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Estimation of Venous Oxygen Saturation Through Non-Invasive Optical Sensing at the Jugular Veins

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Abstract: Non-invasive, real-time venous oxygen saturation (SvO_2) measurements provide the potential to improve health outcomes in transfusions, ventilator care, and in the intensive care unit. Current methods use catheters which are invasive, expensive, and pose potential high-risk, with only discrete measurements from a jugular vein obtained. This research designed, developed, and tested a proof-of-concept optical sensor similar to a pulse oximeter for non-invasive, continuous SvO_2 monitoring at the external jugular vein (EJV). Testing on three subjects met the aim of correctly identifying the EJV waveform and provided an SvO_2 estimation within the usual healthy range of 60-90%. SvO_2 estimates from the EJV pulse of 71.1%, 72.2%, and 70.4% and breathing pulse of 74.7%, 75.3%, and 74.1%, all fall within range, with trials capturing clear EJV waveforms from the single-point sensor. Further research is necessary to calibrate and validate the device against gold-standard blood gas analysers. However, the initial results prove the sensor's reliability and potential in detecting and estimating SvO_2 non-invasively, which has the potential to benefit patients across a wide range of clinical settings.

Keywords: Non-invasive, Optical Sensing, SvO_2 Estimation, Pulse Oximetry, Jugular Veins, EJV

1 Introduction

Venous oxygen saturation (SvO_2) is a basic parameter that can be used to assess internal oxygen delivery and oxygen extraction [1]. After blood has travelled around the body providing tissues with oxygen, SvO_2 specifies the oxygen content of the blood entering the heart's right side, determined by oxygen delivery and consumption [1, 2].

Monitoring SvO_2 and hence oxygen extraction is crucial for intensive (ICU) care, especially for sepsis and cardiogenic shock diagnosis, along with ventilator care [2]. Additionally, it can play a vital role in assessing the need for transfusions by offering insight into the balance between oxygen delivery and consumption [3]. This is highlighted by the National Heart, Lung, and Blood Institute (NHLBI) urging studies on "bedside O_2 consumption measurement" and devices "that reflect either tissue O_2 levels or insufficient O_2 delivery" [3].

Peripheral venous blood is typically non-pulsatile [2]. Therefore, unlike arterial oxygen saturation (SaO_2), which can be estimated non-invasively with a pulse oximeter, measuring SvO_2 often requires invasive techniques [5]. SvO_2 readings are dependent on the collection site, with different areas of the body having varying levels. Ranges of 60-90% for SvO_2 measured from the neck are typical, being lower than the average SaO_2 at 95-100% [4-8]. Most commonly, SvO_2 for healthy patients lies between 70-75% [9-11]. However, sick patients can experience saturations as low as 30% [1].

Mixed venous oxygen saturation ($SmvO_2$) is measured using an invasive pulmonary artery catheter (PAC) inserted into a central vein, commonly the external or internal jugular (EJV or IJC), to measure whole-body oxygen extraction [1, 12]. A central venous catheter (CVC) can also be inserted to provide central venous oxygen saturation ($ScvO_2$). Blood is withdrawn from the catheter and run through a blood gas analyser to determine SvO_2. This procedure provides intermittent SvO_2 measures with repeated blood draws increasing costs and contributing to blood loss in critically ill patients [1, 12].

Continuous SvO_2 monitoring can be performed with fibreoptic catheters via reflection spectrophotometry with data displayed every 2 seconds [1, 2, 13]. Continuous monitoring allows fluctuations to be monitored, which is beneficial, especially for critically ill patients, where saturation can drop suddenly [1, 13]. However, this method is still invasive and expensive, with the accuracy influenced by several factors, such as blood velocity flow and catheter placement [2, 13].

Research has examined measuring SvO_2 through pulsations in the EJV and IJV [4]. These veins are pulsatile due to their proximity to the heart, with the pulse reflecting the

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pressure changes in the right atrium during the cardiac cycle [5, 14]. The IJV can be difficult to find due to its depth from the skin, situated behind the sternocleidomastoid muscle [15-17]. It is also adjacent to the carotid artery whose pulsations can dominate those in the IJV [17]. However, as it drains into the superior vena cava without valves, pulsations are less likely affected than the EJV where valves are present, reducing its usability despite being easier to visualise [16-18].

Both the EJV and IJV have two pulsations present per systole in the waveform as seen in Figure 1, which can vary with respiration, differentiating from the carotid artery [14]. These pulsations are in line with phases from the cardiac cycle from atrial contraction (A wave) to emptying of the atrium (Y wave).

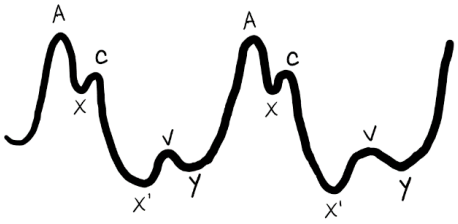

Figure 1: Jugular venous pulse waveform.

Using light from the visible to mid-infrared range, optical sensing can be entirely non-invasive. Through known optical sensing concepts used in pulse oximetry for SaO_2, a SvO_2 measurement can be obtained, utilizing the pulsatile nature of the EJV and IJV. Currently, no market device provides a continuous, non-invasive SvO_2 estimate. Therefore, a non-invasive optical sensor was designed, developed, and tested as a proof-of-concept device for reliable SvO_2 measurement to improve outcomes for patients. Specifically, $SpvO_2$ is obtained with the p denoting that the measurement is obtained through a form of pulse oximetry.

2 Methods

The hardware used for $SpvO_2$ estimation consists of a simple drive and sensor board. The drive board contains a 57mA constant current LED driver (PCA9745B, NXP) for driving the two combined 660 nm (red) and 940 nm (infrared, IR) LEDs (XZM2MRTNI55W-8, SunLED) on the sensor board. A Teensy 4.0 was used as the microcontroller with a seven-connector cable connecting the two boards.

A graphical user interface (GUI) was created to plot the detected pulsations in near-real-time and save sensor data for post-processing. Raw data was collated and filtered using a finite impulse response (FIR) bandpass 4th order Butterworth filter. The sampling rate (fs) was set to 1000 Hz, with a low-pass frequency of 0.1 Hz and high-pass of 6 Hz set to include the heart rate pulse (~ 1 Hz) and breathing rates (~0.2 Hz), while removing higher frequency mains noise. Noise can introduce additional peaks and troughs to the signal, which can reduce the accuracy of calculated $SpvO_2$.

MATLAB (2023a, Natick, MA) built-in peak and trough detection algorithm (*findpeaks*) was implemented, with set minimum heights and prominence. The AC signal was determined through the amplitude difference between the identified peak and trough for each measured pulse. DC signals were determined as the mean of the peak/trough signal.

This process was applied to both the 660 nm and 940 nm data. Taking the ratio of the AC component to the DC component creates a normalised absorption ratio for each wavelength. The two wavelengths can be compared to determine the ratio of ratios (R):

$$R = \frac{\frac{AC_{RED}}{DC_{RED}}}{\frac{AC_{IR}}{DC_{IR}}} \quad (1)$$

Using Equation 1, $SpvO_2$ can be estimated:

$$S_{pv}O_2 = 111 - 40.5R \quad (2)$$

Equation 2 was specifically developed for $SpvO_2$ estimation from experiments with artificial pulsation through a pneumatic system placed on the finger [5]. The coefficients from this equation were adapted for venous oxygen saturation from the arterial pulse oximetry equation coefficients based on venous blood gas analyser data from the experiments performed by Khan et al during their sensor calibration [5]. As the sensor is calibrated, Equation 2's coefficients will be adjusted accordingly, as performed with all pulse oximetry devices.

Three healthy subjects, consisting of a 22-year-old female, a 24-year-old female, and a 28-year-old male were each tested three times. The sensor was lightly taped on the right side of the neck and slowly moved around until a strong pulse EJV was found, seen on the GUI. Subjects were laid in a supine position of approximately 45° with their head slightly tilted to the left and relaxed for best EJV visibility and identification while preventing collapsing of the vein [15, 17, 18].

No blood samples were taken for blood gas analysis due to the trial being proof-of-concept only. The aim was to determine if the EJV waveform shape could be identified and if an accurate estimation could then be made.

3 Results

Testing conducted on the neck detected the EJV pulse with the waveform identified for all subjects as seen in Figure 2. Two pulsations in one cycle were detected signalling the jugular venous pressure (JVP) and not the carotid artery, matching the

ideal waveform from Figure 1. After filtering and peak and trough detection, a median $SpvO_2$ between the three trials of 71.1%, 72.2% and 70.4% was determined for each subject, using A and X' as the peak and troughs respectively.

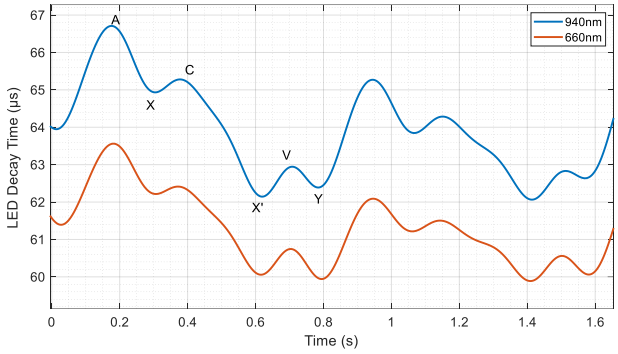

Figure 2: Identified jugular venous pulse waveform measured at the EJV for Subject 1, Trial 1.

The EJV pulse is affected by breathing at a frequency of approximately 0.2 Hz due to its proximity to the chest, adding a larger sinusoidal waveform to the individual EJV pulses (Figure 3). The median estimated breathing $SpvO_2$ was 74.8%, 75.3%, and 74.1% taking the peaks and troughs from the breathing sinusoid.

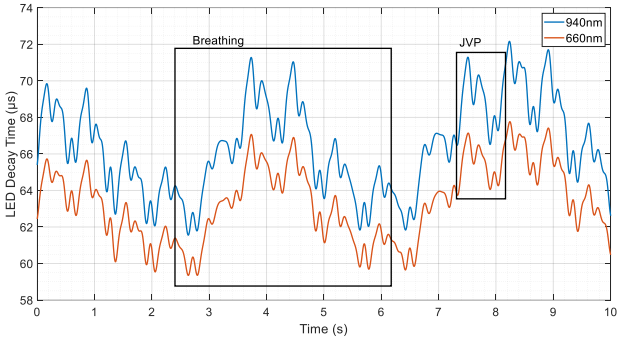

Figure 3: Breathing (large box) and JVP (small box) waveforms measured at the EJV on Subject 2, Trial 2.

4 Discussion

All subjects' measurements from both the JVP and breathing are in the valid $SpvO_2$ measurement range of 60-90% and all but one fall within the more common range of 70-75%. Breathing peaks and troughs are easier to identify precisely than JVP peaks during data processing. A clear signal with accurate extraction of the correctly identified peaks from JVP is required for a precise $SpvO_2$ estimation. Due to noise affecting the signal and the need to extract a single peak from two possible pulses, JVP estimation introduces more potential for error compared to the clearer peaks and troughs observed during breathing, occurring at approximately 0.2 Hz. Further research into the most accurate and consistent measurement method is required to optimise the device.

Both estimations lie within the common range and crucially the waveform shape with two pulsations was identified, with all correct corresponding peaks and troughs. This shows the EJV waveform can be detected and a reasonable $SpvO_2$ estimate made, confirming the proof-of-concept sensor device.

Gas analyser data collected from a catheter is required to validate the sensor and provide means for accurate calibration. The results meet the aim of a proof-of-concept test, showing the sensor can detect the correct waveform shapes and estimate venous oxygen saturation. However, as all sensors need calibration and invasively collected data for validation, a comparison to the gold standard blood gas analyser is required.

Only three subjects were tested, due to the trial being proof-of-concept only. This small pool provided fewer results, which can induce bias in the results. Testing and calibration with a much larger subject cohort are required to confirm results and accurately determine Equation 2's coefficients.

A strong EJV pulse was difficult to conclusively find. Waveforms and estimates were still correctly identified with the single-point sensor. However, different placements combined with different angles of supine positioning may increase the accessibility leading to better data. The IJV could not be found preventing any data collection for comparison with the EJV.

Future work consisting of a larger sensor array that can be flexed around the neck would increase the detection area, increasing detection ability. A combined sensor that could detect the carotid artery, and both/either EJV and IJV would allow arterial and venous oxygen saturations to be determined non-invasively from one sensor, providing critical information on oxygen extraction and consumption.

5 Conclusion

This work provides proof-of-concept results that $SpvO_2$ can be detected, with waveforms identified and in-range estimations made through non-invasive optical sensing methods at the EJV. Future work calibrating the device with gold-standard blood gas analyser measurements and longer trials with more subjects is required for complete sensor validation. However, results show the sensor can reliably detect and estimate venous oxygen saturations. With calibration and a larger sensor array for improved EJV/IJV detection, the sensor provides the potential for accurate non-invasive $SpvO_2$ estimations. This sensor offers a reduced risk and more cost-effective continuous, real-time measure of tissue oxygen extraction

which has several potentially significant uses in ICU care, transfusion, sepsis diagnosis, and ventilator care, all of which would help to improve patient outcomes.

Author Statement

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Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration and has been approved by the Human Research Ethics Committee, University of Canterbury (Ref: HREC 2023/68/LR).

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