Analysing the Effects of Cold, Normal, and Warm Digits on Transmittance Pulse Oximetry

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Abstract

Non-invasive estimation of arterial oxygen saturation (SpO_2) and heart rate using pulse oximeters is widely used in hospitals. Pulse oximeters rely on photoplethysmographic (PPG) signals from a peripherally placed optical sensor. However, pulse oximeters can be less accurate if the sensor site is relatively cold. This research investigates the effects on PPG signal quality of local site temperatures for 20 healthy adult volunteers (24.5 ±4.1 years of age). Raw PPG data, composed of Infrared (*IR*) and Red (*RD*) signals, was obtained from a transmittance finger probe using a custom pulse oximeter (PO) system. Three tests were performed with the subject's hand surface temperature maintained at baseline (29 ±2°C), cold (19 ±2°C), and warm (33 ±2°C) conditions. Median root mean square (RMS) of PPG signal during the Cold test dropped by 54.0% for *IR* and 30.6% for *RD* from the baseline values. In contrast, the PPG RMS increased by 64.4% and 60.2% for *RD* and *IR*, respectively, during the Warm test. Mean PPG pulse amplitudes decreased by 59.5% for *IR* and 46.1% for *RD* in the cold test when compared to baseline, but improved by 70.1% for IR and 59.0% for RD in the warm test. This improvement of up to 4x in signal quality during the warm condition was associated with a closer match (median difference of 1.5%) between the SpO_2 values estimated by the PO system and a commercial pulse oximeter. The differences measured in RMS and mean amplitudes for the three tests were statistically significant ($p < 0.001$). Overall, warm temperatures significantly improve PPG signal quality and SpO_2 estimation accuracy. Sensor site temperature is recommended to be maintained near 33°C for reliable transmittance pulse oximetry.

Keywords*:* Pulse oximetry; non-invasive; photoplethysmograph; arterial blood oxygen saturation; signal processing; sensor; thermocouple; perfusion; vasoconstriction; vasodilation.

1. Introduction

Pulse oximeters are ubiquitous devices in hospital wards, operating rooms, and intensive care units (ICU). They are used to non-invasively estimate arterial blood oxygen saturation (SpO_2) and monitor heart rate (HR), and are a standard of care for patient oxygenation monitoring [1-3]. Pulse oximetry uses photoplethysmographic (PPG) signals acquired by an optical sensor, typically mounted on a finger, toe, or ear-lobe to optically detect blood volume changes in the tissue. Conventional pulse oximetry relies on the pulsatile nature of arterial blood and differential absorption of oxyhaemoglobin and de-oxyhaemoglobin at red (*RD*) and infrared (*IR*) wavelengths to estimate SpO_2 and HR [4, 5].

Typical transmittance pulse oximeter probes consist of two high output *RD* and *IR* light emitting diodes (LEDs) and a sensitive photo-detector (PD). Light energy transmitted through tissue is detected by the PD, which generates the PPG signal. From the PPG signal, the slowly changing (*DC*) and rapidly changing (*AC*) signals are extracted. The *DC* signal predominantly captures the unchanging light scattering and absorption, whereas the *AC* signal predominantly captures the varying absorption due to pulsatile arterial blood and is synchronous with HR. By taking the appropriate *AC*/*DC* ratios and calibration, SpO_2 can be reliably estimated [5, 6]. Hence, the quality of pulse oximeter SpO_2 estimation is directly dependent on the quality of detected PPG signals.

While the predominant application of pulse oximeters has been to estimate arterial oxygen saturation (SaO_2), the raw PPG signal (PPG_{Raw}) is rich with physiological information. The PPG_{Raw} signal contains a complex mixture of the influences of arterial, venous, autonomic and respiratory system responses on the peripheral circulation [7-9]. For example, non-

invasive assessment of blood flow changes in muscle and bone using PPG was previously reported, showing that the *AC* component of the PPG corresponds to blood flow, while the *DC* component corresponds to the blood volume change [10-12]. Thus, application of PPG is not restricted solely to SpO_2 estimation.

A number of factors have been reported to limit pulse oximeter accuracy. These factors include motion artefacts, environmental noise, skin tone, gender, nail polishes, and ambient light [13-16]. Poor peripheral perfusion triggered by clinical conditions, such as hypovolaemia, hypothermia, and vasoconstriction during surgery, may also result in pulse oximeter error or failure [17]. These clinical conditions often arise due to administration of anaesthetic agents and/or muscle relaxants [18].

Temperature is another, often overlooked, limiting factor for pulse oximetry. It is generally accepted that cold digits may provide inaccurate pulse oximeter readings [19, 20], and simple solutions like rubbing the hands together may solve the problem. However, people with naturally cold fingers or ICU patients with poor perfusion, where room temperature is typically maintained at 20 ± 2°C [21], are examples of cases where this problem can be exacerbated.

Previously, Njoum and Kyriacou [22] investigated the effects of local sympathetic tone on healthy volunteers using a custom built pulse oximeter with a finger based reflectance sensor. They used cold pressor test to induce a drop in temperature of the right hand for 30 seconds. Their research showed that PPG signal pulse amplitude degraded significantly (up to 73%) in

both hands during the ice water immersion, with an increase in pulse repetition time and heart rate. Budidha and Kyriacou [23] conducted similar cold pressor test investigation, but also included an ear canal based reflectance sensor. Their finger based PPG devices reported a substantial drop in PPG signal pulse amplitude (up to 58%) and reported inaccuracy in SpO_2 estimation at low temperatures (8°C). However, neither of these studies investigated the effects on PPG in naturally cold fingers, nor they presented any subject specific data. They also did not provide any advice to improve PPG signal quality derived from the finger in such cases. Finally, neither study considered transmittance PPG.

Poor PPG signal quality can produce erroneous readings in pulse oximeters that can result in false alarms [3]. This study investigates the effects of temperature on PPG signal quality in finger based transmittance PPG. The initial hypothesis is that PPG signal quality is severely degraded in cold digits, resulting in inaccurate SpO_2 readings and thus, limits the application of PPG. Use of a continuous heat source close to the sensor site was tested to assess improvement in PPG signal quality and reliable SpO_2 estimation as a function of temperature.

2. Materials and Methods

2.0 Test Equipment

A standard transmission mode sensor (model: 320701001, Biometric Cables, Guindy, Chennai, India) was used for PPG data acquisition. The sensor uses 660 nm and 940 nm wavelength light for the *RD* and *IR* LEDs, respectively. Finger sensor control and PPG data acquisition was accomplished through a custom-built pulse oximeter (PO) development system, shown in Figure 1. The PO system is based on the CY8CKIT-050 PSoC® 5LP Development Kit (Cypress Semiconductor, San Jose, CA, USA). This custom equipment enabled direct control over LED intensity, signal conditioning, and sampling frequency.

Feedback control of the PO system incrementally increased the LED intensity up to a certain level and then adjusted it automatically for each subject. This procedure was to maximise PPG amplitude without saturating the photo-detector. This procedure also maximises the signal-to-noise ratio (SNR) received by the photo detector. The signal from the photo-detector was time demultiplexed so that the *RD* and *IR* PPG signals can be processed independently. Analog PPG signals were sampled at 50 Hz by the 16-bit analog-to-digital converter (ADC) on the development board. Sampled data were sent to a PC via serial communication and saved as text files for offline signal processing in MATLAB (R2014a, MathWorks, Natick, MA, USA).

A Nellcor NPB-75 (Covidien, Minneapolis, MN, USA) pulse oximeter was employed for comparison with the PO system. This hospital grade commercial pulse oximeter can provide continuous SpO_2 and HR readings. In addition, this device can display the real-time PPG for qualitative comparison.

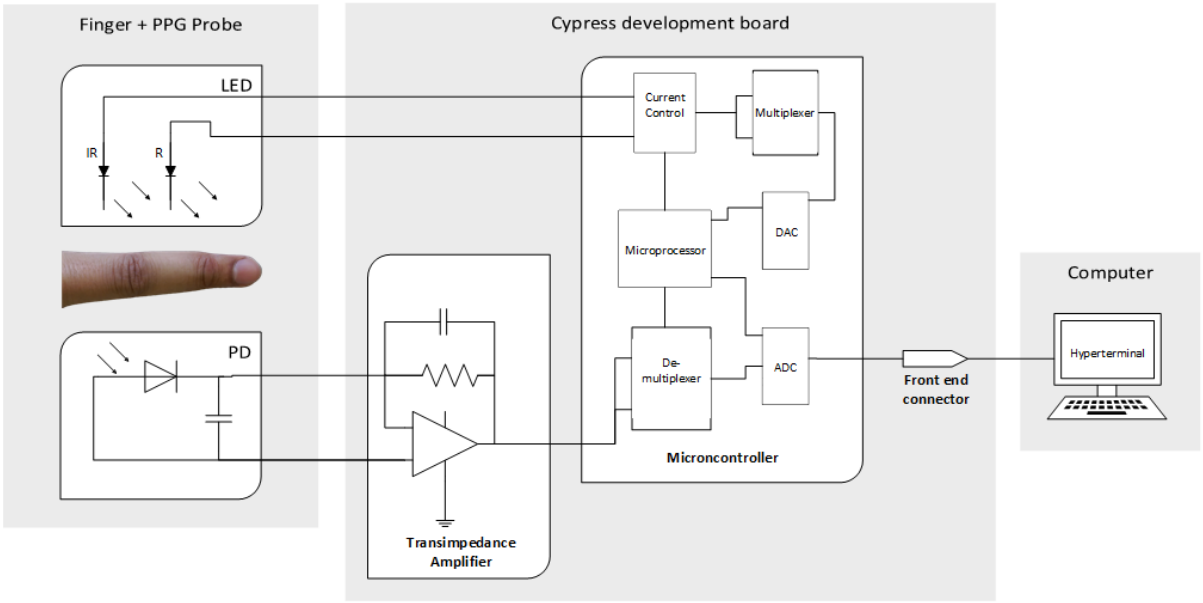


Figure 1. Block diagram of the PO system, showing all the components for PPG data acquisition.

A Type-T surface mount thermocouple probe (Omega, Stamford, CT, USA) was taped to the surface of the skin, next to the pulse oximeter sensor, to obtain skin surface temperature data. The probe was nominally accurate to ±0.5°C above 0°C [24]. Temperature data was continuously logged using a PC running LabVIEW via an NI cDAQ-9172 (National Instruments, Austin, TX, USA) multifunction data acquisition device.

2.1 Experimental Protocol

Twenty healthy adults (24.5 ±4.1 years of age) with no pre-existing medical conditions were recruited for this study. Subjects were asked to refrain from smoking, caffeinated hot drinks, and strenuous physical activities for at least 2 hours prior to the experiment. This study and

use of data were approved by the Human Ethics Committee, University of Canterbury (HEC 2015/04/LR-PS).

The experiment was conducted inside an air-conditioned room regulated at 20 ±2°C (typical ICU room temperature). During the study, subjects were comfortably seated while resting their left or right hand on a flat surface, at approximately the same height as their heart, with minimum movement. Subjects were asked to breathe normally for the duration of the experiment. The following three protocols were then implemented, with 5 min intervals, as shown in Figure 2.

2.1.1 Protocol 1: Baseline Test

Two minutes of baseline PPG readings, at normal digit temperature (29 ±2°C), were recorded using the PO system at the beginning of the experiment. At the same time, temperature data was logged from the sensor site. NPB-75 measurements were taken at the same time from an alternate finger of the same hand.

2.1.2 Protocol 2: Cold Test

Subjects immersed their hand up to the wrist in an ice-water bucket maintained at a temperature of ~ 0°C for approximately 2 min, resulting in a skin temperature of 19 ±2°C. After 2 min, subjects were asked to take their hands out of the bucket and quickly dry their hands. PPG, temperature, and NPB-75 data were then logged for approximately 2 min.

2.1.3 Protocol 3: Warm Test

Subjects rested their palm facing downwards on a hot water bottle maintained at a temperature of ~ 55 ±2°C for approximately 5 min, resulting in a skin temperature of 33 ±2°C. PPG, temperature, and NPB-75 data were then logged for 2 min. During PPG acquisition, subjects kept their hand on the hot water bottle, but not the fingers, to prevent rapid temperature drops during PPG data acquisition.

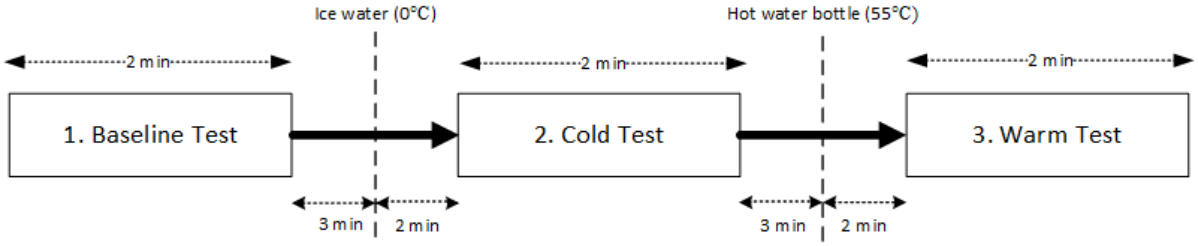


Figure 2. Flowchart of the experimental protocol, showing the step-by-step process.

2.2 Signal Processing

2.2.1 Filtering

A two-stage filter was implemented for offline processing of raw PPG signals. Stage 1 consisted of a finite impulse response (FIR) low-pass Equiripple filter with a cut-off frequency of 10 Hz to remove high frequency noise from PPG_{Raw}. Stage 2 composed of two parallel infinite impulse response (IIR) filters to extract AC and DC signals from the filtered PPG_{Raw}. Zero phase filtering was applied at each filter stage to prevent any phase distortion.

In Stage 2, one of the IIR filter was a low-pass Butterworth filter that extracted the slowly changing *DC* signals, below a cut-off frequency of 0.67 Hz. The low threshold of 0.67 Hz was chosen because the HR of any individual will not typically be less than 40 beats per minute (bpm). Therefore, pulsatility effects due to the heart's pumping will be excluded from

the *DC* signal. The second parallel IIR filter was a band-pass Butterworth filter that extracted rapidly changing *AC* signals, such as the cardiac frequencies, with pass band frequencies 0.67–4.5 Hz. The upper threshold of 4.5 Hz captured HR and harmonics to a maximum of 135 bpm, which is well above expected HRs for this study.

2.2.2 Processing

A peak-trough detection algorithm was applied to the extracted *AC* signals to determine the amplitudes relating to each heartbeat, $|AC|$. Additionally for each heart beat the corresponding mean *DC* value was also determined, DC_{Mean}. The ratio of these values for each of the *RD* and *IR* was used to calculate R for each heartbeat [9]:

$$R = \frac{(|AC|/DC_{Mean})_{RD}}{(|AC|/DC_{Mean})_{IR}} \quad (1)$$

Instantaneous oxygen saturations were estimated using Webster's empirical calibration equation [25], for each *R* value, applied to a given section of a signal:

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

The median of these instantaneous saturation estimations from Equation 2 was calculated over a 2-min window to estimate SpO_2, for this study. Equation 2 is also used to calibrate Nellcor commercial pulse oximeters [26, 27] and is a linear approximation of empirical data obtained from volunteer studies [26].

The PPG_{AC} signal is synchronous to the heart rate and is directly correlated to pulsatile blood flow [10-12, 28]. This variation in pulse amplitude for the *IR* signal over a period of time can be used as a marker to monitor the trend in relative blood flow changes [10-12]. Therefore, subject-specific mean amplitude of the *IR* channel PPG_{AC} signal, at intervals of 20 seconds, was calculated to provide an indication of the blood flow trend pattern in the PPG site during the three tests.

2.3 Signal Analysis

In this study, the *AC* portion of the raw *IR* and *RD* PPG signals were analysed. This choice is based on the fact that PPG_{AC} is the primary signal of interest in conventional pulse oximetry, dominates the signal-to-noise ratio (SNR), and is directly related to arterial blood flow [10-12, 28]. PPG_{AC} is thus most affected by any temperature induced change in perfusion. PPG_{DC} is filtered and therefore noise is filtered out. Additionally, no apparent changes were observed in the *DC* portion of the PPG in this study.

The root mean square (RMS) value of the PPG_{AC} signals was calculated for each subject to provide a measure of signal quality and SNR for each protocol. Low energy signals resulted in low RMS values, thus provided a measure of poor SNR. The subject specific RMS data for each protocol test were fit to a linear line. This procedure generated a tri-linear model of RMS, and thus SNR, as a function of temperature. As a result, the overall trend in signal RMS over temperature can be seen for each test.

In addition to RMS, average PPG_{AC} pulse amplitude was calculated for each subject for each test. The mean of subject specific mean PPG_{AC} amplitudes were calculated to give a measure of the overall PPG pulse magnitude for each test condition (Protocols 1-3). Kruskal-Wallis one way analysis of variance on ranks was performed on the PPG data from the Cold, Baseline, and Warm tests to determine any statistically significant difference for the RMS values and mean PPG amplitudes across these three test conditions. Significance level was set at $p < 0.005$. Non-parametric test was used for PPG signal analysis, since some of the data were not normally distributed. All statistical analysis was performed using MATLAB.

3. Results

Individual subject demographics, PPG_{AC} derived RMS signal values, and corresponding temperature data are presented in Table 1. During the Cold test, the median signal RMS dropped by 9.4 mV (54.0%) for *IR* and 3 mV (30.6%) for *RD* from the baseline values. In contrast, signal RMS increased by 11.2 mV (64.4%) and 5.9 mV (60.2%) for *RD* and *IR*, respectively, during the Warm test. The median change between the Warm and Cold test RMS were 20.6 mV (112.6%) for *IR* and 8.9 mV (79.1%) for *RD*. All of these differences were statistically significant, as shown in Table 2.

Table 1. Demographics**,** PPG signal RMS, and temperature data for all subjects from the study

Subject	Gender	Age	Baseline			Cold Test			Warm Test		
			IR_{RMS} (mV)	RD_{RMS} (mV)	T (°C)	IR_{RMS} (mV)	RD_{RMS} (mV)	T (°C)	IR_{RMS} (mV)	RD_{RMS} (mV)	T (°C)
1	M	26	26.9	13.9	30.1	4.8	3.7	20.1	25.2	13.2	33.8
2	M	23	38.7	21.1	30.4	11.2	9.7	18.0	32.0	17.1	31.0
3	M	23	16.0	10.1	31.5	5.6	5.4	18.0	37.1	20.5	31.9
4	M	29	10.5	5.9	26.8	5.8	4.6	17.0	41.2	21.7	32.5
5	M	23	14.5	8.1	28.5	5.7	5.8	19.0	29.1	15.6	33.1
6	F	21	5.8	5.3	26.2	4.7	4.1	19.6	13.1	7.3	31.5
7	F	23	12.8	6.7	29.0	5.1	4.9	22.0	31.0	16.3	32.7
8	F	23	6.4	6.3	25.0	3.9	3.8	19.5	24.6	14.1	32.0
9	M	27	27.1	15.1	30.0	11.7	8.0	20.5	56.2	31.2	32.0
10	F	23	34.5	19.0	30.1	7.9	7.4	23.0	29.3	15.6	35.0
11	M	35	26.3	15.0	28.7	18.3	10.6	19.0	28.6	15.7	33.0
12	M	35	36.7	21.3	28.0	11.7	8.2	20.0	28.6	16.1	35.0
13	M	22	8.2	5.6	27.0	5.7	5.4	21.6	28.0	14.2	31.4
14	M	27	32.9	16.9	29.5	15.6	8.8	21.9	28.6	15.1	34.5
15	M	30	10.3	8.0	30.2	10.4	7.2	22.0	25.8	14.1	32.0
16	F	24	25.9	13.3	30.4	7.5	7.1	18.5	27.8	14.7	35.2
17	F	25	18.7	9.4	30.5	13.8	8.0	21.0	22.0	12.4	35.0
18	M	27	9.3	8.6	25.8	8.0	6.8	18.4	26.5	16.2	34.2
19	M	28	30.0	15.9	27.8	8.3	4.8	20.1	44.1	23.7	33.8
20	F	21	13.9	7.6	25.5	8.7	6.8	17.0	30.2	16.0	34.6
Median		24.5	17.4	9.8	28.9	8.0	6.8	19.8	28.6	15.7	33.1
Interquartile Range		23.0 – 27.5	10.4 – 28.6	7.2 – 15.5	26.9 – 30.2	5.7 – 11.5	4.9 – 8.1	18.5 – 21.3	26.2 – 31.5	14.2 – 16.7	32.0 – 34.6

Table 2. Results of non-parametric statistical test comparison between experimental data sets

Signal	Parameter	Median[IQR]			*p* value (Kruskal Wallis)
		Cold	Baseline	Warm	
IR	RMS	8.0 [5.7 - 11.5]	17.4 [10.4 - 28.6]	28.6 [26.2 - 31.5]	< 0.001
	Mean Amplitude	17.2 [12.9 - 26.1]	38.4 [21.2 - 71.8]	80.1 [69.6 - 90.4]	
RD	RMS	6.8 [4.9 - 8.1]	9.8 [7.2 - 15.5]	15.7 [14.2 - 16.7]	
	Mean Amplitude	15.7 [11.7 - 19.1]	24.6 [18.4 - 44.5]	42.9 [38.9 - 47.9]	

Figure 3 shows the PPG signal RMS (*IR* and *RD*) versus temperatures of 17 – 35°C for all subjects from each test. All the RMS points for the Cold test were below 20 mV for *IR* and 11mV for *RD*. Points for the Baseline test were scattered over a wider RMS range of 5 – 40 mV for *IR* and 5 – 23 mV for *RD*. The wide Baseline spread indicated how any given subject may have good or poor PPG signal quality as a function of digit temperature. However, for the Warm test all the points lied between an elevated range of 12.5 – 60 mV and 7 – 32 mV for *IR* and *RD*, respectively. A clear separation between the Cold and Warm state as a function of RMS signal quality was evident. Hence, while Baseline state was subject dependant, controlled temperatures were achieved for all subjects in Cold and Warm states.

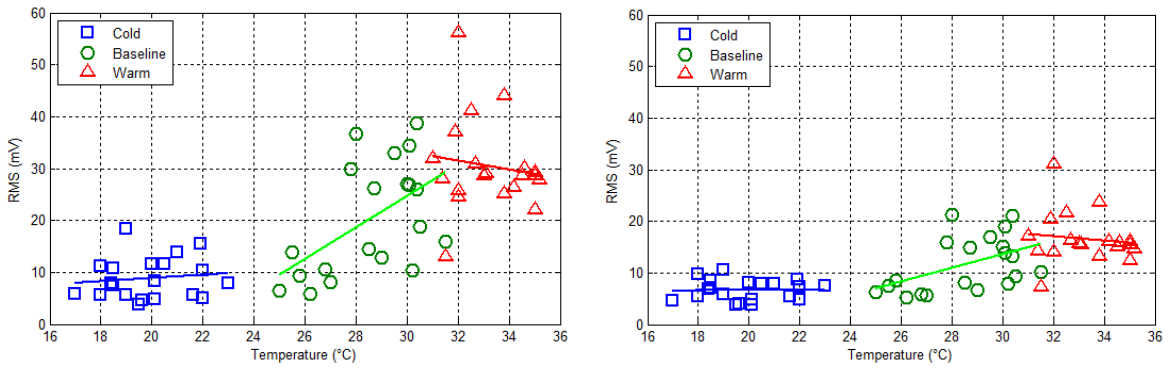


Figure 3. PPG_{AC} RMS versus temperature from the three different experiments: *IR* (left), *RD* (right).

Piecewise linear least-squares fitting resulted in a low, relatively flat fit for Cold data, a steeper gradient for the mixed Baseline data and a high, relatively flat fit for Warm data for both *IR* and *RD* channels. Therefore, the results were consistent and general across the cohort. The tri-linear fits provided an outline for a simple model of signal RMS and quality as a function of temperature.

Mean of the subject-specific mean PPG_{AC} pulse amplitude values across the cohort is shown in Figure 4. During the Cold state, the average signal amplitude reduced by 29.2 mv (59.5%) for *IR* and 13.3 mV (46.1%) for *RD* from the Baseline state. In contrast, average signal amplitude improved by 34.4 mV (70.1%) for *IR* and 17 mV (59.0%) for *RD* during the Warm state. The mean amplitude percentage difference between the Cold and Warm states were 63.6 mV (123%) and 30.3 mv (98.9%) for *IR* and *RD*, respectively. Table 2 shows these differences were statistically significant.

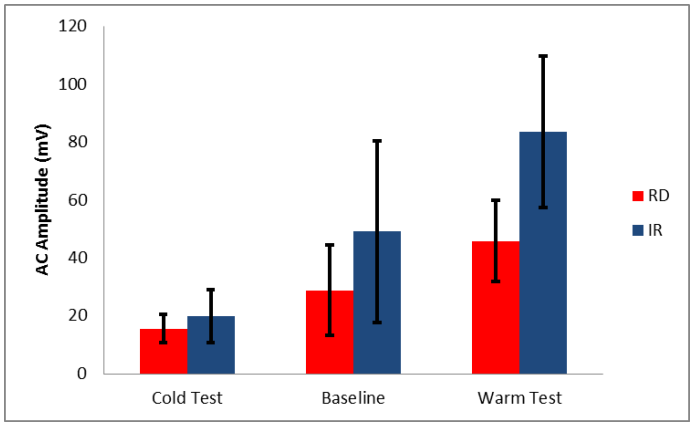


Figure 4. Mean of subject-specific PPG_{AC} amplitude mean values, for cohort from the three tests.

Figure 5 shows the PPG_{AC} of Subjects 19 and 20 recorded for each test, as an example. The Cold test PPG waveform was almost flat, with a substantial decrease in signal pulse amplitude compared to the Baseline test. Pulse amplitude was highest during the Warm test, almost double the Baseline. Clear dicrotic notches, indicated in Figure 5, were observed occasionally in the Baseline test, but regularly in Warm test PPG for all subjects. Equally, the typical PPG signal pulse used to determine heart rate was only clearly evident, despite filtering, in these two cases. Hence the reduced quality noted in other studies with low temperatures [22, 23] is apparent here, as well as in Tables 1-2 and Figures 2-3.

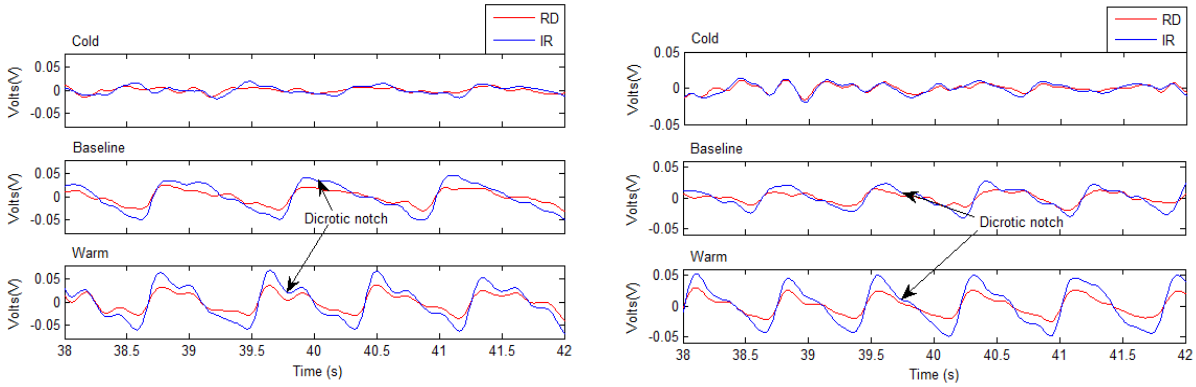


Figure 5. PPG_{AC} signals from the three tests for Subjects 19 (Left) and 20 (Right): Cold (top), Baseline (middle), Warm (Bottom).

Figure 6 shows the blood flow trend during the three tests for Subjects 19 and 20. The significant difference in mean amplitude between the tests confirmed the reduction in flow during the Cold condition but increase in flow at Warm conditions. Baseline condition represented normal flow and was subject dependant. These results mirrored the high Warm test and low Cold test RMS signal quality results, with a widely varying Baseline set of results due to inter-patient variability.

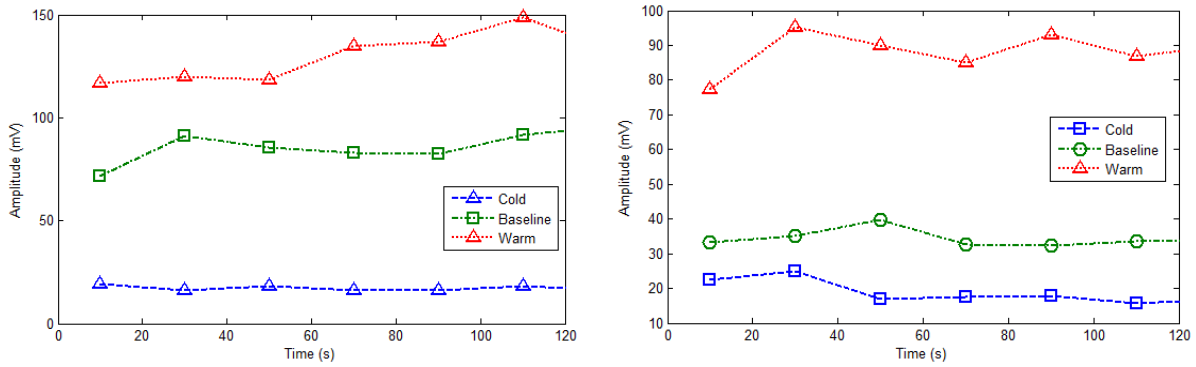
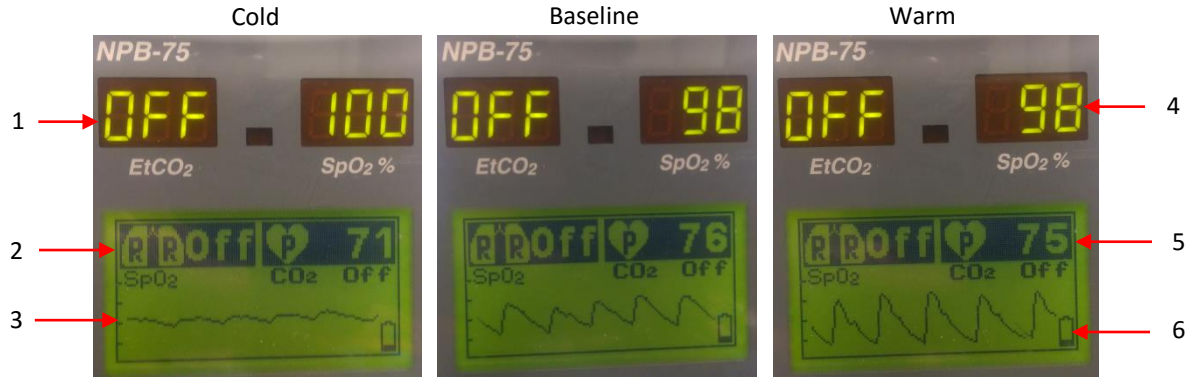


Figure 6. Relative blood flow change trend during the three tests: Subjects 19 (left) and 20 (right).

For comparison to Figures 5 and 6, Figure 7 shows the PPG_{AC} displayed by the Nellcor NPB-75 pulse oximeter for Subject 20, as an example, for all three tests. The Cold test waveform was almost flat with very low-amplitude and no visible dicrotic notch. Baseline measurements had relatively high-amplitude waveform with occasional dicrotic notches. In contrast to the previous two cases, the Warm test regularly had high-amplitude waveforms with clear dicrotic notches. The PPG waveform trends for the NPB-75 matched what was observed with the custom pulse oximeter.



1.	End-tidal carbon dioxide	4.	SpO_2 estimate
2.	Respiratory rate	5.	Pulse rate
3.	PPG display	6.	Battery indicator

Figure 7. Front panel of NPB-75 displaying PPG signal and data for Subject 20: Cold (left), Baseline (middle) and Warm (right).

Table 3 compares the estimated SpO_2 data acquired by the PO system and NPB-75. The two pulse oximeters showed very good correlation in the Warm test, with a median SpO_2 difference of 1.5%. Confidence in SpO_2 estimation between the two pulse oximeters was marginally reduced in Baseline test, increasing the median SpO_2 difference to 2.2% when compared to the Warm test. Poor correlation between the PO system and NPB-75 was shown in the Cold test, with a large median SpO_2 difference of 11%.

Table 3. SpO_2 data for all subjects from the experiment

Subjects	Baseline SpO_2 (%)			Cold Test SpO_2 (%)			Warm Test SpO_2 (%)		
	NPB-75*	PO†	Δ	NPB-75*	PO†	Δ	NPB-75*	PO†	Δ
1	98.0	96.8	1.2	99.0	90.9	8.1	98.0	96.9	1.1
2	98.0	96.4	1.6	97.0	87.4	9.6	98.0	96.8	1.2
3	98.0	93.1	4.9	100.0	86.2	13.8	98.0	96.6	1.4
4	100.0	95.8	4.2	100.0	89.1	10.9	99.0	96.5	2.5
5	97.0	95.3	1.7	89.0	84.6	4.4	98.0	96.1	1.9
6	100.0	86.8	13.2	100.0	87.8	12.2	98.0	96.3	1.7
7	98.0	96.9	1.1	100.0	87.5	12.5	98.0	97.1	0.9
8	96.0	86.5	9.5	95.0	86.3	8.7	97.0	95.7	1.3
9	98.0	96.0	2.0	98.0	92.4	5.6	98.0	96.1	1.9
10	97.0	95.8	1.2	87.0	86.9	0.1	99.0	97.4	1.6
11	97.0	95.3	1.7	98.0	94.4	3.6	98.0	96.2	1.8
12	99.0	95.7	3.3	97.0	93.2	3.8	98.0	96.0	2.0
13	99.0	93.3	5.7	99.0	86.9	12.1	99.0	97.6	1.4
14	99.0	97.1	1.9	100.0	94.0	6.0	99.0	97.0	2.0
15	97.0	88.6	8.4	100.0	92.4	7.6	99.0	96.1	2.9
16	98.0	97.0	1.0	100.0	87.3	12.7	98.0	96.8	1.2
17	98.0	97.8	0.2	100.0	93.9	6.1	99.0	95.9	3.1
18	100.0	86.9	13.1	99.0	87.3	11.7	96.0	94.8	1.2
19	97.0	96.6	0.4	100.0	93.8	6.2	98.0	96.4	1.6
20	98.0	96.7	1.3	100.0	90.0	10.0	98.0	97.0	1.0
Median	98.0	95.8	1.8	99.5	88.5	8.4	98.0	96.5	1.6
IQR	97.0 – 99.0	93.2 – 96.8	1.2 – 5.3	98.0 – 100.0	87.1 – 92.8	5.8 – 11.9	98.0 – 99.0	96.1 – 97.0	1.2 – 2.0

* NPB-75 refers to the commercial pulse oximeter SpO_2 readings
† PO refers to the custom pulse oximeter $Sp0_2$ readings
Δ $Sp0_2$ difference between NPB-75 and PO

4. Discussion

The warm condition significantly improved the quality of the PPG signals, up to 4x (Tables 1-2). This improved quality was associated with a closer match between the SpO_2 values (Table 2) estimated by the PO system and the NPB-75. The only outlier was Subject 6. However, the signal RMS was still 2.8x and 2.3x better compared to the Cold test and Baseline measurements, respectively, for this subject.

Lesser inter-subject variability was observed with the results of SpO_2 values from the Warm test as a result of variability in signal quality (RMS) seen in Figure 3. However, greater variability in SpO_2 outcome at Baseline and Cold tests occured because of individual variability in the physiological response of blood flow to local temperature [29, 30]. Hence, the warm condition provided consistency that was not evident in typical cohorts at and below room temperature.

In particular, for the Warm test, the PPG quality was good in general across the cohort, with high signal RMS, while maintaining expected shape. This improvement in quality was likely a result of enhanced perfusion and blood flow at warm temperatures [31-33]. Local heat stimulation influenced an increase in vasodilation of peripheral blood vessels even in naturally cold digits. The increase in cross sectional area of blood vessels reduced peripheral vascular resistance and promoted enhanced systemic blood flow to the digits.

Cold temperatures tend to reduce peripheral blood flow in digits [33-35]. The reduction in blood flow is predominantly due to vasoconstriction of the peripheral blood vessels, resulting in a rise in both systolic and diastolic blood pressure (sympathetic tone) [22, 23]. When a hand at baseline temperature is immersed into ice water, the drastic drop in temperature causes the thermoregulatory system to stimulate the sympathetic nervous system to maintain homeostasis. Consequently, an increase in peripheral blood vessel resistance, volumetric elasticity, and wall stiffness follows, all of which reduces flow and perfusion, and thus signal quality, strength, and reliability of SpO_2 estimation.

Subject 20, as an example, had naturally low baseline skin temperature and thus likely lower peripheral blood flow, resulting in relatively poor baseline PPG quality (see Figures 5 and 7). During the Cold test, the PPG quality was further reduced. In fact, RMS signal strength for every individual during the Cold test was much lower compared to their Baseline and Warm test counterparts, as shown in Table 1. The drop in signal IR_{RMS} was about 1.6x more than RD_{RMS} for median PPG. The changes in blood pressure and flow also suggest that induced sympathetic tone alters the optical path length and the tissue absorption coefficients during blood circulation [22], further affecting signal quality.

SpO_2 estimation in conventional pulse oximetry relies on the R values derived from ratio of $|AC|/DC$ of the *RD* to *IR* signals in Equation 1. High *AC* amplitude will provide a high R value, and thus high SpO_2. During the Warm and Baseline test, the average *AC* amplitude was typically high, resulting in acceptable SpO_2 values for healthy adults [36, 37], and correlated well to the commercial pulse oximeter's results (Table 3). However, the agreement

between the two pulse oximeters diminished for the Cold test, as shown by significant deviation SpO_2 estimation in Table 3.

A normal arterial PPG waveform seen in typical pulse oximeter monitors may vary greatly, but typically includes sharp ascending (systolic phase) and descending (diastolic phase) limbs, which form a pulse. A characteristic notch on the descending limb is often visible in a good PPG waveform [3, 7], as shown in Figure 5. This notch resembles the dicrotic notch feature seen in an aortic pressure waveform, indicating the closure of the heart's aortic valve.

The dicrotic notch appeared regularly for Warm test PPG, and occasionally visible on a Baseline PPG, as seen in Figure 5. When the peripheral perfusion is low, such as at very low temperatures, the *AC* signal power (amplitude) can be low and may miss this dynamic and suppress other features. In addition, the PPG waveform's shape can become inconsistent and non-uniform. Such abnormalities in the PPG waveform can cause the peak-trough detection algorithm to determine incorrect peaks and troughs, as a result affecting any SpO_2, HR, or other estimations.

At normal or high arterial oxygen saturation conditions, the *IR* PPG_{AC} signal pulse amplitude is much greater than the *RD* PPG_{AC} [38]. However, at low SaO_2 conditions the *RD* pulse amplitude becomes larger than its *IR* counterpart [38]. Since SaO_2 is a global variable, it would not vary from site to site for the healthy subjects in this study. Thus, low SaO_2 was not a factor. In addition, both *RD* and *IR* signals changed correspondingly in all the tests.

Therefore, the average PPG_{AC} amplitude degradation for both *RD* and *IR* signals during the cold test points to overall compromised signal quality, rather than any actual change in SaO_2.

It should be noted that the typical pulse oximeter waveform presented, as in the case of NPB-75, is a highly filtered and processed version of the original PPG signal. With a highly processed signal, commercial pulse oximeters can still provide inaccurate readings in low perfusion scenarios. For example, the NPB-75 SpO_2 estimates for Subjects 5 and 10 from the Cold test were below the reported minimum of 95% for healthy adults [36, 37], and far closer to the values based on directly measured PO signals. SpO_2 of 100% was reported by the NPB-75 for 8 subjects, even with low PPG pulse amplitude (see Figure 7), which was actually higher than the corresponding Baseline and Warm test measurements on the same subjects (see Subjects 3,7,14-17,19 and 20 in Table 3). However, is also not clear how commercial pulse oximeter can provide a reasonable SpO_2 estimate for the other subjects with cold digits and poor PPG signal.

Commercial pulse oximeters are typically calibrated with well perfused, normothermic healthy volunteers. Pulse oximeter manufacturers use adaptive noise reduction based signal conditioning and advanced digital signal processing techniques which enable the pulse oximeter to separate sources and noise signals [6, 39, 40]. In addition, complex algorithms are used to evaluate the shape of each potential pulses and extract useful pulses from noisy signals [39, 40]. Auto-centering and auto-gain routines are applied to the displayed waveforms so as to minimize variations in the displayed signal [41, 42]. Although such signal processing techniques may be useful in estimating SpO_2, it often comes at the expense of losing valuable physiological data [43].

A limitation of this study was that it was not possible to obtain a true reference for blood gas data during the three tests. Required ethics to conduct invasive blood sampling for blood gas analysis was not achieved at that time. However outcome of this study, justifies the need to have a reference measurement. Recently ethics was approved by the Human Ethics Committee, University of Canterbury to perform invasive measurements and repeat the study.

5. Conclusion

This study investigated the effects of local tissue and room temperature conditions on PPG signal quality as applied to pulse oximeters using transmittance sensors. Cold temperature conditions significantly reduce PPG signal quality, as shown by reduced signal RMS and amplitude, and thus the accuracy of the resulting SpO_2 estimate. This degradation in signal quality is interrelated with decrease in blood volume and blood flow, due to induced vasoconstriction (sympathetic tone). Baseline measurements from naturally very cold digits also showed poor PPG quality and inaccurate SpO_2 estimation.

Warm temperature conditions significantly improved the quality of the PPG signals, up to 4x, as well as SpO_2 estimation. This improvement in signal quality can be correlated with increase in blood volume and blood flow, due to induced vasodilation. Warming of the hand increased the confidence in accuracy of SpO_2 estimation for subjects with naturally cold fingers. The overall experimental outcomes from this research suggest that warm skin temperature conditions (about 33°C) should to be maintained for reliable transmittance pulse oximetry, and any further clinical use of these signals in monitoring or measuring parameters related to peripheral oxygen extraction and circulation.

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Conflict of Interest

All the authors would like to declare that there is no conflict of interests regarding the publication of this paper.

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