Comparison of bi-wavelength and tri-wavelength photoplethysmography sensors placed on the forehead

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***Abstract*—Photoplethysmography is a well-established minimally invasive method for estimating heart rate and blood oxygen saturation in clinical settings. Photoplethysmography, with limitations, can also be extended to estimate respiration rate. Recently many off the shelf photoplethysmography sensors have been released in a form factor suitable for wearable devices. In this study we evaluate two photoplethysmography front ends (inclusive of suitable signal conditioning module and digitizer) from Maxim Integrated™. The tri-wavelength MAX30101 sensor and bi-wavelength MAX30102 sensor were evaluated on the forehead, in a truly non-obtrusive wearable friendly position. Heart rate, respiration rate and blood oxygen saturation were extracted from both sensors and compared with a FDA/TGA/CE approved photoplethysmography device placed on the finger. All data were captured simultaneously and at rest. The MAX30101 sensor was more accurate in measuring heart rate, blood oxygen saturation and respiration rate compared to the MAX30102. Additionally, we found that the red wavelength was best for measuring heart rate and the green wavelength was best for respiration rate.**

Keywords—photoplethysmography, comparison, forehead, respiration rate, blood oxygen saturation, SpO_2

I. Introduction

Photoplethysmography (PPG) is a technique using light to measure the volume and composition of organs [1]. It was first demonstrated in 1937 to measure heart rate (HR) by Alrick Hertzman [2], [3]. Since that time, it has become a critical minimally invasive diagnostic tool in estimating patients HR and blood oxygen saturation (SpO_2) in clinical settings.

Today PPG is still used in critical care of patients but has also been embraced by the public as a general health and fitness device. The technology can be found embedded into fitness devices and smart watches [4]. However, PPG embedded in these devices is often unable to estimate SpO_2 due to the absence of emissions in the red (~660 nm) part of the electromagnetic spectrum [4].

Throughout the cardiac cycle, the heart exerts a pressure wave that travels through the cardio-vascular system. This can be detected using PPG as the volume of blood in the arterioles changes causing changes in the amount of light absorbed to change over time [5]. Heart rate can be estimated from PPG using several methods. A commonly used method is to measure the instantaneous time between peaks in the waveform. Using a rolling window, a mean value is calculated for the window.

SpO_2 is estimated from a PPG by measuring the ratio of oxyhaemoglobin (HbO_2) and deoxyhaemoglobin (Hb) [6-9]. Oxyhaemoglobin and deoxyhaemoglobin have different spectral properties at ~660 nm (red) and ~880 nm (infrared) wavelengths [10, 11] (Fig. 1). These differences in spectral properties can be probed using red (~660 nm) and infrared (~880 nm) light emitting diodes (LEDs), enabling a PPG sensor to determine changes in the concentration of HbO_2 and Hb (Fig. 1).

PPG has also been used to estimate respiration rate. The act of respiration exerts several changes to the cardio-vascular system which are visible in a PPG signal. One method used is Respiratory Induced Intensity Variation (RIIV) [12-16] This method uses a secondary waveform present within the PPG signal as a change in the baseline of the signal over time [12-16]. Using this method, the respiration rate can be detected all three commonly used emission wavelengths of PPG (green, red and infrared).

The aim of this study was to compare two off-the-shelf PPG sensors from Maxim Integrated™ (Maxim Integrated™, San Jose, CA, USA) for suitability in a wearable device

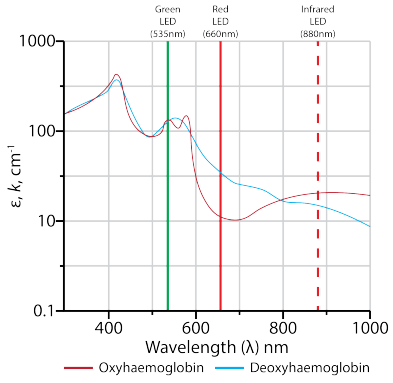

Fig. 1 Spectral properties of oxyhaemoglobin and deoxyhaemoglobin. The absorbance of light by oxyhaemoglobin (red) and deoxyhaemoglobin (IR). Emission wavelengths of the MAX30101 (green, red and IR) and the MAX30102 (red and IR) are shown as vertical bars on the figure. Adapted from [10,11].

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application when placed on the forehead. The sensors were compared in terms of their ability to estimate HR, SpO_2 and respiration rate in comparison to a suitable reference data.

II. Methods

A. PPG Sensors

This study compared the functionality of two Maxim Integrated™ PPG sensors, MAX30101 and MAX30102. The MAX30102 PPG sensor is a bi-wavelength sensor with light emission wavelengths in the red (660 nm) and infrared (880 nm) wavelengths [11]. The MAX30101 sensor is a tri-wavelength PPG sensor and has emission wavelengths in green (537 nm), red (660 nm) and infrared (880 nm) wavelengths [17]. The dimensions and printed circuit board footprint were the same for both sensors, as were their power requirements [11, 17].

Both sensors had embedded analogue-to-digital conversion (ADC) and an I^2C interface controller [11, 17]. Similarly, both sensors had essentially the same I^2C register schema with the exception that the MAX30101 sensor includes commands for controlling the green emission wavelength.

In this study we used off-the-shelf evaluation kits for these sensors. For the MAX30101 sensor we utilized the MAX30101ACCEVKIT, while for the MAX30102 we used the MAXREFDES112 kit. There are a few key differences between these kits. The MAX30101ACCEKIT is packaged with an associated microcontroller USB interface board for direct connection to a computer. However, the MAXREFDES112 kit requires the use of a third-party microcontroller to interface with a computer.

The included microcontroller interface board included in the MAX30101ACCEKIT was used for collecting data from the MAX30101 sensor. The microcontroller firmware supplied by Maxim Integrated™ was also used. Microsoft Windows compatible software supplied by Maxim Integrated™ was used for controlling the sensor and for collection of data during this study.

To interface with the MAX30102 on the MAXREFDES112 kit, a Node MCU microcontroller with custom written firmware was used. The data were collected from the microcontroller using a serial interface.

Both sensors were embedded in skin safe black silicone with only the sensor window exposed. This was affixed to an elastic material and sewn into the inside surface of a hat, such that the sensors were facing the forehead (Fig. 2).

B. Reference Data

Reference data for heart rate and SpO_2 data were captured from a commercial FDA/TGA/CE approved CONTEC™ CMS50D Pulse Oximeter, (CONTEC Medical Systems, Qinhuangdao, China). The pulse oximeter was fixed into a frame with a Microsoft LifeCam (Microsoft Corporation, Redmond, WA, USA) positioned facing the pulse oximeter (Fig. 2). Using optical character recognition software within MATLAB (MathWorks®, Natick, MA, USA), the values for HR and SpO_2 were recorded into a MATLAB workspace.

We used guided breathing to create respiration reference data at 6 second intervals (10 respirations per minute). Breathing was guided using a recorded voice instruction to initiate the test, and to guide when to inhale and exhale. A MATLAB script was used to provide the voice prompts at exactly 3 second intervals switching between inhalation and exhalation.

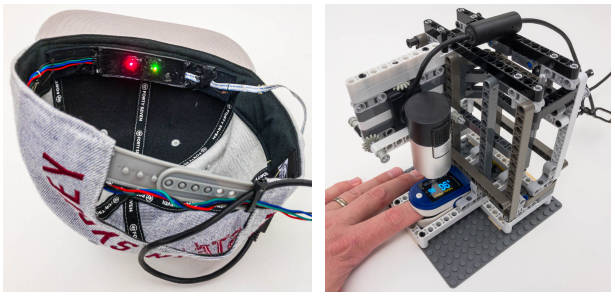

Fig. 2 PPG sensors imbedded in hat (left). The sensor emitting red is the MAX30102 sensor. The sensor emitting green is the MAX30101 sensor. Commercial pulse oximeter optical character recognition station (right). The pulse oximeter was affixed to the bottom of a frame holding a USB webcam. This was then used to capture video of the pulse oximeter, and optical character recognition performed post capture to record the heart rate and SpO_2 values.

C. Synchronisation

As software was not integrated across data streams (both PPG sensors, pulse oximeter and guided breathing), automatic synchronisation of data was not feasible. To synchronise data streams, both PPG sensors were initiated simultaneously. The guided breathing script was then started with a 5 second countdown to the first inhalation, at which point the video stream recording was initiated. The PPG sensors were tapped with the hand to add a movement artefact to both PPG sensors, synchronous with the start of the video capture.

Following data recording, the PPG streams were visually analysed to locate the induced movement artefacts. Data recorded prior to the induced movement artefacts were removed, synchronising the data streams. Any minor synchronisation differences between the PPG sensors and the pulse oximeter reference data were inconsequential, as the pulse oximeter readings are averaged over the one minute of data capture.

D. Participants

Two participants were included in this study. Both participants were authors of this paper. The participants consisted of one female participant 42 years of age, and one male participant 41 years of age. Both participants were healthy non-smokers of average fitness.

E. Experiment Protocol

The sensor hat was placed on the head ensuring that the sensors were not impeded from direct contact with the forehead from hair or other materials. The second finger on the left hand was placed in the commercial pulse oximeter. Data recordings were initiated and synchronised as detailed in previous sections, the recording duration was two minutes. At the end of two minutes, the video recording automatically stopped, and OCR of the frames was conducted automatically. Each participant repeated the experiment ten times.

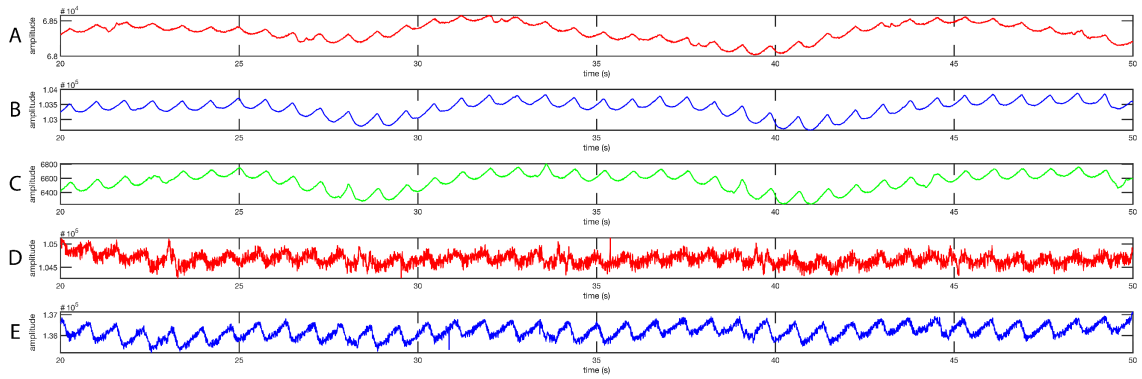

Fig. 3 Unprocessed PPG waveforms. The MAX30101 waveforms for the red (A), infrared (B) and green (C) emission wavelenghts, and the MAX30102 waveforms for the red (D) and infrared (E) emission wavelengths.

F. Data Analysis

Following data synchronisation a MATLAB script extracted the heart rate, SpO_2 and respiration rate from the individual sensor streams as per the method described in Longmore, et al. [18]. One modification to the method was the inclusion of heart rate and respiration calculated for the green channel on the MAX30101 sensor. This was achieved in exactly the same manner as for the red and infrared channels. SpO_2 was not calculated for the MAX30101 green channel.

Heart rate and SpO_2 data were compared with the commercial pulse oximeter data for accuracy. The respiration rate data were compared with the guided breathing cycle of 10 respirations per minute (RPM) for accuracy.

III. Results

A. Unprocessed Waveform

A visual comparison of the unprocessed waveforms shows that the MAX30101 sensor contained less noise in the red and infrared waveform, compared to the MAX30102. The MAX30102 does not contain a green channel, and therefore cannot be directly compared with the MAX30101 (Fig. 3). The respiration waveform is visible on the MAX30101 waveform as a wandering of the baseline over time.

B. Heart Rate

The MAX30101 sensor had an error of 1.2% (±0.98%) in the red emission wavelength, while the MAX30102 sensor had 8.5% (±18%) (TABLE I). In the infrared emission wavelength, the MAX30101 had and error of 3.1% (±3.7%), and the MAX30102 29% (±28%). An error of 1.5% (±1.1%) was observed in the green wavelength for the MAX30101 sensor (TABLE I).

C. Blood Oxygen Saturation

SpO_2 estimation for the MAX30101 sensor was observed to have an error of 1.5% (±0.55%), while the MAX30102 sensor had an 2.1% (±2.3%) error (TABLE II).

D. Respiration Rate

The respiration rate error in the red emission wavelength for the MAX30101 sensor was 7.5 rpm (±13) (respirations per minute), the MAX30102 sensor error was 16 rpm (±13) (TABLE III). The error in the infrared emission wavelength was 9.2 rpm (±7.4) for the MAX30101 and 9.2 rpm (±7.4) for the MAX30102 (TABLE III). The MAX30101 sensor recorded an error of 4.4 rpm (±5.6) in the green wavelength (TABLE III).

With outlier tests removed from the dataset, the MAX30101 red channel had a mean error of 1.3 rpm (±1.8), the MAX30102 was 2.1 rpm (±1.8) (TABLE IV). In the IR emission wavelength, the mean error for the MAX30101 mean error was 2.1 rpm (±1.8) and for the MAX30102 2.1 rpm (±1.8) (TABLE IV). The green wavelength on the MAX30101 sensor had an error of 2.1 rpm (±1.8) (TABLE IV).

TABLE I. Comparison Of Heart Rate Error

Sensor	Red (s.d.)	Infrared (s.d.)	Green (s.d.)
MAX30101	1.2% (±0.98%)	3.1% (±3.7%)	1.5% (±1.1%)
MAX30102	8.5% (±18%)	29% (±28%)	n/a

TABLE II. Comparison Of Blood Oxygen Saturation Error

Sensor	SpO_2 (s.d.)
MAX30101	1.5% (±0.55%)
MAX30102	2.1% (±2.3%)

TABLE III. Comparison Of Respiration Rate Error

Sensor	Red (s.d.)	Infrared (s.d.)	Green (s.d.)
MAX30101	7.5 rpm (±13)	5.4 rpm (±7.6)	4.4 rpm (±5.6)
MAX30102	16 rpm (±13)	9.2 rpm (±7.4)	n/a

TABLE IV. Comparison Of Respiration Rate Error with Outliers Removed

Sensor	Red (s.d.)	Infrared (s.d.)	Green (s.d.)
MAX30101	1.3 rpm (±1.8)	2.1 rpm (±1.8)	2.1 rpm (±2.1)
MAX30102	13 rpm (±12)	7.4 rpm (±5.3)	n/a

IV. Discussion

The MAX30101 and MAX30102 sensors appear to be similar on paper. Both sensors have the same external dimensions and package layout and the power requirements for both sensors are similar. Both sensors use the same wavelengths for emission in the red and infrared part of the electromagnetic spectrum. However, with the addition of the green emission wavelength, the MAX30101 appears to be a more capable sensor.

When examining the unprocessed waveform produced by the two sensors, the MAX30101 produced a waveform that was less noisy in all emission wavelengths (Fig. 3). This was particularly evident in the red channel (Fig. 3). Although a

comparison of the green waveform is not possible due to the exclusion of green emission in the MAX30102, the green waveform in the MAX30101 is clean, and relatively noise free (Fig. 3).

For estimation of heart rate, overall the MAX30101 outperformed the MAX30102. The MAX30101 had a lower error in the red channel (1.2% (±0.98%)) compared to the MAX30102 in the red channel (8.5% (±18%)) (TABLE I). The results were similar for the infrared channel, with the MAX30101 having a lower mean error (3.1% (±3.7%)) compared to the MAX30102 (29% (±28%)) (TABLE I). In the comparison between all the channels across both sensors, the MAX30101 red channel was most accurate (TABLE I).

Since estimation of SpO2 can only be performed using the red and infrared due to the spectral properties of haemoglobin, the MAX30101 does not have an advantage of an extra channel to increase overall accuracy. However, the MAX30101 (1.5% (±0.55%)) was found to be more accurate than the MAX30102 in estimating SpO2 (2.1% (±2.3%)) (TABLE II).

As with HR and SpO2 the MAX30101 was more accurate in the red emission wavelength for respiration rate estimation (7.5 rpm (±13)) than MAX30102 (16 rpm (±13)) (TABLE III). Additionally, the MAX30101 was also found to be more accurate in estimating respiration rate in the infrared wavelength (5.4 rpm (±7.6)) compared to the MAX30101 (9.2 rpm (±7.4)) (TABLE III). The green wavelength on the MAX30101 was found to be most accurate for respiration rate estimation (TABLE III).

However, it should be noted that respiration accuracy was poor for both sensors. Four datasets contained unusually high mean errors for respiration rate. When these outliers were removed, the mean error reduced for all channels on both sensors. Without outliers, the red channel (1.3 rpm (±1.8)) on the MAX30101 was found to be most accurate for respiration rate estimation (TABLE IV). Both emission wavelengths on the MAX30102 still performed poorly for respiration rate. The use of alternative respiration estimation methods such as Respiratory Induced Amplitude Variation or Respiratory Induced Frequency Variation may yield better results [15, 19].

In our comparison between the two sensors, the MAX30101 outperformed the MAX30102 sensor in all metrics tested when positioned on the forehead.

Some limitations of this study include that only one location was tested (the forehead). It would be recommended that other anatomical positions such as the fingertip and wrist be tested in the future. Additionally, the tests were performed while at rest. Testing these sensors under light or mild exercise may yield different results. Future tests should include unguided breathing with an appropriate reference measurement of respiration rate. Finally, the means by which the sensors were fitted to the forehead may have biased their potential accuracy. Indeed, there was no crossover, where each sensor was evaluated at each position. Future work should attempt to limit this bias.

V. Conclusion

The MAX30101 was found to have a lower rate of error compared to the MAX30102 in all metrics tested. With the addition of the green emission wavelength, and less noise in the red and infrared channels, the MAX30101 may be a more suitable sensor for applications such as emergency triage, medical monitoring, research and fitness tracking. Future studies should include comparison of sensors at other anatomical locations such as the fingers and wrist and should consider assessment while undertaking mild exercising.

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