Instantaneous venous oxygenation estimation using Photoplethysmograph (PPG) waveform

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Abstract. In this study oesophageal photoplethysmograph data from eight patients under positive pressure ventilation was analysed to test the hypothesis that the modulations created by the ventilation in the AC PPG single could be used to estimate the venous saturation. In order to estimate the instantaneous arterial and venous saturation Smoothed-pseudo Wigner-Ville Distribution (SPWVD) was utilised. The result from this study showed that there was no significant different in the conventional (time domain) arterial saturation and the instantaneous arterial saturation. However, the instantaneous venous saturation estimated with the ventilator modulation were significantly lower then the conventional arterial saturation (P=0.008) and also from the instantaneous arterial saturation (P=0.008)

1. Introduction

In the last twenty years pulse oximeter has become one of the most commonly used medical devices in clinical environment [1]. In its most basic form the device is used to measure arterial saturation (SpO2) and heart rate (HR). However, the advancement of digital signal processing has allowed further in-depth analysis of Photoplethysmograph (PPG) signal resulting in extraction of information related to other physiological parameters e.g. respiration. In order to estimate SpO2 pulse oximeter relays on two conditions (1) pulsatile flow and (2) differential spectral absorbance [2]. Due to pulsatile flow the spectral absorbance of the tissue can be measured at maximum and minimum perfusion state. The change in the spectral absorbance profile of the tissue during this transition allows for the calculation of the spectral properties of the blood in motion, and hence its oxygen saturation.

In conventional pulse oximetry the pulsatile component (ac part of the PPG signal) is associated with the arterial blood. But in previous studies it has been shown that motion of venous blood can also be detected using the PPG signal. In most cases, this phenomenon is seen as a source of artefact which interferes with the estimation of arterial saturation [3]. However, by using the two conditions mentioned above for the estimation of SpO2 with this moving venous component the saturation associated with the venous blood can also be estimated. Reliable estimation of venous saturation simultaneously with arterial saturation, with the help of conventional pulse oximeter, can provide useful information about local oxygen extraction. This information may reflect adequacy of tissue perfusion in the area being measured. Real time non-invasive estimation of tissue perfusion would be beneficial in monitoring and detecting important clinical events such as early phases of shock. Also,

by measuring venous saturation at different sites such as ear forehead finger etc. it might be possible to estimate the true mixed venous saturation which is known to provide valuable clinical information. This study presents the results obtained from the analysis carried out on oesophageal PPG signals in order to estimate the instantaneous arterial and venous saturation. Before presenting the analysis method and results, some of the previous studies dealing with the estimation of venous saturation through the use of PPG signal will be discussed in the section.

2. Previous studies on estimation of venous saturation using PPG signals

One of the main problems in the estimation of venous saturation is the continuous and reliable detection of pulsatile venous blood component. In literature studies two different methods have been proposed to achieve this pulsatility by mechanically inducing volume variation in venous compartment. In two previous studies [4, 5] the volume in the venous compartment is increased by occluding the venous outflow using a pressure cuff. The saturation values are then estimated before and after the occlusion to detect the venous saturation. Significant correlation ($n = 19,\ r = 0.7,\ p < 0.0001$) was found when the venous saturation values obtained using this method were compared with the values obtained from co-oximetry (i.e., the gold standard in vitro method).

There are two major problems in estimating venous saturation with the help of venous occlusion. Firstly, the method does not allow continuous measurement of venous saturation as it relies on discrete interventions separated by enough time for the tissue to reach equilibrium. Secondly, use of this method for an extended period could lead to potential complications such as venous stasis, venous thrombosis, and interference with intravenous access. These deficiencies were address in another study [6] where a finger pressure cuff, driven by a pneumatic generator, was used to create low pressure modulations in the finger at a frequency that does not overlap with the frequency of cardiac signal and its harmonics. A conventional PPG probe was placed on the same finger distal to the cuff. The pressure cuff frequency was set at approximately 7.5 Hz. Using conventional frequency domain algorithms the arterial saturation was estimated with the values at the cardiac frequency (~ 1 Hz) and venous saturation is estimated using the values at pressure cuff frequency (~ 7.5 Hz).

The performance of this system was evaluated in patients undergoing cardiopulmonary bypass (CPB). The saturation values obtained with this method were compared with the saturation measured by the CPB machine on the blood that was travelling from the patient to the machine. Since the values obtained from the machine were indicative of central venous saturation it was not possible to perform a direct comparison with the values obtained from pulse oximeter setup as they represented peripheral venous saturation. However, similar changes were observed in both venous saturation values with changes in temperature, VO2, and cardiac index.

In all the studies described so far an external source (pressure cuff) was used to create pulsatile venous component however, in a more recent study [7] venous saturation was estimated by taking advantage of the fact that PPG waveform is influenced by both positive pressure ventilation [8] and the peripheral venous pulsations [9]. In this study analysis was carried out on PPG signals that were collected, using a special-purpose built PPG probe [10], in the oesophagus of ten patients undergoing coronary artery bypass surgery and postoperative care in the intensive care unit [11]. In order to estimate the arterial and venous saturation several time and frequency domain methods were employed. The time domain estimation is done in the conventional manner by calculating R (ratio of ratios) as presented in Eq. (1). Using the R value the saturation is estimated by employing the linear relationship presented in Eq. (2).

$$R = \frac{AC_{red}/DC_{red}}{AC_{ired}/DC_{ired}} \quad (1)$$

$$Saturation = 110 - 25R \quad (2)$$

In order to estimate the arterial saturation the numerator of the R (Eq. (1)) was calculated by dividing the peak-to-trough amplitude of the AC PPG waveform with the DC offset value for the red signal while , for the denominator the corresponding values associated with the infrared signal were used. In case of the venous saturation the AC_{red} and AC_{ired} were calculated by using the peak-to-trough amplitude of the DC PPG signal. The calculations of venous saturation were done in this way as the modulation in the PPG DC waveforms are dominated by the influence of the positive pressure ventilation. These modulations are thought to be due to the volume changes in the venous compartment. Thus, the saturation estimated using these values should be lower than the arterial saturation. Apart from these time domain measurements of arterial and venous saturation which were defined in terms of peak-to-trough values of the AC PPG signals relied an instantaneous saturation (InstSat) was also estimated. In this case at every time instance (t_k) a new saturation value was calculated by utilising an R value which was obtained as shown in Eq. (3).

$$R(t_k) = \frac{(AC_{red}\ (t_k) - AC_{red}\ \min)\Big/_{DC_{red}(t_k)}}{(AC_{ired}\ (t_k) - AC_{ired}\ \min)\Big/_{DC_{ired}(t_k)}} \qquad 3$$

Where $AC_{red}min$ and $AC_{ired}min$ in Eq. (3) represent the preceding trough values of the red and infrared AC PPG signal.

The InstSat was aimed to provide a moment-by-moment measurement of the average saturation of the blood in all the vascular compartments in the vicinity of the probe. One complication of InstSat calculated in this way was the fact that near the trough of the AC PPG signal the saturation values become unstable. This instability was dealt with in two steps. The saturation values were not updated (kept constant) at time instances where the numerator or the denominator of Eq. (3).becomes less than 0.03 (3%). The first step produced artefact in the saturation values at the point where the numerator or the denominator of Eq. (3) crosses the 3% criterion. Therefore, InstSat values within 0.5 s of this point were replaced by mean InstSat values. The resulting InstSat waveform was pulsatile with peaks approximately coinciding with the peaks in the AC PPG waveform. The envelope joining the peaks of the InstSat saturation was used as the arterial instantaneous saturation while the venous instantaneous saturation was obtained by creating the envelope by joining the troughs of the InstSat waveform. The results of the study showed that the venous saturation estimated using the time domain method and the instantaneous method both were significantly lower than the time domain arterial saturation.

These results provided evidence that it might be possible to utilize the modulations produced in the PPG signal due to positive pressure ventilation (breathing) to estimate the venous saturation. However, the instantaneous saturation estimation in time domain has stability issues. Therefore, to deal with these problems in this study the modulation due to the positive ventilation has been extracted from the AC PPG signal and then Smoothed-pseudo Wigner-Ville Distribution (SPWVD), which is a quadratic transform from Cohen's class [12], has been used to estimate the instantaneous arterial and venous saturations.

3. Methods

3.1. Subject and Protocol

In this study oesophageal PPG data from eight patients was analysed. This data was collected in previous studies [10, 13], after obtaining ethical approval, from ASA 1 and 2 adult healthy patients who underwent tracheal intubation as a routine part of general anaesthesia. Following induction of general anaesthesia the oesophageal probe was advanced under direct vision into the oesophagus until

the end of the probe was 25 to 30 cm from the upper incisors. The identical reflectance finger probe was also placed on the index finger of the patient.

3.2. Data Processing

In this section the steps involved in separating the ventilator modulation form the AC PPG signal and the estimation of instantaneous saturation will be discussed.

3.2.1. PPG peak detection

In order to detect the peaks and troughs of the ac PPG signals the first step was to detect peak frequency related to the cardiac frequency and then finding the frequencies on both side of this peak where the amplitude dropped to 10% of the amplitude at the peak frequency. This frequency range was considered to be the cardiac frequency band. A digital bandpass FIR (Finite Impulse Response) filter was then used to separate the cardiac frequency component of the PPG signal from the raw signal. An adaptive threshold was made by convolving the absolute values of the filtered signal with a square window of 80 samples (which is slightly less then the width of the PPG pulse at a sampling rate of 100 Hz). This threshold was used to detect the peaks of the AC PPG signal. A possible peak was detected in the region where the filtered signal crosses the threshold. The peak was considered to be a true PPG peak if it does not occurs within 0.2s of the previously confirmed PPG peak and its amplitude lays within 0.2 and 3 time the average amplitude, calculated from the last five of the last five correctly detected peaks. Similar technique was also used to detect the troughs of the PPG signal.

3.2.2. Instantaneous Saturation estimation

After detecting the peaks and troughs of the AC PPG signal an upper and lower envelope was constructed by joining the peaks and troughs using cubic spline interpolation. Using these upper and lower envelopes the mean envelope was constructed. This signal was used as the estimate of the ventilator modulation presented in the AC PPG signal and subtracted from the raw PPG signal to obtain the cardiac component which was used as the AC signal in estimation of arterial saturation.

After separating the venous and cardiac component SPWVD was used to estimate the instantaneous amplitude related to the AC venous, cardiac and the DC PPG signal. The derivation of the discrete SPWVD is presented in detail in the literature [14]. For a discrete sequence $s[n]$, the discrete SPWVD can be expressed as shown in Eq. (4).

$$SPWVD_x[n,k] = \sum_{l=-P+1}^{P-1} h[l] \sum_{lm=-Q+1}^{Q-1} g[m] \times r[n-m,l] e^{-j2lk\pi/M} \quad 4$$

Where $r[n,l] = s[n+l]s^*[n-l]$ is the instantaneous autocorrelation function. In this case the smoothing in the time direction is done using a window $g[m]$ of length $2Q+1$ and window $h[l]$ of length $2P-1$ is used for frequency smoothing. The signals were analysed in their analytical form. In this study both the time and frequency smoothing were done using Hamming windows 5.02 s and 10.02 s respectively.

3.3. Statistical test

A non-parametric test (Wilcoxon, signed rank test) was used to compare the time domain arterial saturation with the instantaneous arterial and venous saturation. Comparison was also made between the instantaneous arterial and venous saturation. The statistical analysis was carried out using SigmaStat 2.03 (Systat Software Inc., USA). The significance level was set at $P<0.05$ for all tests.

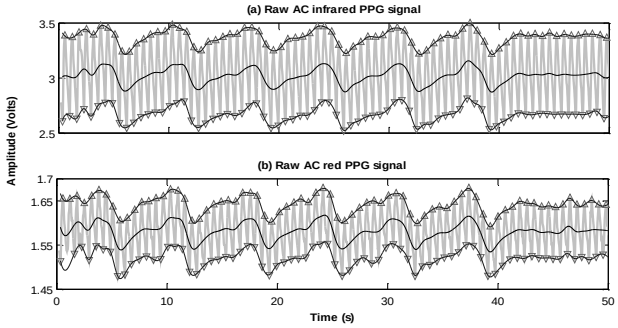

Fig. 2. Peak, trough detection and mean envelope detection results in one of the data set analysed in this study; (a) results from the infrared AC PPG signal; (b) results from the red AC PPG signal

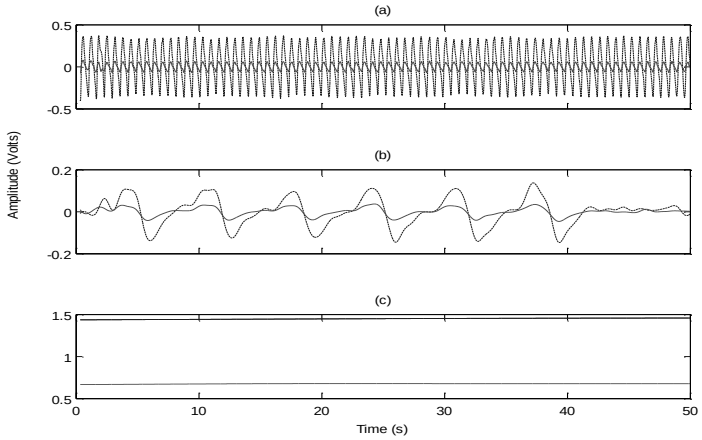

Fig. 1. (a) Signal obtained after subtracting the venous modulation from the raw AC PPG signals; (a) AC signals related to cardiac component; (b) Ac signal related to the venous component; (c) DC PPG signals. In Each part the infrared signal is presented with dashed lines while the red signal is presented with solid lines.

4. Results

The peak, trough detection and the estimation of mean envelop (ventilator modulation signal) results in red and infrared ac PPG signals in one of the signal analysed in this study are shown in Fig. 1. The ventilator modulation signal was subtracted from the raw AC signal as mentioned before. The resulting AC signals associated with the cardiac and ventilator modulation and the DC PPG signals which were used for the estimation of instantaneous arterial and venous saturation are shown in Fig 2.

The instantaneous arterial and venous saturation estimated from the signals shown in Fig. 2 are presented in Fig. 3. Figure 3(a) also showed the conventional time domain estimation of arterial saturation. From the result presented in this figure it can be seen that there is a close match between the time domain (average) and instantaneous arterial saturation values and also the instantaneous venous saturation shown in Fig. 3(b) are lower then the arterial saturation. It is also interesting to see that the venous saturation is showing slight changes synchronous with the ventilator frequency this also shows that the venous blood is moving due to the positive pressure ventilation.

4.1. Statistical test results

Statistical test was carried out using Wilcoxon Signed Rank Test. For the time domain arterial saturation the median and percentile (25% -75%) values were 98.1 (96.4 - 99.6) while the values for instantaneous arterial and venous saturation were 98.9 (95.3 - 100.4) and 82.5 (81.6 - 84.1)

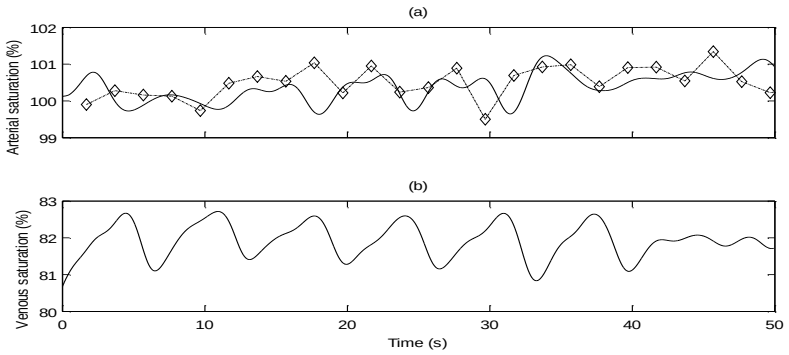

Fig. 3. Saturation results obtained from the signals shows in Fig. 1; (a) Conventional (time domain) arterial saturation (diamond marker with dashed line) and instantaneous arterial saturation; (b) instantaneous venous saturation

respectively. The results of the test showed that there was no significant difference between time domain and instantaneous arterial saturations while the venous saturation was significantly lower compared to the time domain arterial saturation (P=0.008) and also compared to the instantaneous arterial saturation (P=0.008).

5. Conclusion

In this study oesophageal PPG data was analysed to test the hypothesis that modulations produced ion the AC PPG signal due to positive pressure ventilation could be used to estimate the venous saturation. The result of the study showed that in the eight patients data that was analysed the ventilator modulation produced saturation which were constantly lower then the arterial saturation. Unlike previous study where instantaneous saturation estimated in the time domain required thresholding to deal with the instabilities near the troughs of AC PPG signal in this analysis the instantaneous saturation estimated with the help of SPWVD has no such issues. By avoiding these instability the slight changes cause in the venous saturation due to ventilation could be seen easily this could provide useful clinical information. Also, it provides a strong evidence of the hypothesis that positive ventilation causes movement in the venous compartment.

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