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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 ($29 \pm 2\,^{\circ}C$), cold ($19 \pm 2\,^{\circ}C$), and warm ($33 \pm 2\,^{\circ}C$) 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 $4\times$ 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 $33\,^{\circ}C$ for reliable transmittance pulse oximetry.

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

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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 $20 \pm 2\,^{\circ}C$ [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 s. 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

2.1. 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 Fig. 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.

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.

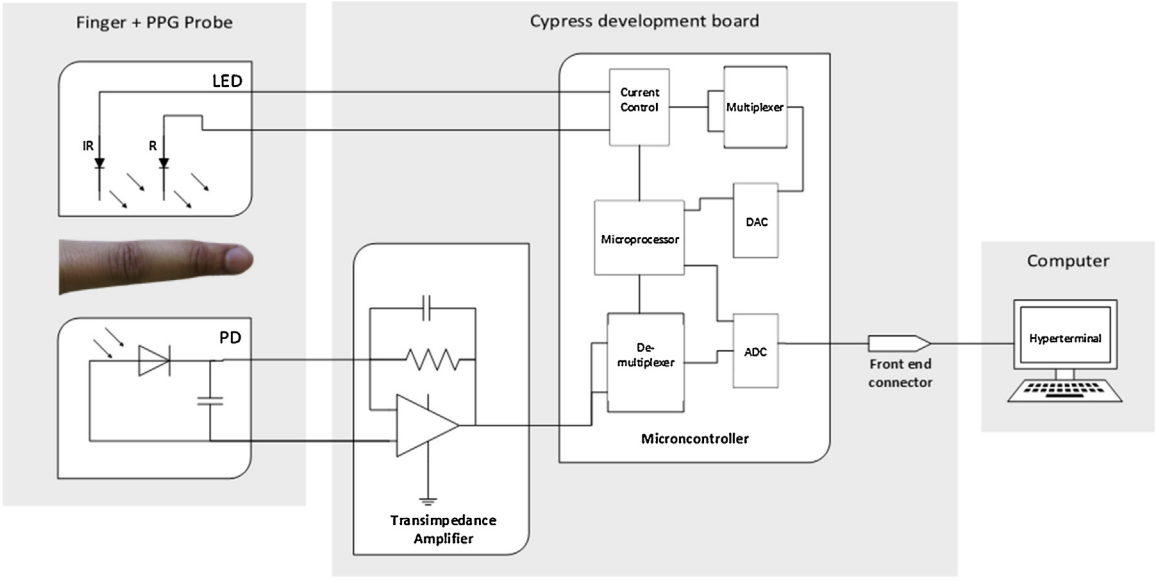

Fig. 1. Block diagram of the PO system, showing all the components for PPG data acquisition.