 (3.8)	98.5 (3.7)	100.0 (0.6)
13	20.0	96.8 (3.3)	96.6 (3.1)	98.5 (2.8)	100.3 (0.3)
12	21.0	96.3 (3.6)	96.8 (2.7)	97.6 (3.2)	100.1 (0.4)
14	22.0	94.4 (4.3)	96.6 (3.1)	98.1 (2.7)	99.9 (0.6)
15	23.0	96.1 (2.7)	96.4 (2.7)	98.8 (1.6)	99.8 (0.6)
15	24.0	96.8 (3.1)	96.4 (3.1)	98.1 (2.0)	99.6 (0.6)
15	25.0	97.6 (3.1)	95.9 (3.5)	98.1 (1.5)	99.6 (0.7)
17	26.0	102.8 (8.8)	95.6 (3.0)	98.2 (3.9)	99.6 (0.6)
17	27.0	96.2 (3.3)	95.4 (2.9)	97.9 (2.3)	99.4 (0.7)
17	28.0	96.5 (3.0)	95.3 (3.7)	97.6 (2.3)	99.2 (0.8)
15	29.0	95.3 (2.7)	94.6 (3.4)	97.3 (2.4)	99.1 (0.8)
14	30.0	94.5 (4.0)	94.0 (3.0)	97.0 (2.4)	92.5 (23.9)
13	31.0	95.6 (2.3)	94.4 (3.2)	97.0 (2.6)	99.1 (0.9)
14	32.0	95.8 (2.1)	93.5 (3.1)	97.2 (2.2)	98.8 (1.2)
10	33.0	95.6 (3.4)	93.5 (3.7)	97.1 (2.4)	98.8 (1.1)
7	34.0	95.0 (2.4)	95.9 (6.9)	97.0 (1.9)	98.5 (1.1)
4	35.0	94.1 (3.2)	97.8 (8.8)	96.4 (2.1)	98.4 (1.2)

Table 3. Percentage failures of the reflectance (Ref), transmittance (Tr), transreflectance (TrR) and the commercial (Com) pulse oximeters at difference temperature ranges (T range).

T range (°C)	Ref (%)	Tr (%)	TrR (%)	Com (%)
13–17	55.6	11.1	0.0	44.4
18–21	28.6	14.3	2.4	26.2
22–25	5	1.7	0	3.3
26–29	3	1.5	0	3
30–34	1.7	0	0	0

4.2. Blood oxygen saturation (SpO₂) values

Mean SpO₂ values were calculated (see table 2) from the reflectance (Ref), transmittance (Tr), transreflectance (TrR) and the commercial (Com) pulse oximeters at each temperature from the respective number of total volunteers (n). Table 3 shows percentage failures of all the pulse oximeters at different ranges of temperatures (T range). The temperature of only one ($n = 1$) volunteer (out of 20) dropped to 13 °C (table 2), where the commercial and the reflectance pulse oximeters failed to estimate SpO₂ values. At 13 °C, the SpO₂ values from the uncalibrated transmittance pulse oximeter was 109.7%. The estimated SpO₂ value from the transreflectance (TrR) pulse oximeter was 96.2%, which seems relatively accurate than the SpO₂ values from the transmittance pulse oximeter. In the same volunteer at 14 °C, again the reflectance pulse oximeter failed to calculate any SpO₂ values, whereas the SpO₂ values from the transmittance, transreflectance and commercial pulse oximeter were 109.6%, 96.4% and 100.2% respectively. SpO₂ values were calculated from all the four

pulse oximeters at 15 °C with no failures. At 16 °C, the three pulse oximeters (reflectance, transmittance and the commercial) failed to produce any SpO₂ values, whereas SpO₂ values were successfully estimated from the transreflectance pulse oximeter. The temperature of four volunteers ($n = 4$) dropped to 17 °C. At this temperature, the reflectance and the commercial pulse oximeter failed to estimate SpO₂ values in two volunteers (table 3), whereas SpO₂ values were calculated successfully from the transmittance and transreflectance pulse oximeters from all the four volunteers.

At 18 °C (when $n = 8$), the commercial pulse oximeter failed to monitor SpO₂ values in four volunteers. In five volunteers, the reflectance pulse oximeter failed at this temperature. The transmittance pulse oximeter failed in two volunteers, whereas SpO₂ values were calculated successfully in all eight volunteers from the transreflectance pulse oximeter. At 19 °C (when $n = 9$), the reflectance and transmittance pulse oximeters failed to estimate SpO₂ values in two volunteers. The commercial pulse oximeter failed in three volunteers. Also at 19 °C, no failures were observed while estimating SpO₂ values from the transreflectance pulse oximeter. At 20 °C (where $n = 13$), the reflectance and transmittance pulse oximeters failed in two volunteers. The commercial pulse oximeter failed twice, whereas the transreflectance pulse oximeter failed in only one volunteer.

At 21 °C (and $n = 12$), the reflectance and commercial pulse oximeters failed in three and one volunteers respectively. At the same temperature, SpO₂ values were calculated from both the transmittance and transreflectance pulse oximeters in all volunteers successfully. SpO₂ values were calculated from 14 volunteers at 22 °C. At this temperature, the reflectance pulse oximeter failed in three volunteers. The commercial pulse oximeter failed in one volunteer, whereas SpO₂ values were calculated successfully in all volunteers from the transreflectance and transmittance pulse oximeters. No failures were recorded at 23 °C from any of the pulse oximeters.

At 24 and 25 °C from 15 volunteers amongst the four pulse oximeters, only the transmittance and commercial pulse oximeters failed in one volunteer, while SpO₂ values were successfully calculated in all volunteers from the reflectance and transreflectance pulse oximeters. At 26 °C, SpO₂ values were calculated in all seventeen volunteers ($n = 17$) from the transreflectance pulse oximeter, whereas the reflectance and commercial pulse oximeters failed in two volunteers. The transmittance pulse oximeter failed in one volunteer at 26 °C.

From temperatures between 27 and 35 °C, SpO₂ values were calculated successfully in all seventeen volunteers from all four pulse oximeters.

Table 3 shows the percentage failures of the reflectance (Ref), transmittance (Tr), transreflectance (TrR) and the commercial pulse oximeters to estimate SpO₂ values at different temperature ranges (T range). It can be seen that at very low temperatures the transreflectance pulse oximeter had more success than the other pulse oximeters.

5. Conclusion and discussion

In this study, the custom-made multimode PPG probe and the three prototype uncalibrated PPG/SpO₂ sensors and a commercial pulse oximeter sensor were tested in volunteers under conditions of peripheral induced hypothermia by immersing the volunteer's hand in an ice bath, allowing the hand to cool down to a certain temperature. The PPG signals were then acquired and the SpO₂ values were estimated from the reflectance, transmittance and transreflectance modes. SpO₂ values were recorded from the same hand using the commercial pulse oximeter.

Means of the mean peak red and infrared ac PPG amplitudes were calculated from all volunteers at each temperature. The percentages of failures in reflectance and transmittance

PPG modes to detect red ac PPG signals were 9.8% and 3.4%, respectively, at different temperatures (ranging from 13 to 35 °C) in all 20 volunteers. The transreflectance failure to detect red ac PPG signals was 0.43%, which shows better performance than the other conventional techniques to record ac PPG signals. Also, the means of the mean peak red and infrared ac PPG amplitudes from the transreflectance sensor were bigger than the reflectance and transmittance modes (figures 9 and 10).

Also, the results from the ac PPG amplitude analysis were compared using statistical analysis (paired *t*-tests). The conclusion from these comparisons was that out of the three PPG modes, the ac PPG amplitudes from the transreflectance PPG mode were more statistically significant than the reflectance and transmittance PPG modes at very low temperatures (table 1).

The results from these preliminary tests showed that the reflectance probe is most easily compromised when compared with the transmittance and the transreflectance probes, which was evident from the estimated SpO₂ values. The transreflectance probe endures the most and not only allows the estimation of SpO₂ values, but also provides accuracy and consistency when the other modes struggle or completely fail. When compared with the commercial pulse oximeter, the transreflectance pulse oximeter failed in one volunteer at one low temperature, whereas the commercial pulse oximeter failed 19 times at low temperatures in different volunteers.

The amplitudes of both ac and dc PPG signals and the *t*-test results showed that the threshold temperature above which the PPG signals can be reliably considered for SpO₂ estimation is 27 °C. The results from the SpO₂ values also showed that below 27 °C there is higher tendency for the commercial pulse oximeter to fail when estimating SpO₂ values; however, an improved hardware design such as the multimode pulse oximetry probe can enhance the capability of a pulse oximeter in order to estimate SpO₂ values more accurately at lower peripheral tissue (i.e. finger) temperatures.

Such preliminary studies will enable the further understanding of the behaviour of PPGs in cases of peripheral hypothermia and the knowledge generated from such a study will enable optimization in the hardware design and the signal analysis of the PPGs in order to develop more accurate and more robust pulse oximeters which will perform better in these difficult physiological cases.

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