Pulse Oximetry in the Neck - A Proof of Concept

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***Abstract*— Oxygen saturation levels are routinely monitored in clinical settings. Pulse oximetry, in transmittance operation mode, is the most common method of estimating oxygen saturation (SpO_2). This is inexpensive and non-invasive and thus allows for long-term monitoring. However, it suffers from issues such as signal integrity, reliability and patient comfortability. As a result, there is an interest in exploring other locations on the body where oxygen saturation can be measured reliably. In this paper, a wearable device has been designed to study the feasibility of extracting photoplethysmogram (PPG) signals at the neck in reflectance pulse oximetry mode. It explores the signal integrity and strength compared to other locations as well as the presence of motion artefacts in that location. The results demonstrate that the PPG signals acquired at the neck show a very strong correlation (r=0.82) with the SpO_2 values obtained using a commercial device. Further, the SpO_2 values are calculated with an accuracy of 98.6%.**

I. Introduction

Oxygen saturation is an essential physiological parameter that indicates the level of oxygen in a person's blood. It is measured using arterial blood gas (ABG) test where a sample of blood is drawn from an artery usually in the wrist or arm of a person. Oxygen saturation (SaO_2) values are indicative of the overall health of an individual. For a healthy person, the SaO_2 value is typically above 90% [1]. Only if the oxygen level is sufficient can the body function properly. Lack of oxygen results in hypoxia which might lead to brain damage or even death. Because of its utility as a primary indicator of wellbeing, it is commonly used in hospital settings to monitor patients with respiratory and cardiac problems as well as those undergoing or recovering from surgical procedures [2].

Although the ABG test provides an accurate representation of blood oxygen saturation, it is an expensive, invasive, and time-consuming procedure that cannot be used for continuous monitoring [3]. An alternative to this is *pulse oximetry* which provides a non-invasive solution to estimate the oxygen saturation. It works by passing light of two different wavelengths (red and infrared) through the skin and measuring the absorbance of the transmitted or reflected light using a photodiode. This signal received by the photodiode is known as the photoplethysmogram (PPG) which represents the blood flow variations due to the heart pulsation. The light absorption properties of oxygenated and deoxygenated haemoglobin is different for both red and infrared lights. Hence, by passing light through a location on body with good blood flow and using the difference in absorption, and receiving the transmitted or reflected light, it is possible to estimate the oxygen saturation level, known as SpO_2.

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Pulse oximetry is an extremely popular method used commonly across hospitals to estimate oxygen saturation of patients. However, it is not very comfortable to use making it difficult for patients to wear it for long periods of time. It is usually clipped to a patient's fingertip or earlobe, and can easily fall resulting in data loss. Further, small movements can result in huge artefacts making the results unreliable under certain conditions [4]. While fingertip is the most common location for pulse oximetry due to high density of blood capillaries as well as easy access, other locations need to be explored that can mitigate some of the issues described above. This paper looks into the feasibility of using alternative, and more comfortable, body locations for acquiring PPG signals and consequently calculating oxygen saturation values. In particular, it demonstrates that using a wearable sensor attached to the neck can provide reliable results for calculating SpO_2 values. Section II briefly describes the principle of pulse oximetry and explains the hardware that has been designed for PPG signal acquisition at the neck. Section III shows how the PPG signal at the neck compares against a commercial pulse oximeter and analyses the different artefacts that are added to the signal in this location. It also looks at the strength of the signal acquired at the neck and compares this with other locations. Finally, Section IV discusses the advantages and limitations of the current study and the challenges that need to be overcome in the future to use the neck as an alternative location for SpO_2 monitoring.

II. Material and Methods

A. Principle of Pulse Oximetry

Pulse oximeters have two operating modes: *transmittance* and *reflectance*. In the transmittance mode, the light detector is located on the opposite side of the LEDs where the light transmitted through a certain location in the body is measured. This is the mode most commonly mode used by commercial pulse oximeters; with the fingertip and earlobe as the common locations to attach the device. In reflectance mode, the sensor and the light source are placed on the same side. This makes it possible to place the pulse oximeter at alternative locations of the human body such as the forehead [5], wrist [6], chest [7] or neck.

The fundamental principle of pulse oximetry, in both operation modes, is based on the Beer-Lambert Law [8]. Consider a light with intensity I_0 that is passing through a solution. The intensity of the transmitted light I is given as:

$$I = I_0 \times e^{(\sum \varepsilon_i(\lambda) c_i d)} \tag{1}$$

where $\varepsilon(\lambda)$, c and d are absorptivity (extinction coefficient) of the solution at a wavelength λ, concentration of the solution and optical path length, respectively.

By associating with the PPG signal and Δd, the optical path length variation due to pulsation, it becomes:

$$I_{min} = I_{max} \times e^{-[\varepsilon_{H_b} c_{H_b} + \varepsilon_{H_bO_2} c_{H_bO_2}]\Delta d} \tag{2}$$

which leads to a ratio r:

$$r(\lambda) = ln(\frac{I_{max(\lambda)}}{I_{min(\lambda)}}) = [\varepsilon_{H_b} c_{H_b} + \varepsilon_{H_bO_2} c_{H_bO_2}]\Delta d \tag{3}$$

By applying two different wavelengths, an absorption ratio R is obtained:

$$R = \frac{r(\lambda_1)}{r(\lambda_2)} \approx \frac{(\frac{I_{AC}(\lambda_2)}{I_{DC}(\lambda_2)})}{(\frac{I_{AC}(\lambda_1)}{I_{DC}(\lambda_1)})} = \frac{\varepsilon_{H_b}(\lambda_1) c_{H_b} + \varepsilon_{H_bO_2}(\lambda_1) c_{H_bO_2}}{\varepsilon_{H_b}(\lambda_2) c_{H_b} + \varepsilon_{H_bO_2}(\lambda_2) c_{H_bO_2}} \tag{4}$$

By rearranging the above equation, the oxygen saturation is theoretically given by:

$$S_pO_2 = \frac{\varepsilon_{H_b}(\lambda_1) - \varepsilon_{H_b}(\lambda_2)R}{\varepsilon_{H_b}(\lambda_1) - \varepsilon_{H_bO_2}(\lambda_1) + [\varepsilon_{H_bO_2}(\lambda_2) - \varepsilon_{H_b}(\lambda_2)]R} \tag{5}$$

The two wavelengths are chosen to be red and infrared to achieve a higher sensitivity of R and make the term $\varepsilon_{H_bO_2}(\lambda_2) - \varepsilon_{H_b}(\lambda_2) \approx 0$. The oxygen saturation is then computed by an empirical equation as follows:

$$S_pO_2 = f(R) = f(\frac{AC_{red}/DC_{red}}{AC_{infrared}/DC_{infrared}}) \approx A - BR \tag{6}$$

where S_pO_2 is a function of R, the ratio of the normalised AC components of the two lights while A and B are empirical constants.

B. Hardware Design

Fig. 1a shows a block diagram of the data acquisition system designed to obtain the PPG signals from the neck of human subjects. It consists of two LEDs with wavelengths 635nm (red) and 940nm (infrared) together with a photodiode placed next to the LEDs to receive the reflected light and convert it to an electrical current. The detected signal is fed into the analogue front end for signal amplification and filtering. At this stage, the current from the photodiode is first converted to voltage using a transimpedance amplifier. In this system, the AFE4404 chip from Texas Instruments [9] is used for the analogue front end due to its low power and ultra-small packaging size. The digitised PPG signals are read out serially from the ADC and transmitted wirelessly to a receiving device using the nRF52832 chip by Nordic Semiconductor [10].

Fig. 1b shows the final PCB of the data acquistion device which has a diameter of 25 mm. It consists of two stacked PCBs where the main board includes all of the data acquisition and transmission circuitry while the power board includes the battery. On the main board, the analogue front end and the wireless transmitter are well isolated so that the interference caused by the digital circuits is minimized. The entire system is powered using a removable 3.6V Lithium-Ion coin cell and covered by a 3D printed housing that also blocks the ambient light. To record PPG signals, the device is attached to the skin, using double sided adhesive, slightly above the suprasternal notch, as shown in Fig. 1c.

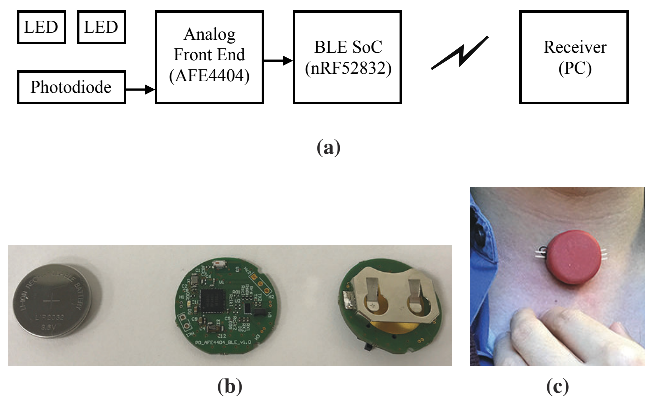

Fig. 1: *(a) Block diagram of the data acquisition hardware; (b) PCB of the final system; (c) A volunteer wearing the device for signal acquisition.*

C. Data Acquistion

Using the data acquistion hardware described above, PPG signals were obtained from two healthy adults (one male and one female). These volunteers reported no prior respiratory problems or other relevant health problems. A commercial pulse oximeter, Beurer P080 [11], was worn simultaneously to provide reference SpO_2 readings needed for calibration. In the first part of this study, the subjects were asked to remain stationary while signals were being acquired. Fig. 2 shows normal PPG signal as acquired by this deivce.

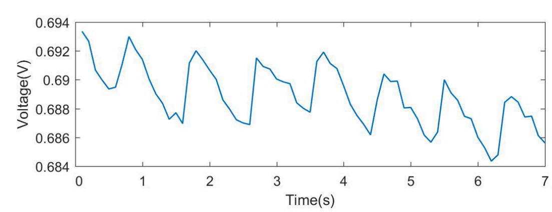

Fig. 2: *Normal PPG signal acquired from a volunteer while remaining stationary.*

In the second part, the subjects were asked to do some movements associated with the neck to acquire PPG signals with motion artefacts. Finally, the same data acquisition device was used to obtain PPG signals from four other locations: fingertip, wrist, forehead, and chest to compare the characteristics of the PPG signal that has been obtained from the neck against the other possible locations.

III. Results

A. SpO_2 Calculation

The SpO_2 values are estimated by calculating the ratio of absorption at red and infrared wavelengths, R, and subsequently using Equation (6). This is a linear equation hence the values of R from the signals obtained at the neck should correlate with the SpO_2 readings obtained from the reference pulse oximeter. Fig. 3 shows a scatter plot of the absorption ratio R against the SpO_2 readings. It can be seen that the R values correlate strongly with the SpO_2 readings with a correlation coefficient of 0.82, demonstrating the feasibility of extracting SpO_2 readings at the neck.

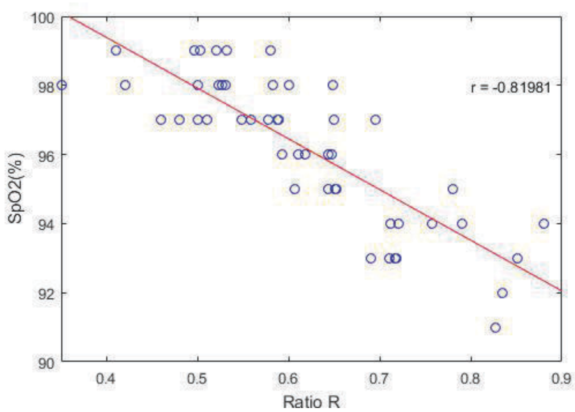

Fig. 3: *Correlation between absorption ratio R and the reference SpO_2 values.*

For SpO_2 calculation, as shown in Equation (6), A and B are empirical constants that are defined by the manufacturers after calibrating their devices against some reference. For this study, the calibration was performed against the reference pulse oximeter that was used to obtain oxygen saturation values. By obtaining the absorption ratio R from the signals acquired at the neck together with SpO_2 readings from the reference pulse oximeter, the constants A and B were calculated as follows:

$$S_pO_2 = f(R) = 105.25 - 14.67R \tag{7}$$

Using this, the SpO_2 values are obtained for all 50 data points recorded for this study. The average error rate in SpO_2 calculation was 1.4%.

B. Artefacts

For this study, the subjects were asked to stay stationary at the time of signal acquisition. In real-world conditions however, even small body movements can distort the signal to a great extent leading to loss of information. Further, the motion artefacts at the neck will be different compared to those at the other body locations such as the fingertip or earlobe. Hence, the different artefacts need to be investigated at this new location for it to be a viable source of PPG signal acquisition. As part of this study, three main types of motion artefacts were identified at the sensor attachment location. These include *deep breathing movement*, *head turning* and *swallowing related movement*.

Deep breathing was found to be the fundamental source of motion artefact leading to signal corruption. It manifested on the signal in the form of a low frequency component as shown in Fig. 4a with a dotted red line. As a result of this, the information of DC level used in calculating the absorption ratio R is lost. It is thus very important to remove this artefact from the PPG signal for accurate SpO_2 calculation. Although the breathing signal is an artefact in this application, its presence allows for the possibility of extracting breathing rate by detecting the envelope frequency of the PPG signal [12].

Head movements can also result in motion artefacts, particularly when turning in different directions. This is because the skin where the sensor is attached gets pulled in the direction of the head movement. The effect of head turns on the PPG signal can be seen in Fig. 4b. However, due to its large signal magnitude change, this artefact can be easily detected by applying appropriate thresholds.

Finally, the act of swallowing also adds artefacts as it results in a major pharyngeal muscle movement. Fig. 4c shows the artefact added to the PPG signal as a result of swallowing. It appears as a particular pulse that has a similar waveform shape to the QRS complex in electrocardiogram (ECG). By establishing its distinctive pattern, it can be easily removed from the PPG signal. Further, the artefact signal itself can be useful in order to develop a novel swallowing detection algorithm based on the PPG.

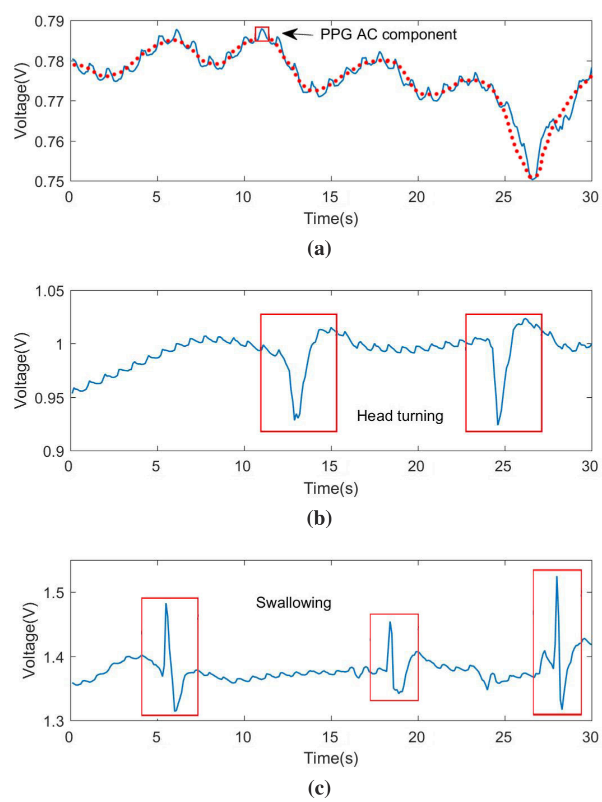

Fig. 4: *PPG Signal with (a) deep breathing artefacts; (b) head turning artefacts; (c) swallowing artefacts.*

C. Comparison of signal at different locations

The neck is being explored in this study as a novel location for extracting PPG signal. It is not the most conventional location but has the advantages of being comfortable and potentially useful for other applications as well. However, compared to other locations the signal being acquired at the neck is not the strongest. To analyse the strength, PPG signals were acquired from five different body locations at the same SpO_2 reading. These include the fingertip, wrist, forehead, chest, and neck. Unsurprisingly, the conventional fingertip location has the strongest signal strength with the highest amplitude due to its high density of blood capillaries. Compared to the signal at the fingertip, the AC component magnitude at the wrist, chest, neck, and forehead were lower by a factor of 0.1, 0.1, 0.18 and 0.7 respectively. This illustrates that while the signal acquired at the neck is relatively weak, it is still possible to extract from the neck.

D. Hardware power consumption

The data acquisition hardware in this study has been designed to ensure it is comfortable to wear, consumes small amount of power, and hence can operate over long period of time. It uses an ultra-low power AFE and BLE SoC which results in an average current consumption of 6.2 mA when the device is operating in active mode (working continuously with BLE communication). Using a LIR2032 coin cell, the device can operate for 36 hours continuously. Both the AFE and BLE modules also offer low power idle modes during which the total current consumption is only 0.4 mA. The overall current consumption when actively using the device can thus be reduced by leveraging these modes at certain times and buffering data to be transmitted at larger intervals.

IV. Discussion

In this paper, the feasibility of extracting PPG signals from an alternative body location has been presented. These signals in turn have been used to estimate the peripheral oxygen saturation values using the principle of reflectance pulse oximetry. In order to acquire signals from this unconventional location, a completely new wearable hardware has been designed. This hardware device consumes very little power and can operate for over 36 hours continuously when powered using a coin cell. The PPG signals acquired using this hardware showed strong correlation with the SpO_2 values as obtained using a commercial pulse oximtery device simultanously. This confirmed that the neck can be used as an alternative location on the body from where PPG signals can be extracted. Moreover, the location itself is advantageous since it can be used to monitor other parameters of the body such as the breathing and heart rates [13], [14].

Despite the high correlation, however, the SpO_2 values calculated after calibration resulted in an error of 1.4% on average. This error can be due to a number of reasons. Firstly, it is likely that the commercial pulse oximeter that is being used for calibration has some error of its own. To mitigate for this, proper lab-standard calibration procedures are needed. Secondly, the signal may be corrupted by some movement artefacts. Even though the subjects were asked to maintain a stable posture at the time of signal acquisition, there were still some small movements adding distortion to the PPG signal. Further, some other hardware considerations such the distance between the LEDs and the photodiode as well as the duty cycle and pulsing frequency for LEDs were not optimised for the neck region. By improving the hardware design, the accuracy of SpO_2 calculation is likely to improve.

It should be noted that despite the high accuracy in SpO_2 values, the work presented in this paper is still at a preliminary stage with potential for further improvements. More signals need to be acquired to achieve better calibration while the reference itself should be more accurate. Currently, artefacts are having an impact on the signal quality. Hence, artefact rejection algorithms need to be developed that can be incorporated on the data acquisition hardware device. However, despite the current limitations, the strong correlation of the PPG signal ratio with a commercial SpO_2 monitor, it can be concluded that the neck is indeed a viable alternative location for long-term oxygen saturation monitoring.

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