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Investigating the Effects of Temperature on Photoplethysmography

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Abstract: Pulse oximetry is a commonly used technique to determine arterial oxygen saturation (SpO_2) and heart rate. This method uses photoplethysmography (PPG) signals to estimate SpO_2. However, pulse oximeters can be less accurate at cold temperatures. In this research, the effects of temperature on PPG signal quality was investigated for a group of 20 adult volunteers. Raw PPG data was obtained using a custom pulse oximeter (PO) system. Three tests were performed with the subject's hand maintained at baseline, cold, and warm temperatures. Analysis showed the median PPG signal RMS, as an indicator of signal-to-noise, for the warm test was 0.0289 V [IQR = 0.0262 – 0.0315 V] compared to the baseline test's 0.0174 V [IQR = 0.0104 – 0.0285 V] and the cold test's 0.0066 V [IQR = 0.0053 – 0.0106V]. This improvement of up to 4x in signal quality was associated with a closer match between the SpO_2 values estimated by the PO system and a commercial pulse oximeter. Paired RMS value comparison between the three tests showed a statistically significant difference for all *P*-values ($P \leq 0.004$). Results indicate that warm temperatures improve PPG quality and thus pulse oximeter accuracy.

Keywords: Pulse oximetry, non-invasive, photoplethysmography, arterial blood oxygen saturation, signal processing, sensor, thermocouple

1. INTRODUCTION

Pulse oximeters are the ubiquitous devices used in hospitals to non-invasively estimate arterial blood oxygen saturation (SpO_2) and monitor heart rate (HR). Pulse oximetry uses photoplethysmograph (PPG) signals acquired by a sensor, typically mounted on a finger, toe, or ear-lobe to optically detect blood volume changes in the tissue. The PPG results from the time-varying amount of blood that is pushed into the vascular bed during systole and diastole. 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 (Jubran, 2009, Mendelson, 1992).

Commercial pulse oximeter probes consist of two high output *RD* and *IR* light emitting diodes (LED) and a very 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 the rapidly changing ("*AC*") signals are extracted. The *DC* signal predominantly captures the unchanging light scattering and absorption. The *AC* signal predominantly captures the varying absorption due to pulsatile arterial blood and is synchronous with HR. Thus, by taking the appropriate *AC/DC* ratios and calibration, SpO_2 can be reliably estimated (Jubran, 2009, Goldman et al., 2000).

While the predominant application of pulse oximeters has been arterial oxygen saturation (SaO_2) estimation, the raw PPG waveform (PPG_{Raw}) is rich with relevant physiological information. Indeed, the PPG_{Raw} contains a complex mixture of the influences of arterial, venous, autonomic and respiratory systems on the peripheral circulation (Murray et al., 1996, Nilsson, 2013, Walton et al., 2010). Non-invasive estimation of blood flow change in muscles and bones using PPG was previously reported (Bergstrand et al., 2009, Naslund et al., 2006, Zhang et al., 2001), showing that the *AC* component of the PPG corresponds to blood flow while the *DC* corresponds to the blood volume change. Thus, application of PPG is not restricted to SpO_2 estimation.

A number of factors have been reported to limit pulse oximeter accuracy, including motion artefacts, environmental noise, skin tone, gender, nail polishes, and ambient light (Fluck et al., 2003, Feiner et al., 2007, Hanning et al., 1995, Petterson et al., 2007). Another important limiting factor is temperature, which is often overlooked. It is generally accepted that cold digits may provide inaccurate pulse oximeter readings (DeMeulenaere, 2007, Fahy et al., 2007), and simple solutions like rubbing the hands together may solve the problem. However, people with naturally very cold fingers or patients in intensive care units, where room temperature is maintained at 20°C, are examples of cases that can be affected by this problem.

This work hypothesises that PPG signal quality is severely degraded in cold digits, resulting in inaccurate SpO_2 readings and limiting the application of PPG. We tested that whether a continuous heat source close to the sensor site can improve PPG signal quality.

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2. MATERIALS AND METHODS

2.1 Test equipment

A standard transmission mode sensor (model: 320701001, Biometric Cables, Guindy, Chennai, India) was used to acquire PPG data from a finger. The sensor uses 660 nm and 940 nm wavelength light for the *RD* and *IR* LEDs, respectively. A Type-T surface mount thermocouple probe was taped to the surface of the skin, next to the pulse oximeter sensor, to obtain temperature data. The probe was nominally accurate to ±0.5°C above 0°C. Temperature data was continuously logged using a PC running LabVIEW via an NI cDAQ-9172 (National Instruments, Austin, TX, USA) multifunction data acquisition device.

Finger sensor control and PPG data acquisition is accomplished through a custom-built pulse oximeter development system (PO). The PO system is based on the CY8CKIT-050 PSoC 5LP Development Kit (Cypress Semiconductor, San Jose, CA, USA) uses an ARM Cortex M3 microcontroller. This custom equipment enabled direct control over LED intensity, signal conditioning, and sampling frequency.

Feedback control is used by the PO system to set the sensor's LED intensities. The control mechanism incrementally increases the LED's intensity to maximise the PPG amplitude without saturating the photo-detector, thus maximising the signal-to-noise ratio (SNR). The signal from the photo-detector is time demultiplexed so that the *RD* and *IR* PPGs can be processed independently. Analog PPG signals are sampled at 50 Hz by the 16-bit analog-to-digital converter (ADC) on the development board. Sampled data is sent to a PC via serial communication and saved as text files for offline signal processing in MATLAB (R2014a, The Mathworks, Natick, MA, USA).

A Nellcor NPB-75 (Covidien, Minneapolis, MN, USA) pulse oximeter was employed for comparison with the PO system. This commercial pulse oximeter can provide SpO2 and HR readings and display PPG in real-time.

2.2 Signal Processing & Analysis

A two-stage filter system is implemented for post-processing of PPG signals. Stage 1 consists of a finite impulse response (FIR) low-pass equiripple filter with a cut-off frequency of 10 Hz to remove unwanted signals, such as high frequency noise. Stage 2 is composed of two parallel infinite impulse response (IIR) filters. A low-pass Butterworth filter extracts the slowly changing signal (denoted "*DC*"), below a cut-off frequency of 0.67 Hz. The lower threshold of 0.67 Hz is chosen because the HR of any individual will not typically be less than 40 beats per minute (bpm). The second, parallel filter is a band-pass Butterworth filter that extracts rapidly changing signals (denoted "*AC*") with pass band frequencies 0.67–4.5 Hz. The upper threshold of 4.5 Hz captures HR and harmonics to a maximum of 135 bpm. A peak and trough detection algorithm is 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 is also determined, DC_{Mean}. SpO_2 is then estimated:

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

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

Walton's time domain equation (Walton et al., 2010) is used to calculate ratio of ratios *R* (Equation 1). *R* is the quantity defined in terms of the *AC* and *DC* waveforms for each of the *RD* and *IR* signals. Instantaneous oxygen saturations were estimated using Webster's empirical calibration equation (Webster, 2002), for each *R* value (Equation 2). Equation 2 was applied to each peak during a given section of a signal. The median of these instantaneous saturation estimations, over a 2 min window, was calculated to estimate SpO_2. It is understood that Equation 2 is used (Rusch et al., 1996, Phillips et al., 2012) to calibrate Nellcor commercial pulse oximeters and is a linear approximation of empirical data obtained from volunteer studies (Rusch et al., 1996).

2.3 Experimental Protocol

Twenty healthy adults (18+ years of age) with no pre-existing medical conditions were recruited for this study. Subjects were asked to refrain from strenuous physical activities for at least 30 minutes prior to the experiment. This study and use of data were approved by the Human Ethics Committee, University of Canterbury.

The experiment was conducted inside an air-conditioned room maintained at 20°C (typical ICU room temperature). During the study, subjects rested their left or right hand on a flat surface, at approximately the same height as their heart, with minimum movement. The subjects were asked to breathe normally for the duration of the experiment. The following three protocols were then implemented.

2.3.1 Protocol 1: Baseline measurement

Two minutes of baseline PPG readings, at normal digit temperature, 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.

2.3.2 Protocol 2: Cold Test

Subjects immersed their hand up to the wrist in an ice-water bucket maintained at a temperature of 0–4°C for approximately 5 min. When the temperature of the digits dropped to about 18-20°C, subjects were asked to take their hands out of the bucket and dry their hands. PPG, temperature, and NPB-75 data were then logged for approximately 2 min.

2.3.3 Protocol 3: Warm Test

Subjects rested their hand on a hot water bottle, maintained at a temperature of about 55°C, for approximately 5 min. Digit temperature was allowed to rise up to 31–35°C. PPG,