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Effect of respiratory-induced intensity variations on finger SpO_2 measurements in volunteers

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***Abstract*—Photoplethysmographic (PPG) signals were recorded from the fingers of 16 healthy volunteers with periods of timed and forced respiration. The aim of this pilot study was to compare estimations of arterial oxygen saturation (SpO_2) recorded using a dedicated pulse oximetry system while subjects were breathing regularly with and without a mouthpiece containing a flow resistor. The experiments were designed to mimic the effects of mechanical ventilation in anaesthetized patients. The effect of estimated airway pressures of ±15 cmH_2O caused observable modulation in the recorded red and PPG signals. SpO_2 values were calculated from the pre-recorded PPG signals. Mean SpO_2 values were 95.4% with the flow resistor compared with 97.3% with no artificial resistance, with statistical significance demonstrated using a Student's t-test ($P = 0.006$).**

I. Introduction

Despite the success of pulse oximetry as an invaluable monitor of arterial oxygen saturation, its limitations are well documented. In particular the accuracy of pulse oximeters may be affected by a wide range of factors including poor peripheral blood supply [1'], the presence of dysfunctional haemoglobins [2'], dark-colored nail polish [3'] and motion artifact [4'].

Many investigators have reported periodic variations in blood volume in the peripheral vascular bed due to respiration, evident as Respiratory-Induced Intensity Variations (RIIVs) on recorded photoplethysmography (PPG) signals during spontaneous and mechanical ventilation [5']. Canneson *et al.* noted that RIIVs of the PPG signal in ventilated patients reduces when intravenous fluids are given and quantified the variation by measuring the difference between maximum and minimum pulse oximetry plethysmogram amplitude (ΔPOP), i.e. $\Delta POP = POP_{max} - POP_{min.}$ They suggest that the ΔPOP variable may be used as an indication of 'fluid responsiveness' (the increase in blood pressure after administration of a given volume of intravenous fluid) [7]. Gesquiere et al. demonstrated that the respiratory modulation increases significantly when 450 mL of blood is removed from the patient [8].

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Pulse oximetry algorithms estimate arterial oxygen saturation (SpO2) from the red and infrared PPG signals. 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 venous blood, skin, muscle bone and pigments such as melanin [2]. As such, any variation in amplitude of the PPG signal has the potential to affect the reported SpO2 value, particularly if the RIIVs affect the red PPG is significantly more than the infrared PPG (or vice versa).

The aim of this study was to investigate the effects of respiration on the SpO_2 values estimated from PPG measurements in healthy volunteers. SpO_2 values measured while subjects performed periodic tidal breathing were compared with values recorded from the same subjects while performing periodic forced respiration.

II. Materials and Methods

A. Measurement system

The measurement system consisted of a custom made finger pulse oximeter. The probe is a standard commercial finger pulse oximeter probe (GE Datex-Ohmeda, Helsinki, Finland). The instrumentation system comprises multiplexed emitter drivers, which produce 40 mA and 25 mA drive current in the red (660 nm) and infrared (940 nm) LEDs contained within the probe.

The output from the photodiode is passed to a transimpedance amplifier, then a demultiplexer to separate the signals into two red and two infrared channels (four channels in total). One red and one infrared signal is high pass filtered using a 2^{nd} order Butterworth filter with -3dB cutoff frequency 0.38 Hz to isolate the PPG signal then passed to a low pass filter with pass band 0–23.4 Hz to remove switching artifact, coupled mains and other interference. These signals are subsequently referred to as AC_R and AC_{IR}. The remaining two signals were low pass filtered using a 2^{nd} order Butterworth filter with -3dB cutoff frequency 0.38 Hz. These signals are subsequently referred to as DC_R and DC_{IR}. All four signals were then digitized using two analog inputs of a National Instruments NI-6216 16-bit data acquisition card (National Instruments Inc., Austin, TX, USA) using a sample rate of 100 Hz.

A mouthpiece consisting of a narrow tube 8 cm long and 8 mm internal diameter was used as a flow resistor to allow significant airway pressures to be generated during forced

breathing. A port at the proximal (mouth) end was used to measure pressure at the mouth to give an estimation of large airway pressure. The port was connected to a signal conditioned 40PC001B1A pressure sensor (Honeywell Inc., Freeport IL, USA) via an airway gas sampling line of length 1.5 m and internal diameter approximately 2.4 mm. The red and infrared photoplethysmographic signals, together with airway pressure signals were recorded in a tab-delimited text file on a notebook computer running LabVIEW (National Instruments Inc.). During data acquisition, the respiratory pressures were displayed on a computer screen using a graphical 'slider' type indicator. This facility enabled subjects to vary their inspiratory and expiratory pressures to a prescribed pressure during forced breathing maneuvers (see next section).

B. Experimental protocol

The protocol was approved by City University Senate Research Ethics Committee. Measurements were made on 10 healthy volunteers (5M, 5F, mean age 33.6 years). Subjects were asked to refrain from smoking and caffeinated drinks for three hours prior to the study and were seated in a chair with the right hand resting on a table in front of them. The pulse oximeter probe was placed on the index finger of the right hand and a commercial pulse oximeter probe (Masimo Corp. Irvine, CA, USA) was placed on the right middle finger. Subjects were asked to breathe tidally at a rate of 10 breaths per minute for one minute. Subjects were then asked to breathe forcefully through the mouthpiece (containing flow resistor and proximally placed pressure sensor), at the same breathing rate, aiming for steady inspiratory and expiratory pressures of $-15\text{cmH}_2\text{O}$ and $+15\text{cmH}_2\text{O}$ respectively for a further minute. Optical signals from the finger probe and airway pressure were recorded on the notebook computer, while oxygen saturation readings on the commercial pulse oximeter were noted at the end of each maneuver.

C. Signal processing and statistical analysis

Oxygen saturation was calculated retrospectively from the recorded signals using the following method: the PPG signals (AC_R and AC_IR) were normalized by dividing by their respective DC signal (DC_R and DC_IR). The 'peak to valley' amplitudes of each cardiac cycle appearing in the signal AC_R and AC_IR were calculated using a peak and valley detection algorithm, with a width-rejection threshold of 20 samples, i.e peaks or valleys less than 20 samples wide were not recognised. This ensures that features such as the dicrotic notch do not cause underestimation of PPG amplitude. The peak to valley amplitude was taken as the difference in normalized amplitude between a peak and the valley immediately preceding it in the signal data (see Fig 1). The mean ratio of ratios $\overline{R_R}$ for each cardiac cycle was then calculated from the following:

$$\overline{R_R} = \frac{\sum_{i=1}^{N} \frac{|P_i - V_i|_R}{|P_i - V_i|_{IR}}}{N} \qquad (1)$$

where $|P_i - V_i|_R$ and $|P_i - V_i|_{IR}$ are the peak-valley differences for red and infrared PPGs respectively corresponding to the *i*th pulse beat in the dataset and *N* is the total number of beats in the dataset (approximately 60-80 beats present in one minute of data). The mean value of R_R was taken for each 60-second measurement period e.g. normal breathing, forced breathing. Oxygen saturation values were calculated for each period using the often-quoted equation used to calibrate Nellcor commercial pulse oximeters; a linear approximation of empirical data obtained from volunteer studies [11]:

$$\text{SpO}_2 = 110 - 25\overline{R_R} \qquad (2)$$

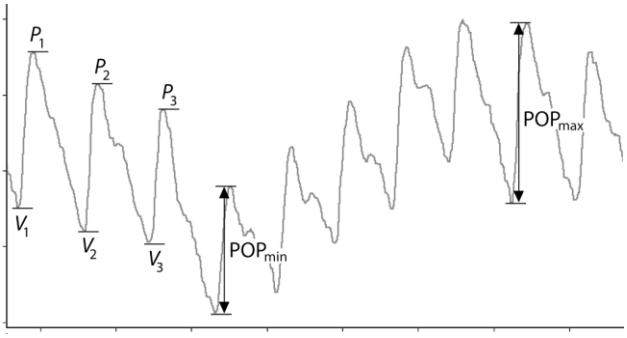

Figure 1. Scheme showing how PPG amplitudes (POP) fare calculated from peaks and valleys in the waveform signal.

The respiratory variation in pulse oximetry plethysmograph amplitude (ΔPOP) was also estimated from the coefficient of variation (CV) of the peak-valley amplitude divided by the mean peak-valley amplitude, i.e. for the red signal,

$$\Delta\text{POP}_\text{R} \approx \frac{\text{SD}(|P_i - V_i|_R)}{\text{Mean}(|P_i - V_i|_R)} \qquad (3)$$

and an equivalent equation was used for the infrared signal variation ($\Delta\text{POP}_\text{IR}$). Oxygen saturation ($\text{SpO}_2$) and respiratory variation in pulse oximetry plethysmograph for red and infrared signals ($\Delta\text{POP}_\text{R}$, $\Delta\text{POP}_\text{IR}$) were calculated and compared for the 60-second normal breathing and forced breathing measurement periods.

III. RESULTS

Figure 2 shows a 120-second sample of simultaneous red and infrared PPG signals and airway pressure recorded during 60 seconds of periodic normal breathing, followed by 60 seconds of forced periodic breathing in one subject (Subject #5). In this example, which is typical, it can be seen that the PPG signals appear to be modulated by respiration, both during normal and forced breathing. The modulations are noticeably stronger during forced breathing compared to normal breathing.

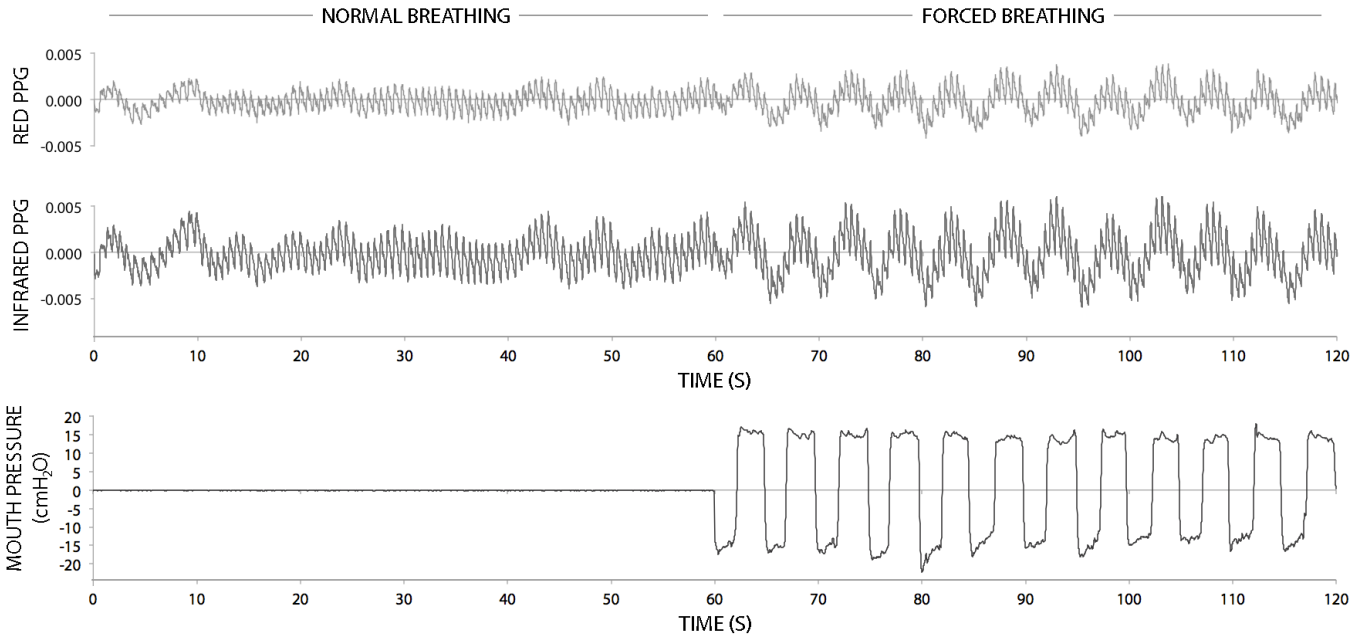

Figure 2. 120-second sample of simultaneous red and infrared PPG signals and airway pressure recorded during 60 seconds of periodic normal breathing, followed by 60 seconds of forced periodic breathing in one subject (Subject #5).

TABLE I. RESPIRATORY VARIATION IN PULSE OXIMETRY PLETHYSMOGRAPH AMPLITUDE (ΔPOP) DURING NORMAL AND FORCED BREATHING

Subject #	Normal Breathing		Forced Breathing	
	ΔPOP_R	ΔPOP_{IR}	ΔPOP_R	ΔPOP_{IR}
1	0.164	0.223	0.181	0.300
2	0.304	0.239	0.472	0.513
3	0.334	0.208	0.393	0.211
4	0.193	0.297	0.419	0.422
5	0.197	0.204	0.248	0.457
6	0.470	0.441	0.553	0.496
7	0.354	0.381	0.445	0.373
8	0.445	0.348	0.443	0.477
9	0.232	0.176	0.399	0.392
10	0.311	0.339	0.319	0.416
11	0.371	0.249	0.425	0.286
12	0.310	0.400	0.440	0.467
13	0.156	0.187	0.441	0.453
14	0.365	0.376	0.535	0.407
15	0.268	0.220	0.420	0.394
16	0.333	0.277	0.449	0.401
Mean	0.300	0.285	0.411	0.404

Table 1 shows the respiratory variation in pulse oximetry plethysmograph amplitude (ΔPOP) during for both red and infrared PPGs calculated during normal and forced breathing in each subject. The mean ΔPOP values for both red and infrared PPGs are considerably higher during forced breathing, indicating increased amplitude modulation of the PPG signals caused by variations in airway pressure.

Table 2 shows the arterial oxygen saturation (SpO_2) values calculated during the 60-second period of normal breathing and the 60-second period of forced breathing. It can be seen that during forced breathing, the mean SpO_2 for all subjects was 1.9% lower than during normal breathing. A paired a Student't t-test showed a significant difference in SpO_2 values measured during normal and forced breathing (P = 0.006).

TABLE II. ARTERIAL OXYGEN SATURATION (SpO_2) VALUES CALCULATED DURING NORMAL AND FORCED BREATHING

Subject #	Normal Breathing	Forced Breathing	Difference
	SpO_2 (%)	SpO_2 (%)	[F–N] (%)
1	97.7	95.6	-2.1
2	98.6	95.4	-3.2
3	98.3	93.7	-4.6
4	96.1	95.9	-0.2
5	96.6	97.6	1.0
6	95.0	92.2	-2.8
7	99.7	93.8	-5.8
8	96.0	95.6	-0.3
9	95.5	95.5	0.0
10	97.4	98.8	1.4
11	98.3	91.1	-7.2
12	97.6	96.4	-1.2
13	95.8	95.3	-0.5
14	99.9	99.2	-0.7
15	96.1	93.7	-2.4
16	97.6	95.9	-1.7
Mean (±SD)	97.3(±1.46)	95.4(±2.13)	-1.90(±2.38)

IV. Discussion

This study clearly demonstrates the effect of variations in airway pressure on recorded PPG signals. The Respiratory-Induced Intensity Variations (RIIVs) were quantified by comparing the ΔPOP values during normal and forced breathing. As may be expected, RIIVs are greater when the variations in airway pressure are significant. Although there was airway pressures during the (periodic) normal breathing were not measured, no doubt there were differences in expiratory and inspiratory pressures. It is almost certain that the pressures were much less than those recorded during the forced maneuvers however.

The reduction in apparent oxygen saturation once forced breathing commences may certainly be attributed to measurement artefact rather than physiological effects. This assumption is valid as it is extremely unlikely that forced breathing would produce desaturation. This finding has potentially serious implications for monitoring ventilated patients, particularly when using high positive airway pressures as erroneous oxygen saturation readings may be reported. Although underestimation of SpO_2 is less serious than overestimation, any error should be considered. Indeed this effect could contribute to the generally accepted (in)accuracy of pulse oximeters, which is usually reported to be within the order of 3%, a value which if improved could further enhance the utility and reputation of pulse oximetry in clinical practice.

The effect on the PPG signals and oxygen saturation of airway pressures other than ±15 cmH_2O were not investigated in these studies, neither were the individual effects of inspiratory (negative) and expiratory (positive) pressures on the PPG. Further studies are thus planned to investigate these effects, both in volunteers and in ventilated anesthetised patients.

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