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Venous pooling and drainage affects photoplethysmographic signals at different vertical hand positions

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ABSTRACT

The aim of the current work is to investigate the possibility of augmenting pulse oximetry algorithms to enable the estimation of venous parameters in peripheral tissues. In order to further understand the contribution of venous blood to the photoplethysmographic (PPG) signal, recordings were made from six healthy volunteer subjects during an exercise in which the right hand was placed in various positions above and below heart level. The left hand was kept at heart level as a control while the right hand was moved. A custom-made two-channel dual wavelength PPG instrumentation system was used to obtain the red and infrared plethysmographic signals from both the right and left index fingers simultaneously using identical sensors. Laser Doppler flowmetry signals were also recorded from an adjacent fingertip on the right hand. Analysis of all acquired PPG signals indicated changes in both ac and dc amplitude of the right hand when the position was changed, while those obtained from the left (control) hand remained relatively constant. Most clearly, in the change from heart level to 50cm below heart level there is a substantial decrease in both dc and ac amplitudes. This decrease in dc amplitude most likely corresponds to increased venous pooling, and hence increased absorption of light. It is speculated that the decrease in ac PPG amplitude is due to reduced arterial emptying during diastole due to increased downstream resistance due to venous pooling.

Keywords: Photoplethysmography, Pulse Oximetry, Venous, Arterial

1. INTRODUCTION

Pulse oximetry has become a standard, non-invasive monitoring tool in critical care and other clinical settings, as it provides information about oxygen transport via arterial blood to tissues and organs in the body, specifically the arterial oxygen saturation [1]. This value is approximately equal everywhere in the body, as there is no appreciable withdrawal of oxygen within the arterial tree. In contrast the oxygen saturation of the venous blood draining from a given tissue region depends on the oxygen uptake by the local tissue and rate of regional blood flow, and thus its value varies from one region to another. Global changes in metabolism however could affect local venous oxygenation [2]. Where it is feasible, the measurement of venous saturation provides information about the rate of regional oxygen uptake. Currently, it is most commonly measured through invasive techniques such as catheterization of jugular veins and analysis using co-oximetry or a fibre-optic spectrophotometric method [3]. The aim of the current work is to investigate the possibility of augmenting pulse oximetry algorithms to enable estimation of local venous oxygen saturation, initially in the peripheral tissues (e.g. the finger) but ultimately in specific regions such as the brain or splanchnic organs. Such a method could provide information valuable information about the oxygen supply-demand requirements of tissues. This would be beneficial in monitoring and detecting important clinical events such as early phases of hemorrhagic shock, metabolic changes, variation in cardiac output or hemodynamic events.

Pulse oximetry utilizes photoplethysmographic (PPG) measurements at red and infrared wavelengths to derive the arterial blood oxygen saturation (SpO_2) [4]. Specifically the ratio of absorbance of red and infrared light by the hemoglobin is calculated using the PPG signals to discriminate between arterial blood and the non-pulsatile absorbers in the tissue such as skin, muscle and bone [1] and assumes venous blood is similarly non-pulsatile. However, it is now recognized that the motion of venous blood can also contribute to the PPG signal [5–6], possibly facilitating a non-invasive method of estimating venous oxygen saturation.

Current methods for measuring peripheral venous oxygen saturation involve mechanically induced pulsation of the tissue using a pressure cuff [7]. The pulses are transmitted predominantly to the veins, producing estimation of the venous saturation from pulsatile venous component of absorption. However, the use of an external source for the creation of the

pulsatile venous component restricts the use of the technique to peripheral measurement sites (e.g. fingers, toes). More recent work [8] takes advantage of the fact that the PPG waveform is influenced by both positive pressure ventilation [9] and peripheral venous pulsations [10]. Walton et. al. [8] used several time and frequency domain methods to analyze esophageal PPG signals from patients undergoing coronary artery bypass surgery to order to estimate the arterial and venous saturation. In this work, they suggested the measurement of instantaneous saturation ('InstSat') to provide a moment-by-moment measurement of the average oxygen saturation of the blood in all vascular compartments in the vicinity of the probe. Shafqat et al [11] used a similar technique to estimate venous oxygen saturation from finger PPG signals cardiothoracic surgery and showed that the motion produced in the venous blood due to the positive pressure ventilation could be used for the non-invasive, continuous and real-time estimation of regional venous oxygen saturation. It should be noted that these methods depend on ventilator-induced modulation of PPG, which limits their application to anesthetized patients.

In a step towards developing a reliable method for non-invasive estimation of venous oxygenation, this work investigates the effects of the venous component on ac and dc PPG amplitudes during a study in which the arms of volunteers were raised and lowered by changing the position of the hand relative to heart level, thereby applying hydrostatic pressure to the tissue bed, altering the venous return from the finger. Ultimately, this work will investigate whether there is an optimum hand position to observe venous-related variations in the PPG signal, and, hence, provide a method of venous oxygenation measurement.

2. METHODOLOGY

2.1 Photoplethysmographic Measurement System

The measurement system consisted of a two-channel custom made pulse oximeter unit [12] and the probes used were standard commercial transmission mode finger pulse oximeter probes (Masimo Corporation, USA). The instrumentation system consisted of two identical pulse oximetry channels. Each channel includes multiplexed current sources to drive the red (660nm) and infrared (940nm) light-emitting diodes (LEDs) with 25mA drive current. The output from the photodiode is passed to a transimpedance amplifier, then a demultiplexer to separate the signals into its red and infrared components. Both components are then passed to a low pass filter with pass band 0–40 Hz to remove switching artifact, coupled mains and other interference. These signals are subsequently referred to as red and infrared dc signals. The dc signals are then band pass filtered (passband: 0.4 – 17 Hz) and amplified in order to isolate the ac PPG signal. These signals are subsequently referred to as red and infrared ac signals. All four signals from each pulse oximetry channel were then digitized using a National Instruments PCIe-6321 16-bit data acquisition card (National Instruments Inc., Austin, TX, USA) using a sample rate of 1000 Hz.

2.2 Experimental Protocol

The protocol was approved by City University Senate Research Ethics Committee. Six healthy volunteers (3 male, 3 female, mean age: 29.7±7.3) with no history of cardiovascular or cardiopulmonary disorders were recruited to the study. Following an explanation of the investigations objective, informed consent was obtained from all subjects. Blood pressure was measured immediately prior to the measurement session. All investigations were carried out in a room with ambient temperature of between 19 and 20ºC.

Measurements were taken from the subject in a seated position. First, it was ensured that the subject was in a comfortable position, with both arms resting at 'heart level', i.e. level with the vertical mid-point of the sternum. The left arm was placed on a static support. A pulse oximeter probe was placed on the left middle finger and connected to a Masimo Radical 7 pulse oximeter (Masimo Corportation, USA). Another probe was placed on the left index finger and connected to the custom-made PPG measurement system.

The right arm was placed on an adjustable hand rest, initially at heart level. A pulse oximeter probe was placed on the right index finger and connected to the second channel of the custom-made PPG processing system. A laser Doppler flowmetry sensor (moorVMS-LDF2, Moor Instruments, UK) with skin temperature sensor was placed on the middle finger of the right hand. All signals were acquired, saved and displayed on a computer running LabVIEW.

Subjects were asked to practice timed breathing for one minute before commencing the measurements. To do this, they were asked to following a breathing rate timer displayed on the screen in front of them. The breathing rate timer was set for 12 breaths per minute in order to increase tidal volume.

While maintaining a constant breathing rate, measurements were taken from all subjects at different positions of the right hand. Initial measurements were taken at heart level (0 cm), before lowering the hand rest to -50cm below heart level. The hand rest was then subsequently moved up to -25cm, 0 cm, +25cm, +50cm, and, finally, 0 cm. All signals were recorded for two minutes at each interval, with 30 seconds allowed for transition between different heights.

2.3 Data Analysis

All signals were processed and analysed in Matlab (The Mathworks, Inc, USA). Red and infrared photoplethysmographic signals from both hands were low-pass filtered using a Type II Chebyshev filter with a cut-off frequency of 20Hz, with 60dB attenuation in the stop band. Ac and dc amplitudes were calculated using a 2 second rolling window. SpO_2 values were estimated using a typical equation in pulse oximetry:

$$SpO_2 = 110 - 25RR \hspace{4cm} (1)$$

where RR is the ratio-of-ratios calculated from the red and infrared ac and dc PPGs.

Figure 1. Red and infrared dc photoplethysmographic signals from the left and right hands for all positions of the right hand from Subject #2. Flux from the right hand is also given.
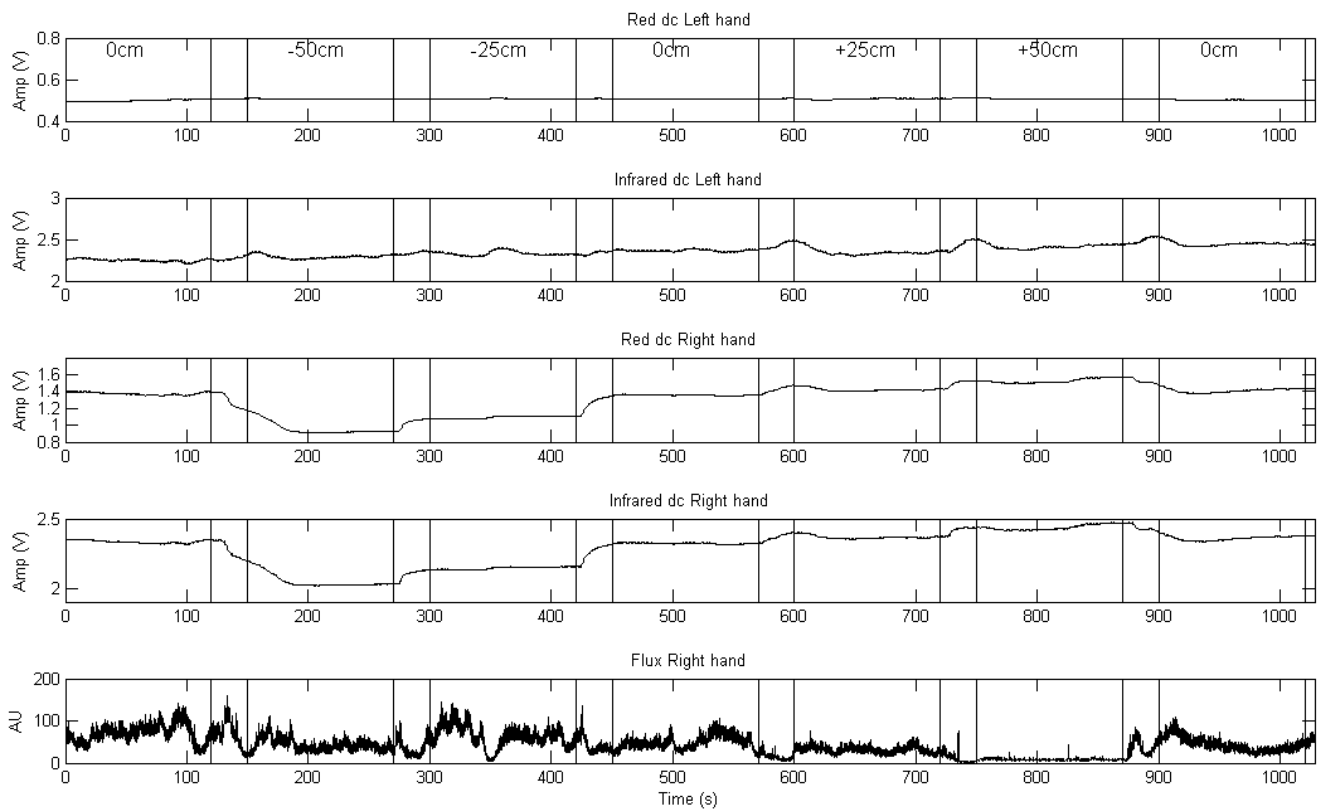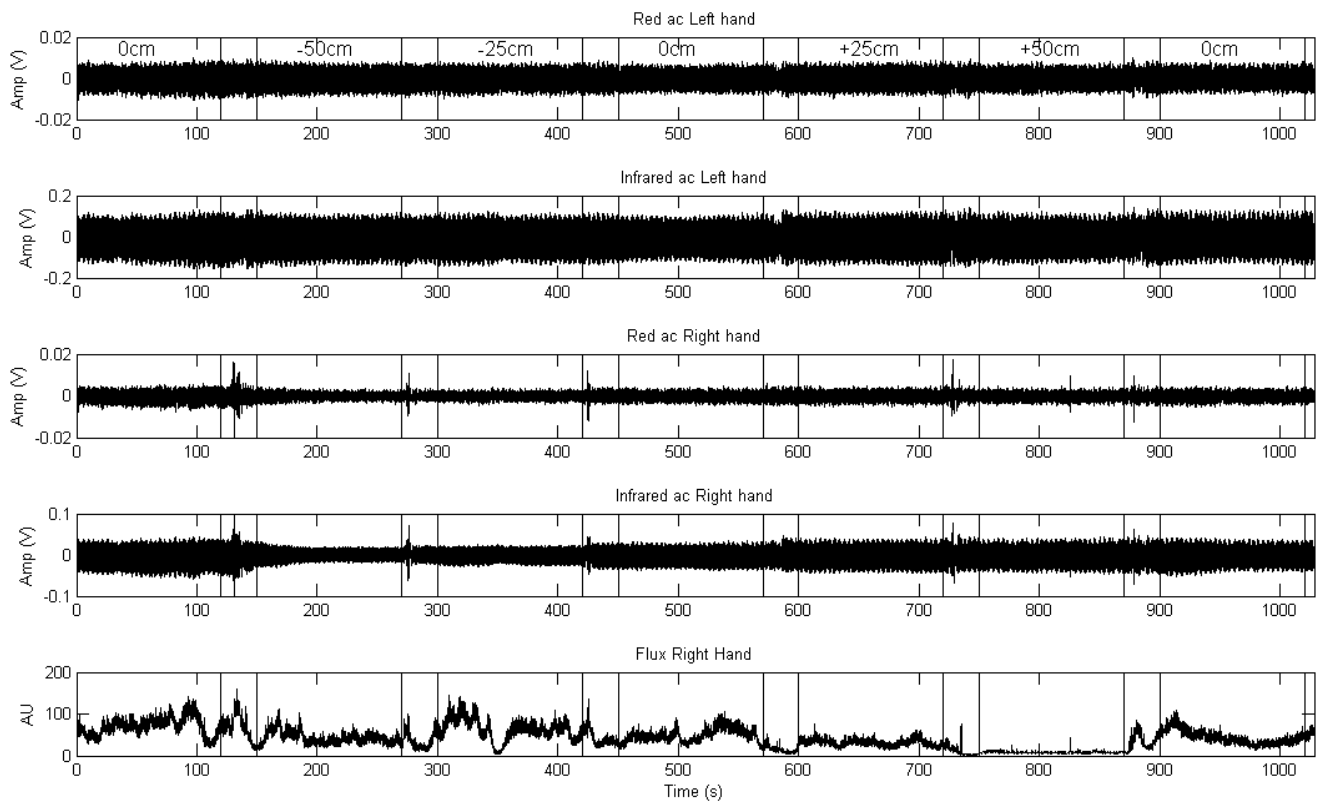
Figure 2. Red and infrared ac photoplethysmographic signals from the left and right hands for all positions of the right hand from Subject # 2. Flux from the right hand is also given.

3. RESULTS

All blood pressure readings taken prior to the measurement session were within the accepted 'normal' range. Figure 1 shows the acquired red and infrared dc PPG signals from the left and right index fingers and LDF signals obtained from one subject (Subject #2) over the course of the protocol. In this example, which is typical, it can be seen that the red and infrared dc PPG signals from the right finger change amplitude according to the position of the hand relative to heart position. There are noticeable step changes, when compared to the corresponding left finger signals, most obvious in the initial change from heart level to -50cm below heart level.

Figure 2 shows the acquired red and infrared ac PPG signals from the left and right index fingers and LDF signals obtained from the same subject (Subject #2) over the course of the protocol. It can be seen that the red and infrared ac PPG signals from the right finger change amplitude in accordance with the position of the hand relative to heart position. For the lowest position, ac PPG signals have the smallest amplitude. They then increase with corresponding increases in hand elevation. This phenomena was noted in 5 out of the six subjects.

In Figure 3, the mean ac and dc amplitudes for the acquired right hand PPGs across all subjects (n=6) for different hand positions are plotted. The mean (n=6) flux values for each position are also shown. It can be seen that the mean ac and dc amplitudes drop when the hand is lowered and then gradually increase as the hand is raised further. The flux right hand, as measured with laser Doppler flowmetry, shows reduced values for all positions compared with heart level.

Table 1 shows the mean SpO_2 across all subjects (n=6) estimated from the photoplethysmographs from the right and left fingers for all hand positions relative to heart level. It is important to note that these values are calculated from an uncalibrated system. However, it can be noted that the estimated values from the right finger vary much more across each subject than those from the left finger. In general, the greatest variation in measurement was observed when the hand is placed 50cm below heart level.
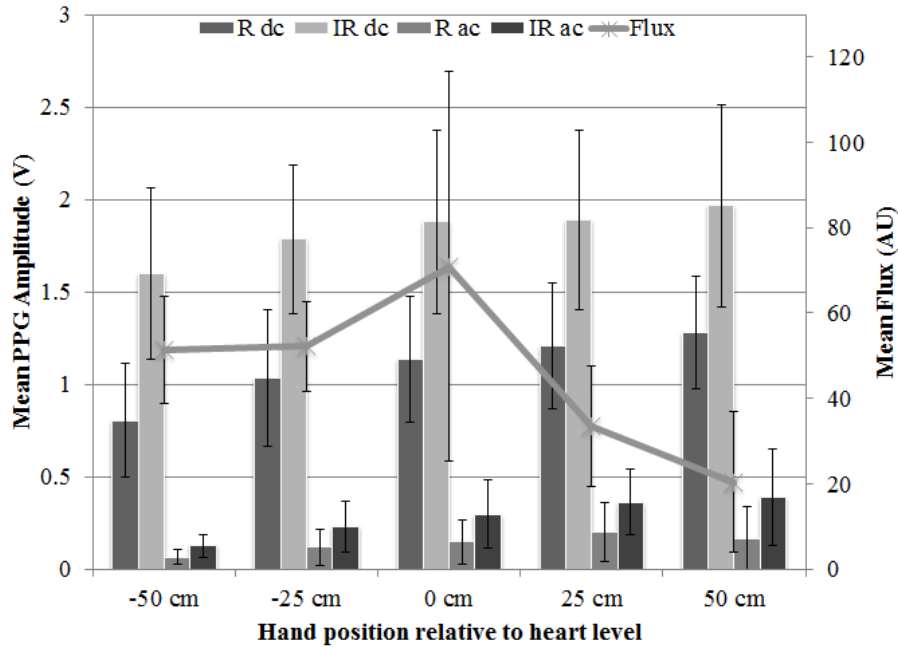
Figure 3. Mean red and infrared ac and dc amplitudes and mean flux for different positions of the right hand relative to heart level (0cm).

Table 1. Mean arterial oxygenation (SpO$_2$) values from the right and left hands for different hand positions.

Hand Position	Right SpO$_2$ (Mean ± SD)	Left SpO$_2$ (Mean ± SD)	Difference [R-L] (Mean ± SD)
-50cm	91.5 ± 9.2	100.1 ± 1.8	-8.5 ± 9.4
-25cm	96.3 ± 4.1	100.2 ± 1.7	-3.9 ± 4.6
0cm	97.9 ± 4.4	99.7 ± 1.7	-1.8 ± 3.7
+25cm	100.5 ± 2.1	99.9 ± 1.8	0.6 ± 1.3
+50cm	101.4 ± 3.2	100.0 ± 1.8	1.3 ± 2.1

4. DISCUSSION

This study demonstrates the effect of variations in hand position on acquired ac and dc PPG amplitudes. In all subjects, both the red and infrared dc amplitudes fell when the hand was lowered to 50 cm below heart level, and then increased as the arm was raised in steps of 25 cm. Furthermore, in five out of the six subjects, ac amplitudes followed the same trend.

By changing the position of the hand, hydrostatic pressure changes are induced in the tissue bed of the hand. In the lowered position, venous return is impeded, as the peripheral venous pressure is generally lower than the induced hydrostatic pressure, so blood pools in the veins, causing an increase in light absorption. This is seen as a decrease in the dc signal amplitude as this correlates with the intensity of light transmitted through the tissue. When the hand is raised, venous return is enhanced, and the dc signal level increases.

The reduction in arterial blood volume changes, as evident in the smaller ac PPG amplitudes obtained at 50cm below heart level, may be explained by an increase in effective downstream vascular resistance. Specifically the diastolic emptying of the arterioles is most likely mitigated by this effect. Similarly, the larger PPG amplitudes on arm raising may be due to decreased effective vascular resistance and increased venous return. The effect of the contribution of

venous blood to the photoplethysmographic signals may have an effect on the estimation of arterial oxygen saturation. As can be seen from Table 1, there was a noticeable variation in SpO$_2$ estimating when the hand was at 50 cm below heart level. It is hypothesized that this is due to inaccuracy caused by estimating oxygen saturations from such small signal amplitudes, particularly the red PPG signal.

This study will be furthered to include more subjects, and to provide a method of extracting venous information from the PPG. However, the results presented here suggest that changes in arm position may be exploited to produce estimations of peripheral venous oxygen saturation.

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