Pilot investigation of anterior fontanelle photoplethysmographic signals and their suitability in estimating arterial oxygen saturation

J. M. May, P. A. Kyriacou, *Senior Member, IEEE*, A. J. Petros

Abstract— **There is a need for more reliable, non-invasive and alternative measurement sites for the monitoring of arterial blood oxygen saturation in critically ill newborns at times of peripheral compromise. A pilot investigation on 14 Intensive Care Unit (ICU) newborns was conducted utilizing custom-made reflectance photoplethysmographic (PPG) sensors placed at the fontanelle and foot. The results suggest that the fontanelle is sensitive to changes in saturation, where saturation values obtained from the custom sensor were compared against commercial pulse oximeter values and results from a blood gas analyzer, however careful placement of the sensor at the fontanelle is an issue that needs further investigation.**

I. INTRODUCTION

Neonatal intensive care relies on constant monitoring of the vital signs of the baby. One of such vital signs is the pulse oximeter which is responsible for the continuous non-invasive estimation of arterial oxygen saturation (SpO_2).

In the newborn it has been shown that at times of periphery supply compromise, such as the onset of hypovolaemia, hypothermia or septicaemia, the pulse oximeter can become unreliable or fail [1 − 5].

The cause of these inaccuracies and failures are due to the fundamental principal on which pulse oximeters work; pulsatile blood at the area of measurement, typically a hand or foot, is detected by a dual-wavelength light source (red and infrared light emitting diodes) and photo detector (a photodiode or phototransistor). The different wavelengths of light are absorbed differently by oxygenated haemoglobin (HbO_2) and deoxygenated haemoglobin (Hb) and the detected intensities are modulated by the pulsatile arterial blood, this modulation is then used to determine what percentage of HbO_2 is present within the arteries. This method of measurement is known as photoplethysmography (PPG). Conditions such as hypovolaemia and hypothermia can cause vasoconstriction at the limbs, which can cause a compromise of blood flow to the periphery, and thus the PPG signal needed for SpO_2 calculation diminishes, and the pulse oximeter may report an incorrect SpO_2 value. It is at these times that a constant SpO_2 reading would be the most beneficial, as an estimation of oxygenated blood may be useful in treatment and diagnosis without having to run a separate blood-gas analysis test, as this takes time and may be obtrusive, especially if the patient has no arterial line present.

It has been proposed that the anterior fontanelle (AF), the soft area of unformed skull on a newborn, be used as an alternative site for saturation monitoring. The hypothesis underlying this is that the blood supply is preferentially preserved in the head and the brain at times of peripheral supply compromise, as the body tries to protect the most vital organs. With no obstruction offered by any bony material, it is theorised that the AF can be used as an optical window where both red and infrared light can be used to make PPG measurements at a point below the scalp to directly monitor saturation. Other studies into SpO_2 readings from the core of the neonate would also support this [6].

Previous measurements have been made from the head in both adults and neonates [7 − 8], but were limited to either the forehead or the earlobe. When the fontanelle is mentioned [9] the work done has been solely focused on ascertaining at what locations of the neonatal scalp would be best suited for intrapartum monitoring, that is monitoring the unborn foetus during labour, using the neonate as a direct analogue model. This study commented that although AF signals were present they suffered from an artefact that they attributed to the pulsations visibly present on the AF, and were therefore unsuitable for SpO_2 monitoring. However preliminary work we have conducted has shown [10] that with careful

instrumentation and sensor design these artefacts can be avoided, and an estimate of SpO_2, close to that of the commercial devices, can be made.

We are presenting our preliminary findings on AF PPGs and SpO_2s on a group of patients on a neonatal ICU

II. METHOD

A. Instrumentation

A reflectance fontanelle PPG sensor has been designed and developed utilizing miniature optical components. The technical details of this sensor have been described previously [11]. An identical (optical and electrical) foot PPG sensor was also developed in order to provide PPG comparison studies between the two sites. A dual channel PPG processing system was also developed to detect and pre-process all acquired PPG signals (fontanelle and foot) simultaneously [11]. All PPG signals were digitized using a 16-bit data acquisition card (USB-6212, National Instruments, USA). A Virtual Instrument (VI) implemented in LabVIEW (National Instruments, USA) was developed to acquire, display (on a laptop computer) and archive all PPG signals. Algorithms were also developed for the real time estimation of SpO_2 from both sensors.

B. Clinical Measurements

Patients were selected from the neonatal ICU at Great Ormond Street Hospital for Children (London, UK).

To provide a baseline reading of arterial oxygen saturation (SaO_2) patients were selected only if an arterial line was present, this would negate the need to perform any potentially uncomfortable procedure that would otherwise be unnecessary to the care of the patient. Parents of 14 patients (9 male, 5 female) were approached and informed of the study, and consent was obtained before the commencement of the trial. The start of the trial was timed with a routine blood gas analysis. The sensors were cleaned at the bedside with alcohol wipes before being placed within a sterile clear adhesive pocket constructed from two Tegaderm sheets (3M Corporation, MN, USA). The instrumentation was switched on prior to placement of the sensors to help locate an optimum position of the sensor over the AF. The sensor was kept flat to the head by a head bandage wrapped around the jawline or back of the skull. The sensors were then left in-situ for up to a maximum time of two hours so that the signals obtained could be compared to any other routine blood gas analysis being taken. Throughout the study, SpO_2 information from the commercial pulse oximeter was noted and matched against SpO_2 values simultaneously recorded by the custom made fontanelle and foot sensors. Figure 1 shows the AF sensor in-situ on a male patient.
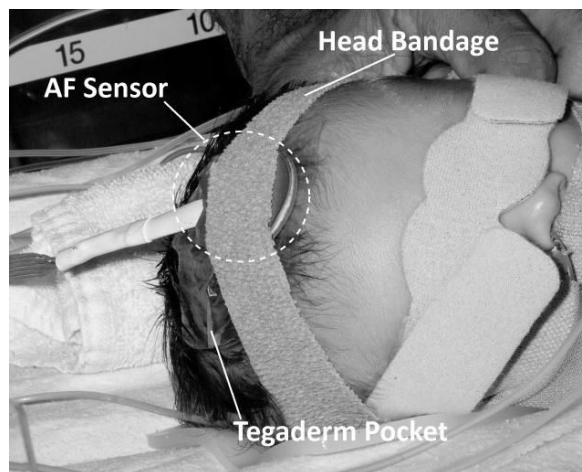

Fig 1: AF sensor in-situ on a male patient.

III. RESULTS

Photoplethysmographic signals were obtained from the AF for a total of 8 hours 4 minutes 29 seconds, with an average measurement period (SD minutes, seconds) of 32 minutes 56 seconds (SD 20 minutes 55 seconds). The mean weight (kg) and age (days) (±SD) of the patients were 3.20 kg (± 0.87), and 38.71 days (± 49.59) respectively. 27 blood samples were taken at an average of two samples per child (±1), using an i-STAT Handheld (Abbott Laboratories, IL, USA).

Figure 2 is a typical 20 second sample of an AF PPG signal, displayed simultaneously with the signal from the foot.

Signals were post-processed and analyzed using MATLAB (The Mathworks, USA). These include, re-sampling and digital filtering to remove aliasing, high frequency noise and respiration/ventilator artefact Also, custom made algorithms were also developed in MATLAB to calculate amplitudes and SpO_2s. The AF AC PPG signal analysis is shown in table 1.
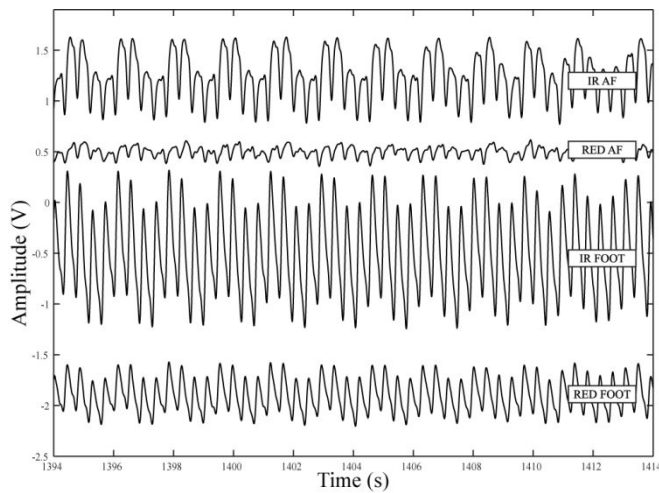
Fig 2: 20 Second RED and IR PPG sample from the foot and fontanelle Simultaneously, HR = 141 bpm, RR = 35. The modulation comes from the rapid respiration of the newborn.
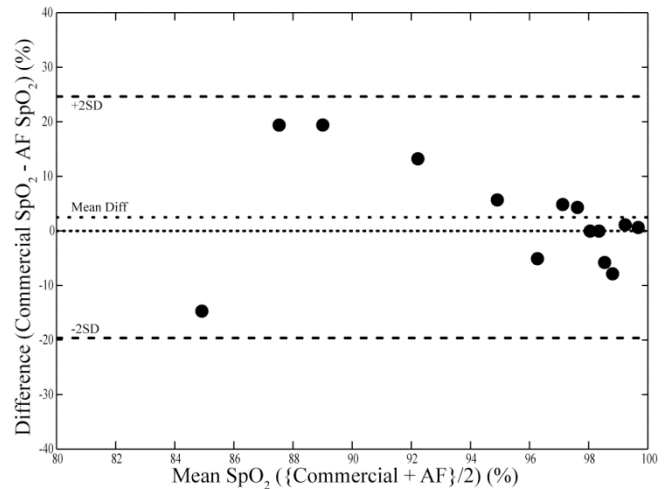

Fig 3: Bland-Altman plot comparing the AF saturation readings with the commercial saturation reading for all 14 patients.

Patient #	Age (Days)	Weight (kg)	Mean AF RED AC Amp (mV)	Mean AF IR AC Amp (mV)
1	5	2.80	1.58	3.89
2	115	3.20	0.64	3.43
3	4	3.20	1.01	3.33
4	7	1.14	0.94	7.91
5	30	2.80	0.98	1.72
6	3	3.00	0.62	1.22
7	36	2.30	1.45	3.92
8	88	3.70	1.70	2.79
9	56	4.95	1.62	5.79
10	161	3.99	2.06	7.09
11	3	3.10	0.66	1.67
12	6	3.90	0.88	2.90
13	24	3.45	1.24	3.19
14	4	2.80	0.69	1.96
Mean	38.71	3.20	1.15	3.63
SD	49.59	0.87	0.46	2.02

Table 1: AF AC PPG amplitude signal analysis.

Estimation of blood oxygen saturation was performed using a linear approximation equation (1), taken from [12];

$$SpO_2 = 110 - 25R \qquad (1)$$

where R is the ratio of ratios of the RED and IR, AC and DC PPG signals,. A between-method difference analysis, [13] was constructed of the mean SpO_2 readings from the individual patients for the AF and the commercial pulse oximetry sensor (see figure 3).

The mean and standard deviation of the SaO_2 and SpO_2 values were calculated across the entire data set, and this is shown as a histogram in figure 4.
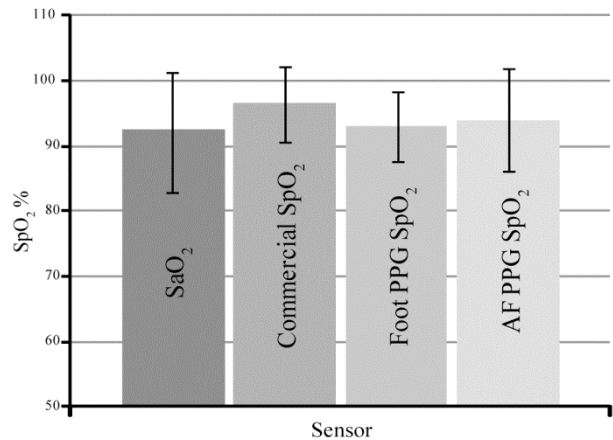

Fig 4: Histogram noting the mean and standard deviation of the SaO_2 and SpO_2 values obtained from all 14 patients using the commercial and custom pulse oximetry sensors

IV. DISCUSSION

Good quality AF PPGs with good signal to noise ratio were obtained with relatively little effort after successful placement of the sensor. Some difficulty was experienced by the clinician when trying to make the sensor lie flat on the AF when the patient had medium to thick hair covering, as the adhesive properties of the clear pouch had little effect when direct contact with the scalp was not possible. The amount of hair present, however, did not seem to inhibit the acquisition of PPGs.

Table 1 demonstrates that older and heavier neonates tend to have larger overall PPG amplitudes for both IR and RED AC signals, as would be expected, however it was noted by the clinician in trials that some newborns had

larger or smaller than average fontanelles, and this may be one cause for the large standard deviation of the amplitudes. AF sensor placement may also not have always been consistent, and the general health of the child may also be a contributing factor. When calculating SpO_2 the smallest amplitudes did present a problem when performing calculations, as the difference between AF SpO_2 and commercial SpO_2 was relatively large. This may be due to hardware limitations at detecting such small amplitudes with adequate resolution, or there may have been a placement issue again that was previously thought to be adequate.

The Bland-Altman plot in figure 3 seems to reveal close agreement between the commercial and AF sensor at high SpO_2 values (> 94 %), at lower values we see larger differences, but all values do fall within the 2 standard deviation (±95 % of the mean difference) upper and lower bounds. This could be explained by the fact that the developed equipment was un-calibrated for SpO_2 measurements, and the linear equation (1) used to calculate SpO_2 offline is unsuitable for low saturation values.

V. CONCLUSION

Contrary to what has been reported previously [9], PPGs from the fontanelle for this pilot study were of reasonable quality to estimate SpO_2. This warrants further trials and different setups to ascertain the optimal positioning of the sensor. Limiting factors such as the hair covering the scalp can be overcome but new methods of sensor attachment need to be investigated in order to make the use of such sensors more practical. More clinical trials trials need to take place in order to test the AF sensor at times of peripheral perfusion compromise.

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