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Estimation of Venous oxygenation saturation using the finger Photoplethysmograph (PPG) waveform

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***Abstract*—In this study, finger photoplethysmograph data obtained from twelve patients undergoing cardiothoracic surgery were analyzed in order to estimate the venous saturation utilizing the modulations created by the positive pressure ventilation in the AC Photoplethysmograph (PPG) signals. The PPG signals were analyzed in the time-domain using a conventional pulse oximetry algorithm to produce estimations of arterial oxygen saturation. The instantaneous arterial and venous saturations were estimated by utilizing time-frequency analysis technique of Smoothed-pseudo Wigner-Ville Distribution (SPWVD). The results showed that there was no significant difference in the traditionally-derived (time-domain) arterial saturation and the instantaneous arterial saturation. However, the instantaneous venous saturation was found to be significantly lower than the time-domain estimated and instantaneous arterial saturation (P=<0.001).**

I. Introduction

THE pulse oximeter has become one of the most commonly used monitoring devices in the clinical environment [1]. Traditionally this device is used for the estimation of arterial oxygen saturation (SpO_2) and heart rate (HR). However, in recent years with the help of advanced digital signal processing techniques, information related to other physiological variables such as respiration has also been extracted from the Photoplethysmograph (PPG) signal [2]. In order to estimate SpO_2 the pulse oximeter relies on two conditions: (1) pulsatile flow and (2) differential spectral absorbance of two hemoglobin species: oxyhemoglobin and deoxyhemoglobin [2]. Due to pulsatile flow the spectral absorbance of the tissue can be measured at a 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 arterial blood; however, in previous studies [3], [4] it has been shown that motion of venous blood can also contribute to the PPG signal. In most cases, this phenomenon is seen as a source of artifact which interferes with the estimation of arterial oxygen saturation [3], [5]. However, by using the two conditions mentioned above with this moving venous component the saturation associated with venous blood can also be estimated. Reliable simultaneous estimation of venous saturation and arterial saturation, with the help of conventional pulse oximeter, can provide useful information about local oxygen extraction. This information may provide valuable information regarding the adequacy of tissue perfusion, indicating whether the supply of oxygenated blood is sufficient for the metabolic demands of the tissue in question. Real time non-invasive estimation of oxygen saturation would be beneficial in monitoring and detecting important clinical events such as early phases of shock.

In two previous studies [6], [7] the estimation of venous saturation was facilitated by mechanically inducing the pulsatility in the venous blood with the help of a pressure cuff. Even though the results from both studies showed that it was possible to estimate the venous saturation using the pulsatile venous component, the use of an external source (pressure cuff) for the creation of pulsatile venous component could restrict the use of such a technique to few peripheral measurement sites (e.g. fingers, toes). In a more recent study [8] venous saturation was estimated by taking advantage of the fact that the PPG waveform is influenced by both positive pressure ventilation [9] and peripheral venous pulsations [10]. In this study [8] analysis was carried out on PPG signals that were collected, using a purpose-built PPG probe [11], from the esophagus of twelve patients undergoing coronary artery bypass surgery and postoperative care in the intensive care unit [12], [13]. Walton *et. al*. [8] used several time and frequency domain methods to estimate the arterial and venous saturation. The time domain (traditional) estimation was done in the conventional manner by calculating *R* (ratio of ratios) as presented in Eq. 1. In the case of the arterial saturation the AC (red and infrared) part in Eq. 1 was due to the cardiac component present in the PPG signal while, in the case of venous saturation the ventilator modulation present in both the red and the infrared PPG signals was considered as the AC part. Using the *R* value the saturation is estimated by employing the linear relationship presented in Eq. 2.

$$R = \frac{AC_{red}/DC_{red}}{AC_{ired}/DC_{ired}} \tag{1}$$

$$SpO_2 = 110 - 25 \times R \tag{2}$$

For the estimation of instantaneous saturation (*InstSat*) at every time instance (t_k) a new saturation value was calculated

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by utilizing an *R* value which was obtained as shown in Eq. 3.

$$R(t_k) = \frac{(AC_{red}(t_k) - AC_{redmin})/DC_{red}(t_k)}{(AC_{ired}(t_k) - AC_{iredmin})/DC_{ired}(t_k)} \quad (3)$$

Where AC_{redmin} and AC_{redmin} 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 oxygen saturation of the blood in all the vascular compartments in the vicinity of the probe. The *InstSat* waveform was pulsatile with peaks approximately coinciding with the peaks in the AC PPG waveform. An upper and lower envelope was created by joining the peaks and troughs of the *InstSat* waveform. The peak envelope was used as the estimate of the instantaneous arterial saturation while the lower envelope was used as the estimate of instantaneous venous saturation. However, it can be seen from Eq. 3 that *InstSat* values near the trough of the AC PPG signal will become unstable. A thresholding and smoothing procedure was employed to deal with these large fluctuations (instabilities) in the saturation values.

In this study the finger PPG data from twelve cardiothoracic patients [12], [13] were analyzed for the estimation of venous saturation. The current study differs from Walton *et. al*. [8] work in two aspects. Firstly, in this study the finger PPGs (instead of esophageal PPGs) were analyzed. These PPGs experienced considerably less ventilator modulation compared to the esophageal PPGs. Secondly, in order to avoid the large fluctuations in the *InstSat* values as estimated by Walton *et. al*. [8] in this study the joint time-frequency analysis technique of Smoothed-pseudo Wigner-Ville Distribution (SPWVD) was used for the estimation of instantaneous arterial and venous saturation.

II. Methods

The steps involved in separating the venous modulation from the finger AC PPG signals and the estimation of instantaneous saturation will be described in detail in this section.

A. AC PPG signal peak and trough detection

In order to detect the peak and trough of the AC PPG signal the first step was to band pass filter the raw signal to reduce artifacts and isolate the cardiac component. This step was carried out by using a FIR (Finite Impulse Response) bandpass filter who's cutoff frequency was chosen by estimating the peak frequency (cardiac frequency) and then finding the frequencies on both sides of this peak where the amplitude dropped to 10% of the amplitude at the peak frequency. For the detection of the peaks an adaptive threshold was used which was created by convolving the absolute values of the filtered signal with a square window of 80 samples (which is slightly less than the width of the PPG pulse at a sampling rate of 100 Hz). A possible peak was detected in the region where the filtered signal crosses the threshold. After detecting a peak a refractory period of 0.2s was allowed and no peaks were detected during this time. Apart from occurring outside the refractory period the peaks were only considered valid if their amplitude laid within 0.2 and 3 times the average amplitude which was calculated from the last five correctly detected peaks. The troughs of the AC PPG signal were detected using a similar technique.

B. Instantaneous Saturation estimation

The peaks of the AC PPG signals were joined together using cubic interpolation to estimate an upper envelope. The detected troughs were connected using a similar procedure to obtain a lower envelope. These upper and lower envelopes were then used to estimate the mean envelope, which was then used as the estimate of the ventilator modulation presented in the AC PPG signal. This ventilator modulation signal was used as the AC component in the estimation of venous saturation. The instantaneous amplitude related to the AC cardiac, venous and the DC PPG signals were estimated by using SPWVD technique. For a discrete sequence $s[n]$, the discrete SPWVD [14], [15] can be expressed as shown in Eq. 4.

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

Where $r[n,l] = s[n+l]\, s^*[n-l]$ is the instantaneous auto correlation function. In Eq. 4 window $g[m]$ of length $2Q-1$ is used for smoothing in time direction while smoothing in the frequency direction is carried out using the window $h[l]$ of length $2P-1$. The signals were analyzed in their analytical form. In this study the time smoothing was carried out using a 5.05 second Gaussian window while a 10.05 second Hamming window was used for frequency smoothing.

C. Statistical test

A non-parametric test (Wilcoxon, signed rank test) was performed to check for statistically significant differences in the time domain arterial saturation, instantaneous arterial and instantaneous venous saturation values estimated using the finger PPG data from twelve cardiothoracic patients. The analysis was carried out using SigmaStat 2.03 (Systat Software Inc., USA). The significance level was set at P<0.05 for all tests.

III. Results

The estimation of the mean envelope (ventilator modulation) using the peaks and troughs detected in the AC PPG signals from data of one of the patients included in this study are shown in Fig. 1. The results from the infrared signal are shown in Fig. 1(a) while the results from the red signal are shown in Fig. 1(b). The mean envelope, which was used as the AC component in the estimation of the instantaneous venous saturation, shown as a dotted line in Fig. 1(a) and (b) were then subtracted from the raw AC PPG signals to obtain the arterial AC component. The cardiac and venous (ventilator modulation signal) AC PPG signals obtained from the raw signal and the corresponding DC PPG signals are shown in Fig. 2.

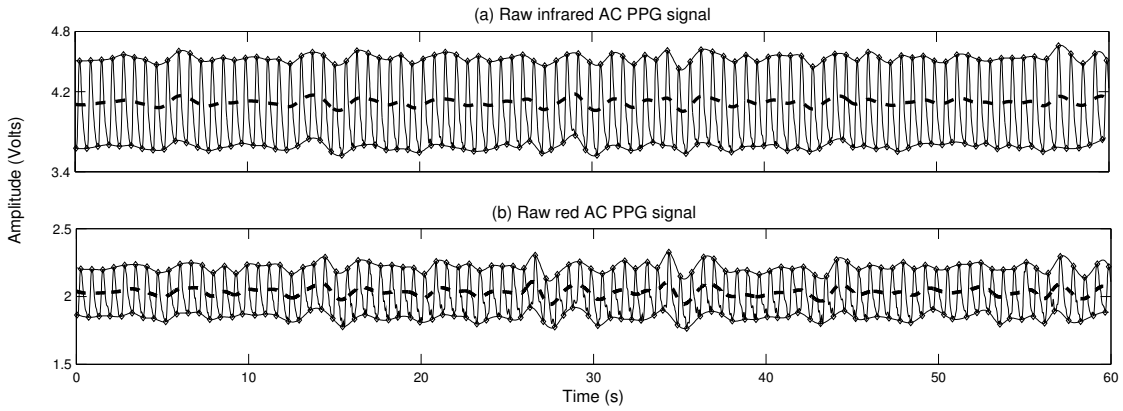

Fig. 1: Peak, trough detection and the estimation of the mean envelope (thick dotted line) in one of the data set analyzed in this study; (a) results from the infrared AC PPG signal; (b) results from the red AC PPG signal

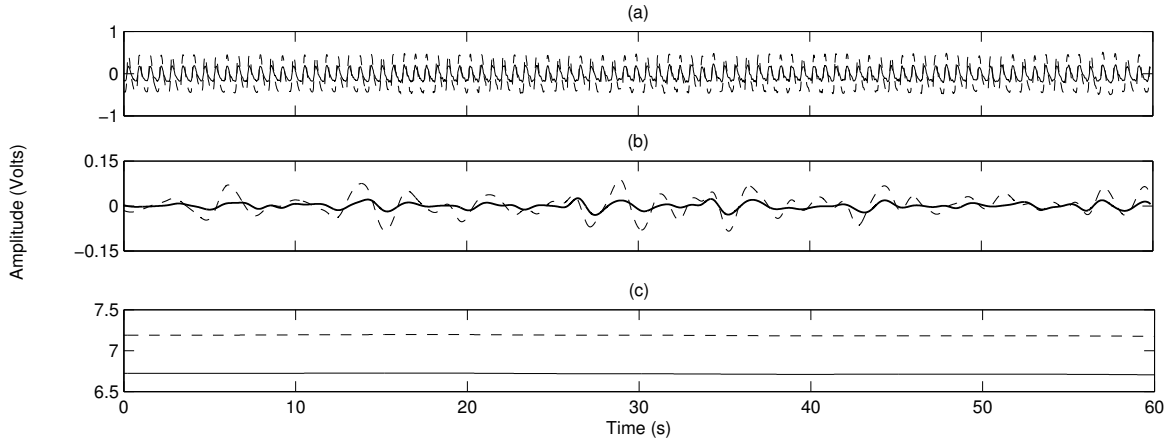

Fig. 2: (a) Arterial AC PPG signal obtained after subtracting the venous modulation from the raw AC PPG signals shown in Fig. 1; (b) AC signal related to the venous component (venous modulation); (c) DC PPG signals. In each part the infrared signal is presented with dotted lines while the red signal is presented with solid lines

Using SPWVD the instantaneous amplitude of the signals presented in Fig. 2 was obtained which was then used to estimate the instantaneous arterial and venous saturations. The traditional (time domain) arterial oxygen saturation was also calculated using the cardiac AC and the corresponding DC PPG signals. These time domain values were estimated after every two seconds. The instantaneous and traditional cardiac (arterial) saturation and instantaneous venous saturation values obtained from the data shown in Fig. 2 are presented in Fig. 3. From the result presented in Fig. 3 it can be seen that there is a close match between the time domain (average) and instantaneous arterial saturation values. Also, the instantaneous venous saturation shown in Fig. 3(b) is lower than the arterial saturation.

A. Statistical test results

A statistical test was carried out using Wilcoxon Signed Rank Test. For the time domain arterial saturation the median and percentile (25% -75%) values were 99.7 (99.3 - 100.6) while the values for instantaneous arterial and venous saturation were 99.7 (99.2 - 100.7) and 94.6 (94.2 - 95.5) respectively. A graphical representation of the results is shown in Fig. 4. 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 both the time domain (traditional) and instantaneous arterial saturations (P=<0.001).

IV. Conclusion

In this study finger PPG data collected from twelve patients undergoing cardiothoracic surgery were analyzed to validate the hypothesis that the modulations produced in the PPG signal due to positive pressure ventilation could be used to estimate venous saturation. The results of this study showed that in all twelve patients' the instantaneous venous saturations estimated with the ventilator modulation were constantly lower

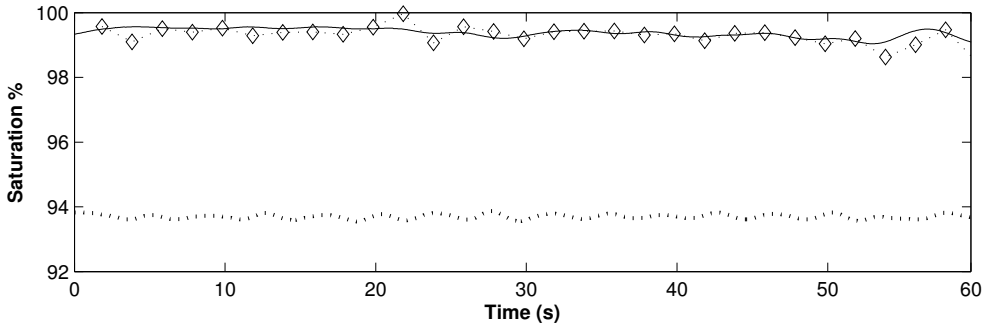

Fig. 3: Oxygen saturation values obtained from the signals shown in Fig. 2. Traditional (time domain) arterial saturation is shown in a dotted line with diamond markers. The instantaneous arterial saturation is shown as a thin solid line while the instantaneous venous saturation is shown in a thick dotted line

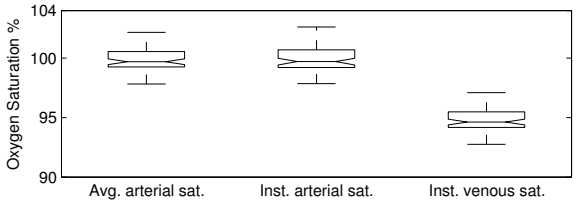

Fig. 4: Box-and-whisker plots showing the percentile (25% -75%) and range for the traditional arterial saturation (Avg. arterial sat), instantaneous arterial (Inst. arterial sat.) and instantaneous venous saturation (Inst. Venous sat.)

than the instantaneous arterial saturations. A major advantage of this study was the use of a joint time-frequency analysis method (SPWVD) for the estimation of instantaneous oxygen saturation values. This method was able to avoid the instabilities near the troughs of the AC PPG signal as encounter by Walton *et al.* [8] while estimating the instantaneous saturation in the time domain. By avoiding these instabilities and therefore the need of thresholding the instantaneous saturation values, the estimation technique used in this study could also reveal slight variations in the venous saturation caused by the ventilation which could provide useful clinical information.

It is important to note that arterial saturation values of slightly more than 100% as recorded in this study was due to the use of a custom made (not calibrated) PPG monitoring system. By using the method proposed in this study, estimation of regional venous saturation could be obtained. Regional venous saturation could be useful in some clinical settings for instance, given the predominate sympathetic innervation of the extremities; early signs of shock may be evident in the venous saturation of blood in the finger before other parts of the body are affected.

It is essential that the venous saturation values estimated with the technique proposed in this study should be compared with a gold standard, such as blood gas analysis or CO-oximetry before the venous saturation could be used for medical diagnosis. However, the results presented in this study provide evidence 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.

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