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Development of an Optoelectronic Sensor for the Investigation of Photoplethysmographic Signals from the Anterior Fontanel of the Newborn

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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. The anterior fontanelle, a unique anatomical feature of the newborn, has been presented as an alternative site for the estimation of oxygen saturation. A multi-wavelength non-invasive optoelectronic sensor has been designed and developed for the investigation of photoplethysmographic (PPG) signals and blood oxygen saturation values from the fontanelle. *In vivo* thermal tests of the optical sensor show that under normal operating conditions the heating at the skin surface was negligible (<0.1°C). Good quality PPGs with large amplitudes and high signal to noise ratio were recorded at all three (red, infrared and green) wavelengths prior to clinical measurements.**

I. Introduction

Pulse oximeters are widely used in neonatal anaesthesia and intensive care but they have some severe limitations. The technique relies on the presence of adequate peripheral arterial pulsations, which are detected as photoplethysmographic signals (PPG). When peripheral perfusion is poor, as in states of hypovolaemia, hypothermia, vasoconstriction, and low cardiac output, seen typically in meningococcal septicemia, oxygenation readings become extremely unreliable or cease [1 - 4]. The problem arises because conventional sensors must be attached to the most peripheral parts of the body, such as the finger or toe, where pulsatile flow is most easily compromised. Hence, pulse oximetry becomes unreliable in a significant group of neonates just at the time when accurate readings are most needed. To overcome this limitation, the anterior fontanelle is proposed as a potential measurement site on the hypothesis that perfusion may well be better preserved at this central site.

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The fontanelles, commonly referred to as the "soft-spots" on the new-born baby's head, are features that allow the skull to flex during labor so that the baby can pass through the birth canal. There is no bone present at these sites, only a thin membrane and the skin on the scalp protects the brain from direct contact. The largest of the fontanelles is the anterior fontanelle (AF) situated on the midline between the coronal and sagittal sutures [5]. Running directly beneath the AF is the sagittal sinus. The fontanelle does not fully close, usually, until about eighteen months after birth. It is surmised that these unique properties will allow the AF to be utilized as an optical window (ultrasonic monitoring already makes use of the AF as an acoustical window to make scans) to the brain for measuring PPGs and therefore enable the estimation of SpO_2 continuously and non-invasively.

An earlier study looked at obtaining PPGs from the scalp of the neonate [6], and included the AF as a study site; however the results were inconclusive as they could not determine whether the signals received were from the scalp or from deeper underlying tissues. It was concluded that pulsations from the sagittal sinus may have been a source of error that influenced the signals received from the scalp at the AF. Considering this, we have surmised that if pulsations are coming from the sagittal sinus, then new information may be gathered from the PPG that goes beyond the standard SpO_2 measurements.

Discussions with clinical experts have revealed that a rise in intracranial pressure (ICP) in the neonate can result in the bulging of the AF, caused by the build-up of cerebrospinal fluid within the brain which cannot drain away. PPG monitoring from the AF in such cases may reveal clues to the rise in ICP and can also aid in the detection of intracranial bleeds.

This paper describes the technical details of a new multi-wavelength (three) reflectance fontanelle PPG/SpO_2 sensor and presents results from the preliminary evaluation stages of the technology prior to clinical trials.

II. Materials & Methods

A. Optical Sensor Construction

Optical component placement (LEDs and photodetector) was determined by the physical characteristics and geometry

of the AF, observations about the general shape, as well as average sizes for different age ranges of neonates and infants found in the literature [7]. It was established that by taking four points from the corners of the AF yielded a tetrahedron. The mean size of the AF on a neonate (term > 33 weeks) was found to be around 220mm^2.

Separation distance between the photodetector and the LEDs was 5mm, which would put all optical components within the boundaries of the average sized AF. This separation distance was determined as a good compromise between that of commercially available reflectance sensors and the upper limits of what is physically possible without placing any of the optical components in an area of the scalp that may be compromised due to either the frontal or parietal plates of the skull. The total surface area of the active footprint of the probe is approximately 36mm^2. Figure 1 is a diagrammatic representation of the probe geometry and component placement.

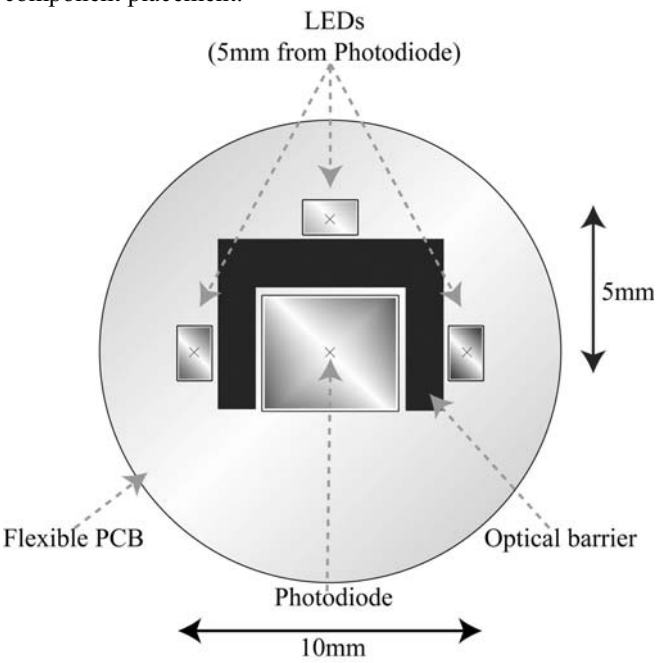

Fig. 1. Scaled representation of the fontanel PPG sensor layout comprising three LEDs, one photodiode and an optical barrier mounted on a flexible PCB base.

The main components of the probe were mounted on a copper-clad kapton sheet (DuPont, Delaware, USA), to provide a flexible PCB-base that can be set into a semi-flexible probe using optically-clear epoxy-resin (DYMAX Corporation, USA). This type of fabrication allows flexibility in the probe to accommodate the curvature of the head, and to electrically isolate the probe components when they come into contact with the skin.

Three LEDs of different wavelengths were chosen for the probe construction; 660nm Red (Perkin Elmer, Massachusetts, USA, 20x12.5x1.1mm), 940nm Infrared (Kingbright, Taipei, Taiwan, 20x12.5x1.1mm) and 520nm Green (Kingbright, Taipei, Taiwan, 20x12.5x0.75mm). The first two LEDs are traditional wavelengths used in pulse oximetry systems and can therefore be used to estimate SpO_2. The green LED has a relatively short penetration depth and therefore will enable the investigation of PPGs (blood volume) in the scalp immediately beneath the probe.

The photodetector is a surface-mount photodiode (Vishay, Pennsylvania, USA, 5x4.5x1mm) with peak sensitivity at 940nm, with enhanced sensitivity down to the blue end of the optical spectrum.

The whole assembly was terminated with a flat ribbon cable and mounted onto a plastic backing, commonly used in ECG electrodes. The finished probe is represented in figure 2.

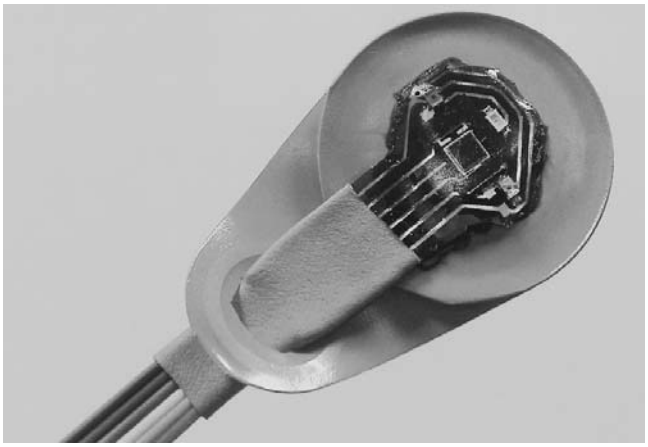

Fig. 2. Finished fontanelle probe mounted onto an ECG electrode plastic base, and terminated with flat ribbon cable.

B. PPG Processing and Data Acquisition System

A battery powered processing system was also developed to pre-process, record and display PPG signals and estimate SpO_2 values on a personal computer. The system is capable of running two separate probes individually (for the purpose of comparative studies) with three wavelengths each. The LEDs are driven by independent constant current sources allowing the flexible adjustment of drive currents for each wavelength on demand. The detected PPG signals were separated into three channels (red, infrared and green) by a demultiplexer. The AC and DC components of the PPG signals were extracted using filters to give six separate outputs. All PPG output signals were digitized by a 16-bit data acquisition card (DAQ USB6212, National Instruments Corporation, Austin, Texas) and sent to a computer where they were analyzed by a Virtual Instrument (VI) implemented in *LabVIEW* (National Instruments Corporation, Austin, Texas). The PPG data were recorded and displayed in real time by the VI on the computer screen. The VI also displayed an online estimation of SpO_2.

An auxiliary analogue input has been included on the system to enable the capture of external data from additional devices (i.e. commercial pulse oximeter). A basic block diagram of the system is shown in figure 3.

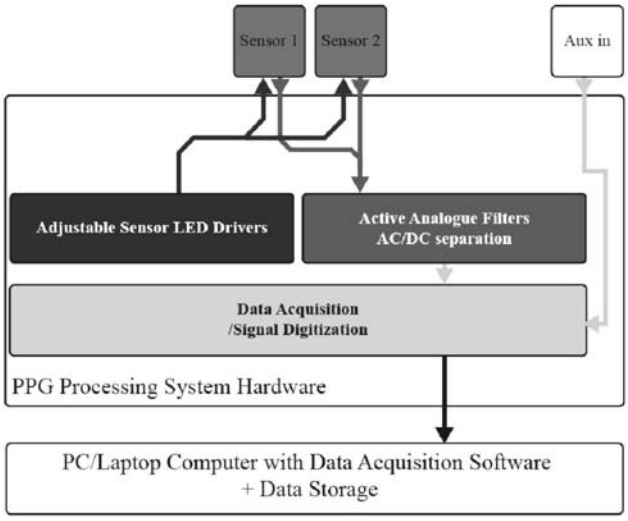

Fig. 3. Basic block diagram of PPG processing and data acquisition system.

C. *Fontanel Probe Evaluation*

The fontanelle PPG sensor was attached to the PPG data-acquisition system. The probe was tested for general operation by attaching the sensor to the temple of an adult volunteer, (see figure 4). The probe was switched on; PPGs were recorded for a period of two minutes. Readings were saved into a standard, tab-separated text data file and viewed offline.

The LEDs are thermally insulated from the tissue by the clear epoxy and the operating current of the LEDs is relatively low (pulsed 20mA on a 1/6 duty cycle). However, *in vivo* temperature tests were conducted to confirm that temperature rises on the fontanelle would not be of clinical significance. The test was repeated at three more current intensities (40mA, 60 mA, and 80 mA) in order to investigate worst case scenarios.

Fig. 4. Fontanel PPG sensor *in situ* at the temple of an adult volunteer.

III. RESULTS

Successful acquisition of PPGs from all three wavelengths was achieved from the temple of the adult and is illustrated in figure 5. The PPG signals exhibit good signal to noise ratio and large amplitudes. Preliminary SpO_2 calculations revealed saturations values in broad agreement with a commercial pulse oximeter.

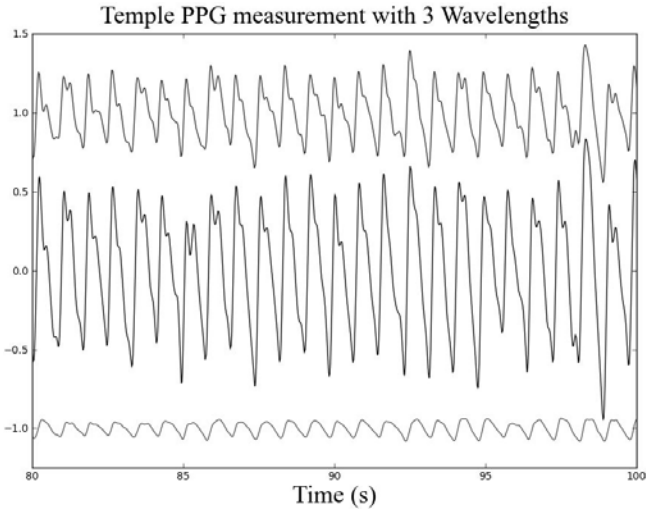

Fig. 5. Twenty second sample of a PPG waveform at three wavelengths, 660nm (top), 940nm (middle), and 520nm (bottom), from the temple of an adult.

The temperature rise at the surface of the skin (beneath the probe) for 20, 40 and 60mA operating currents was less than 0.5°C for all cases. At 80mA the temperature rise was found to be 0.5°C. The results are summarized in table 1. The mean temperature rise was calculated as the difference between steady state off (all LEDs switched off) period and steady state on period (all LEDs switched on).

None of these temperature rises would be expected to result in tissue damage. At no point during the experiment did the volunteer experience any uncomfortable heating sensation, nor was any visible thermal injury observed.

Current / mA	Mean steady temp (probe off) / °C	Mean steady temp (probe on) / °C	Mean temp rise / °C
20	33.0	≈33.0	<0.1
40	32.7	≈33.0	<0.3
60	32.7	≈33.1	<0.5
80	32.6	33.1	≈0.5

Table 1. Temperature rise at the skin surface (immediately beneath the probe) at different operating currents.

IV. Conclusion & Discussion

An optoelectronic sensor has been designed uniquely for the anterior fontanel of the newborn baby. The preliminary technical tests confirm the accurate operability of the probe and the processing system. It is acknowledged that the sensor placement on the temple of an adult isn't analogous to the AF of the newborn, however such a test was necessary before the engagement into clinical trials on neonates. Also, the rich intramural network of superficial arteries and veins that lie just below the skin surface of the skull provide some reference to the PPGs that may be seen in the scalp of the neonate.

Results from the thermal evaluation tests confirm that none of the observed temperature rises would be expected to result in tissue damage and therefore, it was concluded that there would be negligible risk of thermal injury to the fontanelle using the fontanelle probe.

Following all developmental and evaluation stages the technology is now ready for clinical trials.

References

[1] D.L. Reich, A. Timcenko, C.A. Bodian, J. Kraidin, J. Hofman, M. DePerio, S.N. Konstadt, T. Kurki, and J.B. Eisenkraft, "Predictors of pulse oximetry data failure," Anesthesiology, vol. 84, Apr. 1996, pp. 859-864.

[2] J.T. Moller, N.W. Johannessen, K. Espersen, O. Ravlo, B.D. Pedersen, P.F. Jensen, N.H. Rasmussen, L.S. Rasmussen, T. Pedersen, and J.B. Cooper, "Randomized evaluation of pulse oximetry in 20,802 patients: II. Perioperative events and postoperative complications," Anesthesiology, vol. 78, Mar. 1993, pp. 445-453.

[3] P. Iyer, P. McDougall, P. Loughnan, R.B. Mee, K. Al-Tawil, and J. Carlin, "Accuracy of pulse oximetry in hypothermic neonates and infants undergoing cardiac surgery," Critical Care Medicine, vol. 24, Mar. 1996, pp. 507-511.

[4] S. Levene and S.A. McKenzie, "Pulse oximetry in children," Lancet, vol. 1, Feb. 1988, pp. 415-416.

[5] H. Gray, Gray's Anatomy, 1860th ed. London: Arcturus, 2008.

[6] A.C. Dassel, R. Graaff, M. Aardema, W.G. Zijlstra, and J.G. Aarnoudse, "Effect of location of the sensor on reflectance pulse oximetry," British Journal of Obstetrics and Gynaecology, vol. 104, Aug. 1997, pp. 910-916.

[7] D.P. Davies, B.M. Ansari, and T.J. Cooke, "Anterior fontanelle size in the neonate," Archives of Disease in Childhood, vol. 50, Jan. 1975, pp. 81-83.