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Investigation of photoplethysmography and arterial blood oxygen saturation from the ear-canal and the finger under conditions of artificially induced hypothermia

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***Abstract*— Pulse oximeters relay on the technique of photoplethysmography (PPG) to estimate arterial oxygen saturation (SpO_2). In conditions of poor peripheral perfusion such as hypotension, hypothermia, and vasoconstriction, pulse oximeters become inaccurate or provide no reading. This is due to the poor quality of the PPG signals detected at that instance. In order to overcome this problem, the ear canal has been proposed as a alternative measurement site for measuring reliable SpO_2. Hence, an ear canal PPG sensor was developed along with a PPG processing system. The performance of the sensor was evaluated by measuring the red and infrared PPGs and SpO_2 from 10 healthy volunteers undergoing artificially induced hypothermia. The results from the ear canal sensor were compared with simultaneously acquired results from the finger. Hypothermia was induced by exposing the volunteers to cold temperatures of 10 $\pm$ 1^oC. The results acquired suggest that the ear canal pulse oximeter endures more in estimating SpO_2 values accurately when compared with the more common finger pulse oximeter.**

Keywords **- Photoplethysmography, Pulse Oximetry, Hypothermia, Vasoconstriction**

I. INTRODUCTION

Continuous assessment of arterial oxygenation by pulse oximetry (SpO_2) has become widespread during anaesthesia, in the peri-operative period, and in the critically ill. It is now an ASA standard for intraoperative monitoring during all anesthetics [1]. A pulse oximeter estimates SpO_2 by computing the proportion of light absorbances by oxyhaemoglobin and reduced haemoglobin at two different wavelengths amid the cardiac cycle. The two most commonly used wavelengths are 660 nm and 940 nm. The changes in light absorbances during the cardiac cycle are measured as a voltage signal called a photoplethysmograph (PPG). The PPG waveform consists of two components, a pulsatile AC component synchronous with the cardiac cycle and a slowly varying DC component [2].

Pulse oximeters perform reasonably well in most cases, however they are known to fail or produce errors reading in conditions of poor peripheral perfusion. Poor perfusion may result from conditions such as hypotension, hypothermia, vasoconstriction, low cardiac output, hypovolaemia, peripheral vascular disease, infusion of vasoactive drugs, Raynaud's phenomenon and from performing a Valsalva maneuver [3]. The estimated SpO_2 readings become very inaccurate or non-existent in these conditions due to the inability of the pulse oximeter to distinguish between light absorbed by arterial blood (AC PPG) from that of venous blood (DC PPG) in the absence of peripheral arterial pulse. The problem arises as all clinically used pulse oximeter systems are attached to the extremities such as the finger, toe, or ear lobe, where pulsatile flow is very easily compromised [4]. To overcome this limitation, the external auditory canal is proposed as a potential measurement site for monitoring red and infrared PPGs, heart rate and SpO_2. Ear canal as a measurement site provides many advantages which could ensure reproducible measurements of PPGs and SpO_2, when compared to other common sites such as finger. The following key advantages can be highlighted

- Being closer to the trunk, the ear canal could provide a better signal in critical conditions of hypothermia
- The ear canal provides stable temperature close to the core temperature of the body
- also provides good fixing, factor of comfort and invisibility of the device
- Reduced influence of sympathetic nerve activity in conditions leading to low perfusion states [5]
- Can also be used for vital sign monitoring in high risk settings such as aviation, fire fighting or extreme mountaineering

Moreover, the proposed site has the advantage of being non-invasive, when compared with previous attempts made to measure SpO_2 in more central sites such as the oesophagus [6], [4]. In this aspect, a new ear canal pulse oximetry probe was previously developed along with a PPG processing system. The feasibility of measuring PPGs and SpO_2 from the ear canal, and its performance in conditions of induced local peripheral vasoconstriction was demonstrated in [7] and [8]. However, the studies described in [8] has only validated the sensor during states of artificially produced local hypothermia (right hand immersion in ice water). Hence in an attempt to truly show the potential of the measurement location, we tested the sensors performance in volunteers experiencing whole-body cold exposure. This paper describes the proposed technology in brief and illustrates the effects of hypothermia on PPGs and SpO_2.

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II. METHODS AND MATERIALS

A. Measurement system

The measurement system was designed and developed to simultaneously detect, sample, record and display PPG, ECG and temperature signals. The system consists of two custom built PPG/pulse oximetry probes (ear canal and finger), PPG processing system, ECG amplifier, (LDF) laser Doppler blood flow and temperature monitor and data acquisition card.

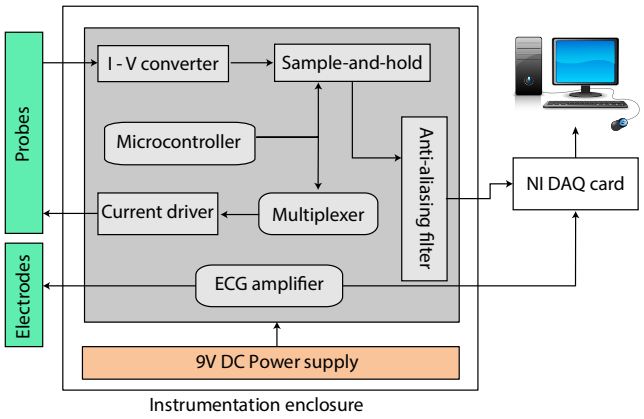

Fig. 1: Block diagram of the PPG Processing system with embedded ECG amplifier

1) PPG processing system: The basic block diagram of the custom made multichannel PPG processing system with embedded ECG amplifier is shown in Fig. 1. The heart of the PPG processing system is the micro-controller (Atmel, ATtiny 2313-20SU), that is used as a master clock and timing generator. The micro-controller generates digital switching signals at a frequency of 800Hz, which are used for LED switching, and sampling of the PPG signals. The LEDs in both the PPG probes are driven by two identical current driver circuits. The multiplexer is to generate a timed switching signal used to turn on the red and infrared LEDs alternatively [9]. This is to allow independent sampling of red and infrared light by the photodetector. The light from the LED is transversed through the vascular tissue and the changes in light attenuations during arterial pulsations are detected by a photodetector. The current from the photodetector is then converted into a mixed voltage signal containing both red and infrared PPGs. This mixed voltage signal is then split into red and infrared PPG signals using a sample-and-hold amplifier. The red and infrared PPG signals are then passed though a anti-aliasing filter to remove high frequency switching noise.

The system also hosts a simple three lead ECG amplifier. ECG signals obtained from the amplifier are used as a timing reference for the acquired PPG signals. The processing system is powered by two 9V PP3 NiMH rechargeable batteries. Skin temperature measurements were made using the the moorVMS-LDF laser Doppler blood flow and temperature monitor *(Moor Instruments, Devon, UK)*. A 16-bit data acquisition card *(DAQpad-6211, National instruments Inc., Austin, TX, USA)* was used to digitise the raw PPG, ECG and the temperature signals acquired from the instrumentation unit. A virtual instrument (VI) system is implemented on LabVIEW *(National Instruments Inc. Austin, TX, USA)* on a personal computer for data acquisition and real time display of the PPG, ECG and temperature signals.

2) PPG Probes: The ear canal PPG probe is a headphone shaped reflectance PPG probe consisting of two surface mount LEDs and a photodiode. The LEDs used emit light at 870 nm in the infrared region and 658 nm in the red region *(CR 50 IRH and CR 50 1M, Excelitas technologies, Massachusetts, USA)*. The photodetector used is a flattop photodiode with an active area of 0.65 mm^2 and peak sensitivity at 900 nm *(SR 10 BP-BH, Excelitas technologies, Massachusetts, USA)*. The LEDs and the photodiode were placed 5 mm apart from each other as experimental studies have shown that a separation of 4 to 5 mm yields a better signal-to-noise ratio [10]. The ear canal probe casing was designed in Solid Works 2012 *(Dassault Systemes SOLIDWORKS Corp, Waltham, Massachusetts, USA)* and was manufactured using a Object24 Desktop 3D printer *(Stratasys Ltd, Minnesota, USA)*. The material used for 3D printing is Object VeroWhite plus RGD835. The sensor has an overall diameter of 7 mm. Fig. 2 shows the 3D sketch and a photograph of the ear canal PPG sensors placed inside the right ear of a volunteer.

A reflectance finger PPG probe, optically identical to the ear canal probe was also developed to facilitate comparisons of SpO_2 measured from the finger and the ear canal. The finger probe was encapsulated with in a conventional pulse oximeter clip. In order to avoid direct contact between the optical components and the skin all the sensors were sealed using medical graded clear epoxy resin *(DYMAX 141-M, Dymax Corporation, Torrington, CT)*.

B. Subjects

With the approval of the Senate Research Ethics Committee of the City University London, 10 healthy volunteers, 6 – male, 4 – female, aged between 19-61 (*mean age* $\pm$ *SD* : 32 ± 12 *years*) were recruited. Individuals with any history of

Fig. 2: 3D model and photographs showing the ear canal PPG probe.

cardiovascular diseases were excluded from the study. The experimental protocol was clearly explained and a written information sheet was also provided to each volunteer. Upon agreeing to participate in the study, a signed consent form was obtained from all the volunteers. The subjects were asked not to smoke nor exercise for at least two hours before the experiment. The subjects were also asked to wear just one layer of clothing during the experiment, this is to maximise the effect of cold temperatures on the cardiovascular system.

C. Experimental protocol

The trials were carried out in the Biomedical Engineering Research laboratory, School of Mathematics, Computer Science and Engineering, City University London. Upon arrival, all the volunteers were seated in a room maintained at $22 \pm 1^{\circ}$C for a minimum of 10 min to acclimatize. During the study, all the subjects were made to sit in a comfortable chair, with both hands resting on arm rests arranged to a height approximately equivalent to their heart position. Once the volunteer was comfortable, heart rate (HR), systolic and diastolic blood pressure (BP) *(HEM-907, Omron Healthcare, Hoofddorp, The Netherlands)* of each individual were measured.

The finger and the ear canal PPG probe were then attached to the respective locations. The LDF monitor was attached just below the left thumb on the back of the hand. Ag-AgCl ECG electrodes *(SKINTACT, F-WA00)* were connected for lead I measurements. Once all the sensors were in place, baseline readings were obtained from all the volunteers for at least 2 *min* before they were moved into an air conditioned room maintained at $10 \pm 1^{\circ}$C for 10 min. Continuous measurements were acquired during the entire time, after which volunteers were then moved back out to the room temperatures. Monitoring continued for another 10 min after the hypothermia period.

D. Data analysis

The performance of the ear canal PPG sensor was evaluated by measuring the mean amplitude of the red and infrared AC PPG signals, and by comparing them with the amplitude of the finger PPG signals, during all three stages of the experiment (before, during and after the induction of hypothermia). The AC and the DC components were extracted using a band-pass filter ($f_c = 0.5$ *Hz and* 20 *Hz*) and a low-pass filter ($f_c = 10$ *Hz*) respectively. Mean amplitudes were measured during baseline for 2 min, and for every 5 min during and after the introduction of cold stimuli. The effect of compromised peripheral perfusion on the estimation of SpO_2 values was demonstrated by calculating SpO_2 from the finger and the ear canal during all three phases of the experiment. SpO_2 was computed using an empirically derived equation

$$SpO_2 = 110 - 25(R); \ \textit{where } R = \frac{AC_{658}/DC_{658}}{AC_{870}/DC_{870}} \qquad (1)$$

SpO_2 value below 92 % during any stage of the experiment was considered as pulse oximeter failure.

III. RESULTS

The PPG signals acquired from both the finger and the ear canal were of very good quality during baseline in all the volunteers. Fig. 3 shows the amplitude of the infrared PPG signals acquired from the finger and the ear canal along with the changes in the skin temperature of the hand, for the entire duration of the study (22 min). The amplitude of the PPG signals acquired from the finger has reduced significantly with time, during exposure to cold temperatures, this is expected due to the profound vasoconstriction resulting from the activation of the sympathetic nervous system. Similarly, the ear canal PPG signals have also reduced in amplitude during the cold stimuli, but the change in amplitude was significantly less when compared to the finger. The skin temperature of the hand has dropped to 21.8°C by the end of the cold stimulus.

The combined mean amplitude of the red and infrared AC PPG signals acquired from the ear canal and the finger during different phases of the experiment in 8 volunteers is shown in Fig. 4. It was not possible to calculate the amplitude or the SpO_2, in a couple of the volunteers due to heavy motion artifact in the acquired signals, which is caused due to shivering. The mean amplitude of red and infrared AC PPG signals acquired from the finger have dropped by 62 % and 65 % respectively in the first 5 min of cold exposure. By the end of the cold stimulus (10 min), the amplitude of the signals dropped down further to 79 % and 85 % respectively. On the other hand, the red and infrared ear canal AC PPG signals have reduced by 30 % and 27 % in the first 5 min of exposure to cold, and by the full 10 min, they dropped down to 35 % and 38 % respectively.

After the cold expose, the amplitude of the PPG signals have started to recover with time in both the ear canal and the finger. The amplitude of the red and infrared AC PPG signal from the finger have increased by 113 % and 170 % by the end of the experiment. However, they did not return to the initial baseline value within the 10 min recovery period. On the contrary, the AC ear canal PPG

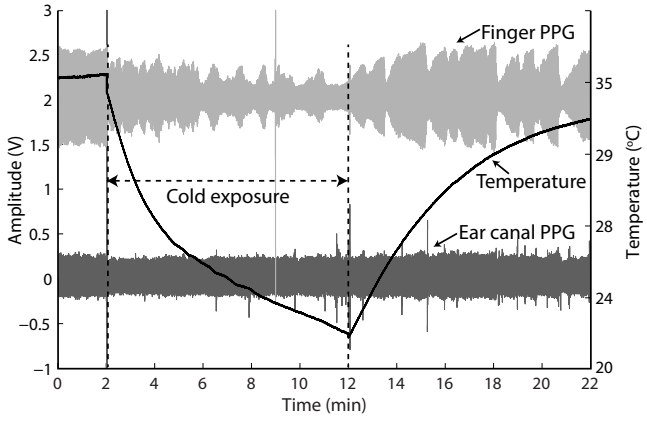

Fig. 3: Changes in amplitude of infrared PPG signals acquired from the finger and the ear canal for the entire duration of the study in one of the randomly selected volunteers.

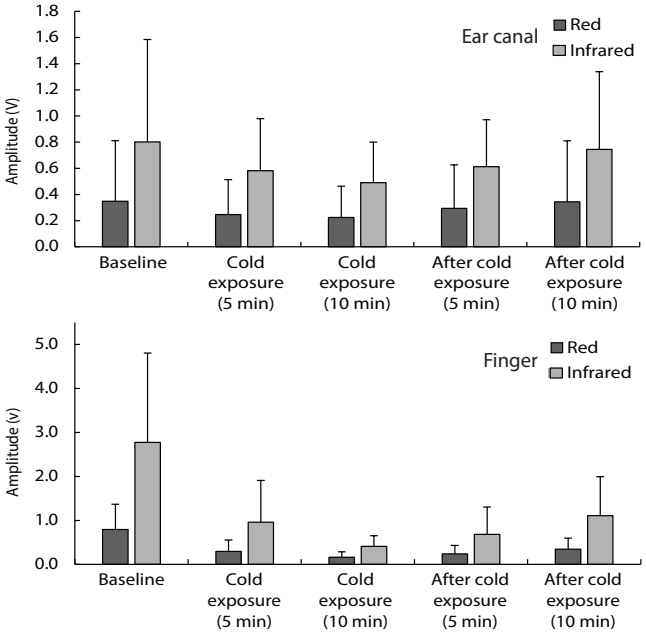

Fig. 4: The mean amplitude of the red and infrared PPG signals has dropped significantly in finger when compared to the ear canal.

signals have approximately returned to the baseline value. This is expected as the drop in the ear canal PPG signals was significantly low compared to the finger.

The mean SpO_2 values were calculated for each volunteer during all the stages of the experiment to demonstrate the effect of hypoperfusion on the estimation of arterial oxygen saturation. Fig. 5 shows the SpO_2 estimated by the

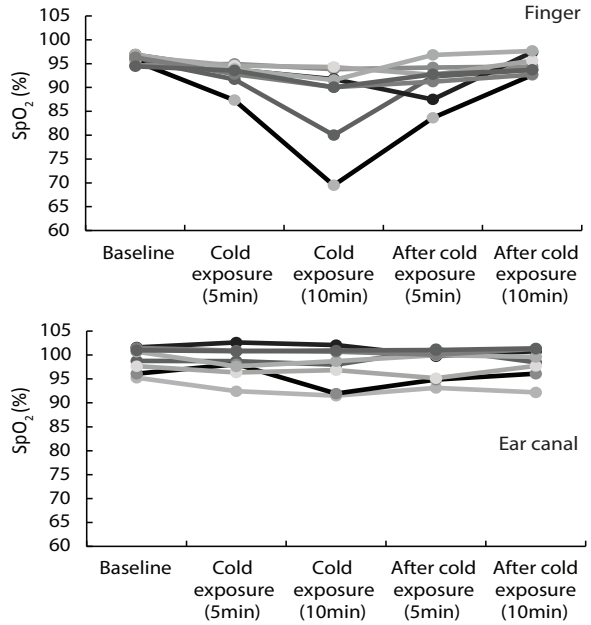

Fig. 5: Mean SpO_2 estimated by the finger and the ear canal pulse oximeter during the experiment

finger and the ear canal pulse oximeters during baseline, cold exposure and recovery. Theoretically, SpO_2 provides a global assessment of blood oxygenation, and hence should not change from one site to another in healthy volunteers. However during the first 5 min of the cold exposure, the finger pulse oximeter has failed in one of volunteers, and by the end of the study it failed in 5 volunteers. The ear canal pulse oximeter has performed well during all the stages of the experiment and has only failed in 1 volunteer towards the end of the cold stimuli. A paired T-test was performed to compare the SpO_2s measured during baseline with cold exposure. Statistically significant difference ($P< 0.001$) were found in SpO_2 estimated by finger sensor during baseline and cold exposure. No significant difference were found in all other cases.

IV. CONCLUSIONS

In this investigation the reliability of the proposed ear canal PPG sensor was tested against the most common finger sensor in conditions of induced hypoperfusion. The results from these tests showed that the finger pulse oximeter is most easily compromised when compared with the newly developed ear canal pulse oximeter under conditions leading to hypothermia. Hence, the ear canal pulse oximeter could be a good alternative for the finger pulse oximeter when measuring PPGs and SpO_2 in conditions of compromised peripheral perfusion. However, more trials need to be conducted in healthy and patients to further assess this hypothesis.

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