

Effect of respiratory-induced intensity variations on finger SpO₂ measurements in volunteers

Justin P. Phillips, *Member, IEEE*, Alla Belhaj, Richard M. Langford,
and Panayiotis A. Kyriacou, *Senior Member, IEEE*

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 (SpO₂) 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 anesthetized patients. The effect of estimated airway pressures of ± 15 cmH₂O caused observable modulation in the recorded red and PPG signals. SpO₂ values were calculated from the pre-recorded PPG signals. Mean SpO₂ 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 hemoglobins [2-3], dark-colored nail polish [4] and motion artifact [5].

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 [6]. Cannesson *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 (Δ POP), i.e. Δ POP = POP_{max} - POP_{min}. They suggest that the Δ POP 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].

Pulse oximetry algorithms estimate arterial oxygen saturation (SpO₂) from the red and infrared PPG signals.

J. P. Phillips and P.A. Kyriacou are with the School of Engineering and Mathematical Sciences, City University London, EC1V 0HB, UK (e-mail: Justin.Phillips.1@city.ac.uk)

A. Belhaj and R. M. Langford are with the Pain and Anaesthesia Research Centre, St Bartholomew's Hospital, London, EC1A 7BE, UK.

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 [9]. 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 significantly more than the infrared PPG (or vice versa).

The aim of this study was to investigate the effects of respiration on the SpO₂ values estimated from PPG measurements in healthy volunteers. SpO₂ 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 2nd 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 2nd 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 16 healthy volunteers (6M, 10F, mean age 29.3 y). 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 left hand. Subjects were asked to breathe tidally at a rate of 12 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 cmH₂O and $+15$ cmH₂O 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 Figure 1). The mean ratio of ratios \overline{R}_R for each cardiac cycle was then calculated from the following:

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

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 [10]:

$$SpO_2 = 110 - 25\overline{R}_R \quad (2)$$

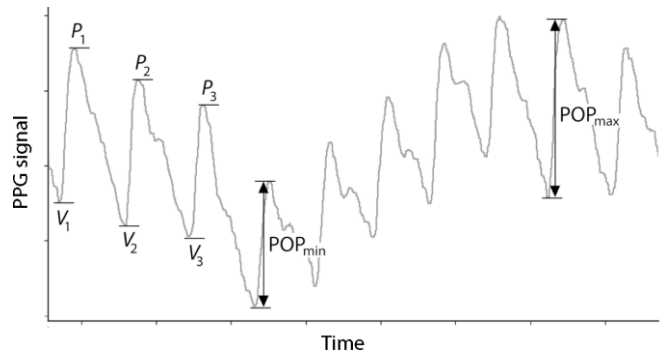


Figure 1. Scheme showing how PPG amplitudes (POP) are calculated from peaks (P_1, P_2 etc.) and valleys (V_1, V_2 etc.) in simulated waveform signals.

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,

$$\Delta POP_R \approx \frac{SD(|P_i - V_i|_R)}{\text{Mean}(|P_i - V_i|_R)} \quad (3)$$

and an equivalent equation was used for the infrared signal variation (ΔPOP_{IR}). Oxygen saturation (SpO_2) and respiratory variation in pulse oximetry plethysmograph for red and infrared signals ($\Delta POP_R, \Delta POP_{IR}$) 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.

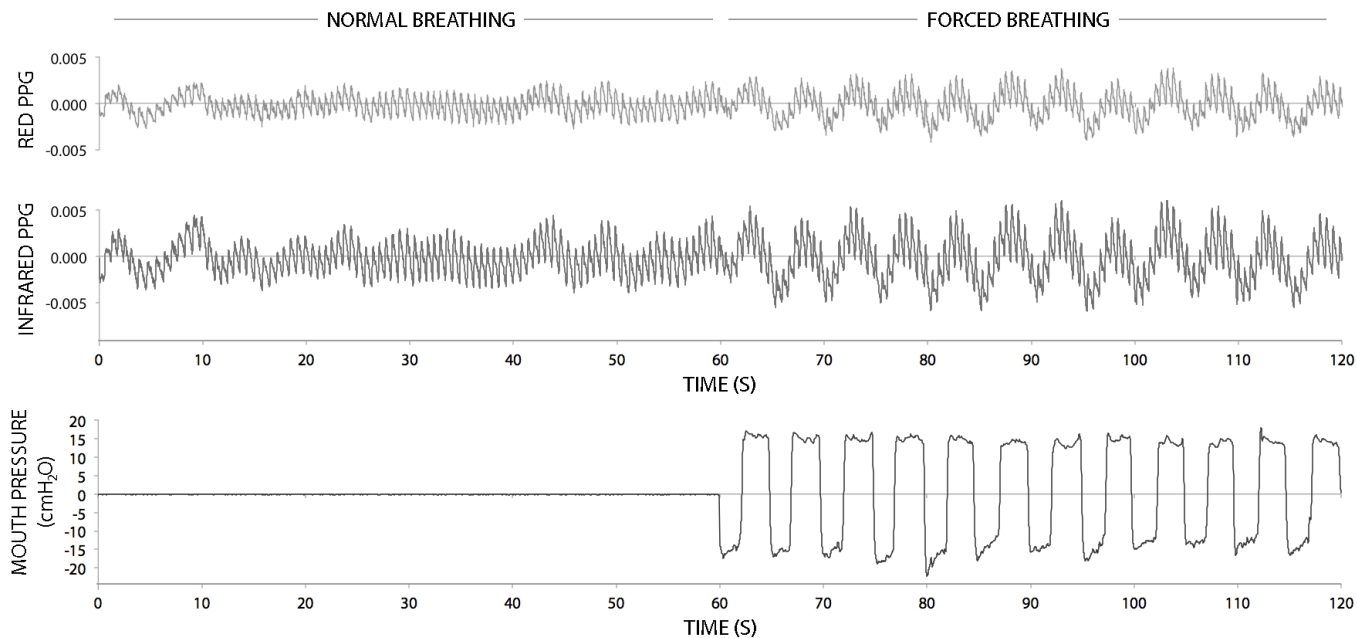


Figure 2. 120-second sample of simultaneous red and infrared PPG signals and airway pressure recorded during 60 seconds of periodic normal breathing, followed by 60 seconds of forced periodic breathing in one subject (Subject #5).

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

| Subject # | Normal Breathing | | Forced Breathing | |
|-------------|---------------------------|----------------------------|---------------------------|----------------------------|
| | Δ POP _R | Δ POP _{IR} | Δ POP _R | Δ POP _{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 (Δ POP) for both red and infrared PPGs calculated during normal and forced breathing in each subject. The mean Δ POP 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's 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 [F-N] (%) |
|----------------------------------|-------------------|-------------------|----------------------|
| | SpO_2 (%) | SpO_2 (%) | |
| 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 (\pmSD) | 97.3(\pm 1.46) | 95.4(\pm 2.13) | -1.90(\pm 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 Δ POP values during normal and forced breathing. As may be expected, RIIVs are greater during forced breathing than during unforced breathing. Although airway pressures during the (periodic) normal breathing were not measured, it is highly likely that the pressures were much less than those recorded during the forced maneuvers.

The reduction in apparent oxygen saturation once forced breathing commences may certainly be attributed to measurement artifact 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 SpO₂ 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 cmH₂O 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 anesthetized patients.

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