PHOTOPLETHYSMOGRAPHY AND PULSE OXIMETRY OF BODY CAVITIES AND ORGANS*

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Pulse oximetry is a non-invasive photometric technique that provides non-invasively information about the global arterial blood oxygen saturation (SpO₂) and heart rate, and has widespread clinical applications. This can be made possible via the peripheral pulse oximetry probes mainly attached to the finger, toe or earlobe. However, there is a need for monitoring perfusion on a more regional level. The direct application of pulse oximetry to an organ such as the esophagus, liver, kidney, brain or the bowel might be a very useful application in determining organ specific SpO₂, regardless if the patient's SpO₂ as measured from an extremity (finger) is normal, and therefore reducing the risk of hypoperfusion, severe ischemia, multiple organ failure, and, ultimately, death.

Also, the placement of a pulse oximetry probe at a more central site such as the esophagus might be proved more reliable at a time where conventional peripheral oximetry fails. The focus of this paper will be in the development and in vivo applications of new custom made photoplethysmographic (PPG) and pulse oximetry optical and fiber optic probes and instrumentation in an effort to investigate their suitability in the estimation of blood oxygen saturation and their contribution in the assessment of organ/tissue perfusion and viability. The paper will cover examples of application areas including real-time PPG monitoring using custom-made probes from body cavities and solid organs, including free flaps.

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Introduction

Optical sensors and medical instrumentation in general have played an important role in medicine and biology for many years. Such technologies have been used extensively for monitoring, diagnostic, prognostic or therapeutic purposes. The current advancements in semiconductor and optoelectronic technologies including the new innovations in biosignal processing techniques enable the developments of more intelligent miniature sensors. Such sensors are challenging the current status quo in medical monitoring as more sensors are now applied invasive or non-invasively in various anatomical parts which was not possible only a few years ago. These sensors reveal for the first time information to clinical experts which will aid in the more optimized treatment of patients and in the further understanding of various pathophysiological phenomena.

A most popular optical sensor that has revolutionized medical monitoring is the pulse oximeter. Pulse oximetry can clearly be claimed as one of the most significant technological advances in clinical monitoring. Pulse oximetry is well understood as a non-invasive photometric technique that provides information about the global arterial blood oxygen saturation (SpO₂) and heart rate, and has widespread clinical applications. So much was the popularity of pulse oximetry, Kelleher reviewed 220 references in an article published in 1989 and in a follow-up review in 1992, Severinghaus and Kelleher found more
than 500 new reports between 1989 and October 1991. Nearly 12,000 further reports on pulse oximetry have been published since October 1991.

It is well accepted that pulse oximetry provides a global indication of perfusion or more specific arterial oxygen saturation. This can be made possible via the peripheral pulse oximetry probes mainly attached to the finger, toe or earlobe. For many years researchers have critically evaluated and compared pulse oximeters under different environments, conditions and clinical cases. Their technological and physiological limitations have been identified and discussed in various scientific and clinical fora. Many pulse oximetry manufacturers have been actively developing and optimizing their designs both in sensors and processing systems in order to overcome some of the well-known pulse oximetry limitations (failures due to low peripheral perfusion and motion artifact, etc.), plus expand the pulse oximetry technology capabilities beyond the traditional arterial oxygen saturation by providing quantifying information on other blood chromophores such as Methemoglobin (MetHb), carboxyhemoglobin (COHb), etc.

Although pulse oximetry seems to be at the peak of its development, there is always room for further improvement, optimization and innovation. Many of these innovations could relate to specific applications and this will be the focus of this paper. Perhaps this is the time to make a step forward and investigate more regional pulse oximetry in body cavities and organs. The direct application of pulse oximetry to an organ such as the esophagus, liver, kidney, brain or the bowel might be a very useful application in determining organ specific SpO₂, regardless of the patients SpO₂ as measured from an extremity (finger) is normal. Also, the placement of a pulse oximetry probe at a more central site such as the esophagus might be proved more reliable at a time where conventional peripheral oximetry fails.

It is not the intention of this paper to provide a review of pulse oximetry (i.e. physics, technology, applications, limitations, etc.). The focus will be in the development and application of photoplethysmographic (PPG) and pulse oximetry optical and fiber optic probes and instrumentation in an effort to investigate their suitability in the estimation of blood oxygen saturation and their contribution in the assessment of organ/tissue perfusion and viability. The paper will cover examples of application areas including real-time PPG monitoring using custom made probes from body cavities and solid organs, including free flaps.

**Technological Developments**

In this section all the optical sensors and instrumentation developed for the various applications will be described in brief. More in depth technical descriptions of these technologies can be found in all relevant references.

**Esophageal Pulse Oximeter** : Esophageal pulse oximetry (adults and neonates) has been assessed utilizing two different probe technologies, one optical and the other fiber optic. For this paper the optical sensors will be described. Further reading on the fiber optic esophageal sensor can be found in the literature.

A reflectance adult optical esophageal pulse oximeter probe was fabricated utilizing two infrared and two red surface mount emitters and a surface mount photodetector (figure 1). The peak emission wavelengths of the infrared and red emitters used were 880 nm and 655 nm, respectively. The esophageal probe was designed to fit into a 20 French gauge plastic transparent disposable stomach/esophageal tube (Pennine Healthcare, Derby, UK). A custom made finger reflectance probe, optically and electronically identical to the esophageal probe has also being developed to facilitate comparisons between the two sites (esophagus and finger).

A neonatal esophageal pulse oximetry sensor was also constructed (dimensions: 14 mm x 2 mm), comprising one infrared (880 nm) and one red (655 nm) surface mount emitter and a surface mount 1 mm² active area photodetector (figure 2). The esophageal probe was designed to be small enough to slide down the lumen of a plastic transparent disposable size 12 French (external diameter of 3.8 mm) nasogastric tube.

![Figure 1: Adult esophageal pulse oximetry probe](image1.jpg)
Splanchnic Pulse Oximetry Probe: Preliminary PPG and SpO₂ measurements from abdominal organs were initially recorded using the esophageal optical probe described above. However, in a follow-up study a new hand-held fiber optical probe was designed for placement in the abdominal cavity, during open laparotomy, on both hollow and solid organs. Fiber optic cables were chosen as a means of transmitting and receiving the light as they are electrically safe and their dimension (cross-sectional area) can be quite small so as to ultimately facilitate insertion of the sensor into a small cavity. Glass silica step index multimode fibers with a Numerical Aperture (NA) of 0.37 and a core diameter of 600 μm were used, with each fiber cable SMA terminated at one end. Two optical fibers were coupled to red and infrared SMA mounted emitters (with peak emission wavelengths of 650 and 850 nm respectively) and the third fiber was coupled to an SMA mounted photodiode (1 mm² active area). To facilitate the multiplexing of the red and infrared signals into a single fiber, a 400 nm bifurcated fiber (or Y-piece) from Ocean Optics (Ocean Optics, Duiven, The Netherlands) was used. In order to compare the PPG signals, acquired from abdominal organs when using the fiber optic sensor, an identical (with the same optical and electrical characteristics) peripheral fiber optic PPG/SpO₂ probe has also been developed. Figure 3 shows both the splanchnic and peripheral probes.

Brain and Spinal Cord Tissue Fiber Optic Pulse Oximetry Probes: A fiber optic pulse oximeter has been developed for assessing blood oxygen saturation in the brain tissue of patients recovering from neurosurgery or head injury. Also, an identical fiber optic probe but with smaller size fibers was used for recording photoplethysmographic signals from the nervous tissue of the spinal cord of animals. The purpose of this probe was to establish whether perfusion is compromised in various states of injury which occur in certain animal models of spinal cord injury, for example compression injury.

The probes consisted of two silica optical fibers (a transmitting fiber and a receiving fiber) each with a core diameter of 400 μm (200 μm for spinal cord tissue study), and a numerical aperture (NA) of 0.39. The light sources used were red and infrared light emitting diodes (LEDs), with peak emission wavelengths at 660 nm and 850 nm, respectively, mounted in SMA packages. Both LEDs were connected to the single transmitting optical fiber using a Y-coupler, i.e., a bifurcated optical fiber assembly. The photodetector was an SMA packaged PIN photodiode of active surface area 0.8 mm². The photodetector was coupled directly to the receiving optical fiber (see figure 4).

For the spinal cord compression experiments, the probe was adapted for use with a compression model apparatus. The distal ends of the fiber were passed along a metal tube attached to a metal bar measuring 4 mm long by 1.5 mm wide. The fiber ends were inserted into the bar so they were flush with the lower surface of the bar as shown in Figure 5(a). The central axes of the two
fibers were laterally separated by a distance of 1.0 mm. The lower surface of the bar was curved to fit the contour of the rat spinal cord thus avoiding any localized compression of the tissue. The metal tube was supported within a stereotactic frame so that it could move in the vertical direction only.

**Anterior Fontanelle and Free Flap Pulse Oximetry Probe:** Reflectance pulse oximetry probes for placement on the anterior fontanelle (AF) of neonates\(^{17}\) and on free flaps\(^{18}\) following plastic microsurgery (adult patients) have also been developed. The geometry and dimensions of these probes were determined by taking into account the physical characteristics and geometry of the AF, and free flaps (with a focus on Deep Inferior Epigastric Perforator (DIEP) free flaps). The main optical components of the probes 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 or free flap, 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; 660 nm red, 940 nm near infrared and 520 nm Green. 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 in the scalp/free flap immediately beneath the probe. The photodetector was a surface-mount photodiode with peak sensitivity at 940 nm, with enhanced sensitivity down to the blue end of the optical spectrum. The finished probe is shown in figure 6.

**Processing and Data Acquisition System:** A dual channel pulse oximetry processing system was constructed to pre-process, record, and display PPG signals and estimate SpO\(_2\) values on a laptop personal computer. Various versions of the processing system\(^{7,8,12,19}\) have been developed within the Biomedical Research Laboratory at City University London over the years, however they all share many similarities and therefore a standard PPG platform has been recently developed to accommodate all probes (custom made and commercial). The new pulse oximetry processing system is named ZenPPG. The ZenPPG is a dual channel, dual wavelength PPG
research system, which combines the advantages of standardization of instrumentation, compatibility with commercial probes and the ability to customize the system for specific projects. The ZenPPG is modular and a constructive design approach was implemented in its design. The main parts of the system are: a system bus, PPG modules (current supplies, probe connector board and transimpedance Page 8 of 28 amplifiers) and power supply conditioning board. All the modules were designed to be as simple as possible allowing incremental improvement during subsequent development of the system. The completed ZenPPG system is shown in figure 7.

The PPG signals at the output of the ZenPPG system were digitized (1000 samples per second) by a 16-bit data acquisition card on a laptop personal computer. The digitized PPG signals were analyzed by a Virtual Instrument (VI) implemented in LabVIEW (National Instruments Corporation, Austin, Texas). This VI (see figure 8) reads the all acquired PPG data, converts them into a spreadsheet format and saves them into a file specified by the user and displays the signals in real time on the screen of the laptop computer. Algorithms were also developed in the VI for the online estimation of SpO₂.

**Clinical Investigation**

**Esophageal PPG Signals and Blood Oxygen Saturation Measurements in Cardiothoracic Surgery Adult Patients**: This study investigated and compared esophageal and finger PPGs and SpO₂s in patients undergoing high-risk operations, such as hypothermic cardiothoracic bypass surgery, in whom conventional pulse oximetry might fail due to poor peripheral circulation. Following ethics approval and written consent fifty adult patients were recruited for this study. Having previously found that PPG signals in the mid esophagus (20 to 25 cm from the upper lip) are of large amplitude, the esophageal pulse oximeter probe was advanced into the esophagus at 30 cm from the lips following induction of anesthesia. Photoplethysmographic signals were observed at various depths in the esophagus until the site that provided the best quality PPG signals was determined. During the esophageal measurements, values of blood oxygen saturation from a commercial transmission type finger pulse oximeter (Marquette, Tram 200A; Marquette Electronics, Milwaukee, Wisconsin) were also recorded. Monitoring with the esophageal pulse oximeter was performed intermittently during the various periods of the operation (during induction of anesthesia, prior to commencing cardiopulmonary bypass, after bypass and postoperative in the intensive care unit). During the above recording periods, samples of arterial blood were taken and...
analyzed by an Instrumentation Laboratories IL BG-1400 Blood Gas Analyzer (BGA) (Instrumentation Laboratories, Lexington, Massachusetts, USA). Simultaneous SpO2 measurements were also recorded from the custom made finger probe and a commercial finger pulse oximeter.

Esophageal PPG Signals and Blood Oxygen Saturation Measurements in Neonates: Local research ethics committee approval and written consent was obtained for this proof-of-concept pilot study. Five neonates (3 male, 2 female) were studied on the neonatal and pediatric intensive care units. The age range (days, ± SD) was (5 to 1398, ± 606) and the weight range (kg, ± SD) was (1.9 to 10.0, ± 3.3). The esophageal SpO2 probe was advanced gently through the mouth to a maximum depth of about 15 cm from the lips. The babies were all mechanically ventilated and adequately sedated. The probe was withdrawn slowly, and PPG signals were observed at various depths to determine the optimal measuring site at which reliable PPG signals were obtained. The probe was then left at this depth for the duration of the study for approximately ten minutes and PPG traces and SpO2 values were recorded simultaneously. During the esophageal measurements values of blood oxygen saturation, from a commercial toe pulse oximeter (Datex Ohmeda Biox 3740, GE Healthcare) with disposable Datex Ohmeda toe sensor (Oxytip Allfit sensor, OXY-AF)) were also recorded for comparison.

Investigation of PPG Signals and Blood Oxygen Saturation from Various Abdominal Organs: Local Research Ethics Committee approval was obtained to investigate ASA 1 and 2 patients undergoing elective laparotomy following informed written consent. Photoplethysmographic measurements were made in seventeen patients, (three male and fourteen female, mean age (± SD) : 54 ± (9.7)), undergoing open laparotomy. All patients were intubated and mechanically ventilated. The fiber optic pulse oximetry probe was placed into a sterile transparent medical ultrasound cover. When the abdominal cavity was open the surgeon placed the splanchnic pulse oximeter probe on the surface of each accessible abdominal organ (bowel, liver, kidney, etc.). PPG signals were acquired for approximately two minutes on each site. For comparison purposes the identical fiber optic finger pulse oximeter probe was placed on the index finger of the right hand. Blood oxygen saturation from a commercial finger pulse oximeter (GE Healthcare, UK), placed on the middle finger of the right hand, was also recorded.

Preliminary Investigation of PPG Signals and Blood Oxygen Saturation from Brain Tissue: This study was approved by the local Research Ethics Committee to study patients who required cranial bolts for their routine neurosurgical care were recruited. Six patients have been recruited so far, aneurism clipping (n = 2) or excision/debulking of tumors (n = 4) [mean (±SD) age 45.5 (±19) years]. Following induction of anesthesia and insertion of the cranial bolt by the neurosurgeon the fibers were then inserted via the bolt, approximately 5 mm into the brain and the luer caps tightened to form a seal around the fiber. The inter-fiber distance was 2 mm (set by the design of the IM-3 system). Five millimeters was chosen as a suitable depth of penetration to ensure that the acquired signals correspond to brain tissue and not from the dura and other surrounding tissue. PPG signals were recorded for several minutes. The patient’s arterial oxygen saturation was monitored using a commercial finger pulse oximeter. After the monitoring period, the fibers and the bolt were removed and the surgery resumed.

Investigation of PPG Signals and Blood Oxygen Saturation from Rat Spinal Cord Tissue: All experimental protocols of this study were approved by the animal care committee of Queen Mary University of London, UK. The spinal cords of six deeply anesthetized (in a fumex box) female Sprague–Dawley rats weighing approximately 250 g were used for this study. Subsequent anesthesia throughout the procedure was maintained using 1.5–2% halothane with oxygen and nitrous oxide at unchanged ratio delivered through a nose-piece. The skin and muscle overlying the spinal column were incised and a laminectomy was then performed at T12, leaving the dura undisturbed. The compression bar, as described in section 2.1.3, was placed in light contact with the spinal cord by suspending the base of the compression platform onto the exposed T12 cord dura under microscopic control (see Figure 5(b)). Baseline PPG measurements were recorded for a period of five minutes. A weight of 50 g was then applied statically to the platform for exactly five minutes, during which time PPG signal recording continued. The weight was then removed and PPG signals recorded for a further five minutes. The platform was then removed, the muscle layers were sutured and the skin layers closed with wound clips.

Investigation of PPG Signals and Blood Oxygen Saturation from the Anterior Fontanelle (AF) of
Critically ill Neonates: Local research ethics committee approval and parental consent was obtained for this proof-of-concept pilot study. Eight mechanically ventilated neonates (5 male, 3 female) were studied on the neonatal and pediatric ICU, Great Ormond Street Hospital, (London, UK). The age range (mean days ± SD) was (62 ±55.5) and the weight range (mean kg ± SD) was (3.05 ±1.09). The sensor was placed on the AF and secured in place using clear medical patches (Tegaderm™, 3M, USA). The continuous acquisition of PPG signals from the AF lasted between 25-50 minutes. During these measurements a custom made toe probe, electrically and optically identical to the fontanelle probe, was also used for comparative purposes. Also, a commercial toe pulse oximeter (Philips Intellivue MP70 Patient Monitor, Philips Healthcare, The Netherlands) was used simultaneously.

Investigation of PPG Signals and Blood Oxygen Saturation in DIEP Free Flaps: Pilot clinical investigations were carried out to evaluate the functionality of the PPG probe in ten patients, [mean (±SD) age 54.8 (±9.4) years], undergoing elective breast reconstruction with DIEP Flap. This study was approved by the local research ethics committee and the patients' consent was sought prior to recruitment to the study. Following the breast reconstructive surgery the PPG probe was taped (Transpore, 3M) onto the exposed skin of the flap and post-operative PPG/SpO2 measurements were obtained intermittently; every 15 minutes in the first two hours, every 30 minutes for the following four hours and hourly for the next 12 hours. Patient vital signs such as HR, BP, SpO2 and temperature were recorded in conjunction with keeping a record of the clinical observations of the free flap performed by the clinical team, i.e. color, temp, capillary refill and the pin prick test results.

Results

Results from the Investigation of Esophageal PPGs and SpO2s in Cardiothoracic Surgery in Adult Patients: Measurable PPG traces at both wavelengths were obtained in the esophagus of all patients. Figure 9 depicts typical traces from one patient undergoing cardiopulmonary bypass surgery during the various monitoring periods as described above (monitoring depth at 17 cm). Figure 9(a) shows esophageal and finger AC PPGs, obtained at both wavelengths, and ECG signals recorded just before sternotomy. Figures 9(b) is showing PPG and ECG signals after bypass in the intensive care unit, respectively.

The esophageal PPG signals recorded from all patients (before and after bypass) were of good quality with large amplitudes. The monitoring esophageal depth ranged from 14 cm to 28 cm, measured from the upper lip (mean ± SD: 17.8 cm ± 3.3 cm). Optimal esophageal monitoring depth for each patient was considered the depth that esophageal PPGs with good signal-to-noise ratio. Table 1 gives the mean ± SE of the AC PPG amplitudes at both wavelengths at the different esophageal monitoring depths for the 50 patients. The amplitudes at the monitoring depths as described in Table 1 were separated into three groups; the upper esophageal depths (14 cm to 17 cm), the mid esophageal depths (18 cm to 22 cm), and the lower esophageal depths (27 cm and 28 cm). The AC PPGs in
the mid to lower esophagus (depths of 18 cm or greater) had larger mean amplitudes at both wavelengths than those in the upper esophagus (14 cm to 17 cm).

In a direct comparison of blood oxygen saturation measurements from the esophagus and values from the blood gas analysis, 155 sets of blood oxygen saturation values from 49 patients were used for the regression analysis, which gave the estimated slope and intercept of the regression line. An average (± SD) of 3.5 (± 1.5) blood samples were collected from each patient. A plot of SpO₂ readings obtained from the reflectance esophageal pulse oximeter (y-axis) and the blood gas analyzer (x-axis) is shown in Figure 10. The equation of the best fit linear regression line was: y = 12.3 + 0.88x; r = 0.86; Standard Error of Estimate (SEE) = 0.86; P<0.001. The mean and standard deviation for the differences between the esophageal pulse oximeter and blood gases were 0.02 ± 0.88 %.

Also, a regression analysis of the ratio of ratios (R) as measured by the esophageal pulse oximeter vs the blood gas analyzer (SpO₂ = 108.2 – 21.1 × (R); r = 0.86; SEE = 0.84; P<0.001. The dashed line represents the empirical calibration equation (SpO₂ = 110–25 × (R)) used for the estimation of esophageal SpO₂. The equation derived from the regression analysis of the ratio of ratios as measured by the esophageal pulse oximeter vs. the blood gas analyzer (SpO₂ = 108.2 – 21.1 × (R) (solid line in Figure 11)) shows that there is close agreement between the two equations. This new esophageal calibration equation can replace the empirical calibration equation (SpO₂ = 110 – (R) × 25) in the Virtual Instrument algorithm for estimating esophageal SpO₂. The new calibration equation would result in esophageal SpO₂ values closer to the blood gas analysis.

![Figure 10](image1.png)

**Figure 10**: Comparison of SpO₂ measurements obtained from the esophageal probe (y-axis) and the Blood Gas Analyzer (x-axis) in 49 patients; the solid line represents the best fit linear regression line. y = 12.3 + 0.88x; r = 0.86; SEE = 0.86; n = 155; P<0.001. The dashed line represents identity. The error bars represent esophageal SpO₂ error of ± 0.8%.

![Figure 11](image2.png)

**Figure 11**: Comparison of the Blood Gas Analyzer (y-axis) and the ratio of ratios measured by the esophageal pulse oximeter (x-axis) in 49 patients. The solid line represents the best fit linear regression line. y = 108.2 – 21.1x; r = 0.86; SEE = 0.84; n = 155; P<0.001. The dashed line represents the empirical calibration equation (y = 110–25x) used for the estimation of esophageal SpO₂.

Table 2 summarizes the results of the regression analysis between saturation values (SpO₂) obtained from the three pulse oximeters (esophageal, custom made finger, and commercial finger) and SaO₂ values obtained from blood gas analysis (BGA).

Of the 50 patients included in the study, it was found that five patients (10%) had one or more periods of at least ten consecutive minutes, during which the commercial and custom made finger pulse oximeters failed to record pulsatile PPG signals and display SpO₂ values, despite being correctly positioned on the finger. The esophageal pulse oximeter operated successfully throughout these
periods of finger monitoring failure. In four of these patients, the finger pulse oximeter failed postoperatively in the intensive care unit (within the first half hour after completion of the surgery), and in the fifth patient, the failure occurred in the operating theatre before bypass. Results from arterial blood gas analysis performed during these periods of failed finger pulse oximetry demonstrate good agreement (mean difference = 0.0%) between the oxygen saturation values obtained from the esophageal pulse oximeter and the blood gas analyzer.

Results from the Investigation of Esophageal PPG Signals and SpO2s in Neonates: Good quality PPG signals from the esophagus were recorded in all patients. The measured effective signal-to-noise ratio was always better than 40dB at the output of the system. Figure 12 depicts typical PPG traces from the esophagus of a 3.2 kg, 5 day old neonate.

| TABLE 2: Calculated values of the relationships between SpO2 and SaO2 obtained from BGA for the esophageal, custom made finger and commercial finger pulse oximeters |
|---------------------------------------------------------------|------------------------|------------------------|
| Mean Difference (± SD)                                       | 0.002 ± 0.88 %         | 0.19 ± 1.24 %          |
| Standard Error of Estimate (SEE)                            | 0.86 %                 | 1.09 %                 |
| Correlation Coefficient (r)                                 | 0.86                   | 0.69                   |
| Commercial Finger vs BGA                                    | 0.33 ± 1.54 %          |

Results from the Investigation of PPG Signals and SpO2s from Various Abdominal Organs: Good quality PPG signals with large amplitudes were recorded in all attempts from the small bowel (n = 17), large bowel (n = 14), liver (n = 5) and stomach (n = 5). Figures 13 depict red (R) and infrared (IR) PPG traces from the small and large bowel, liver, stomach and the finger. The low frequency artifact present on the splanchnic PPG traces was due to the mechanical ventilator and movement of the handheld sensor.

Table 3 shows the mean AC PPG amplitudes for each investigated organ including the finger.

| TABLE 3: Mean (±SD) infrared (IR) and red (R) AC PPG amplitudes for all sites |
|-------------------------------|-----------------------------|-----------------------------|
| Site                          | Mean IR AC (V)              | Mean R AC (V)               |
| Small Bowel (n=17)            | 2.37±1.26                   | 0.76±0.41                   |
| Large Bowel (n=14)            | 2.29±1.11                   | 0.76±0.35                   |
| Liver (n=5)                   | 3.32±2.47                   | 0.91±0.82                   |
| Stomach (n=5)                 | 1.71±0.84                   | 0.62±0.23                   |
| Finger (n=17)                 | 0.85±0.26                   | 0.23±0.07                   |

Although this is an uncalibrated pulse oximetry system, preliminary SpO2 values were calculated for the small bowel, large bowel, liver, stomach and finger (Table 4). The mean SpO2 values from the commercial pulse oximeter are also included for comparison purposes.

Results from the Preliminary Investigation of PPG Signals and SpO2s from Brain Tissue: Figure 14 shows
Figure 13: AC red (R) and infrared (IR) PPG signals from the (a) small bowel, (b) large bowel, (c) liver and (d) stomach. All splanchnic PPGs are accompanied by a finger PPG.

TABLE 4: Mean (±SD) SpO₂ from all investigated organs including finger

<table>
<thead>
<tr>
<th></th>
<th>Small Bowel SpO₂ (%) n=17</th>
<th>Large Bowel SpO₂ (%) n=14</th>
<th>Liver SpO₂ (%) n=5</th>
<th>Stomach SpO₂ (%) n=5</th>
<th>Finger SpO₂ (%) n=17</th>
<th>Commercial Finger SpO₂ (%) n=17</th>
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<tbody>
<tr>
<td>SpO₂ (%)</td>
<td>97.41 ± 3.14</td>
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<td>100.60 ± 2.70</td>
<td>95.80 ± 4.32</td>
<td>97.94 ± 1.87</td>
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</table>

Figure 14. Normalized infrared (top) and red (bottom) PPG signals recorded from the brain tissue via a cranial bolt.
a typical segment of the normalized infrared (top signal) and red (bottom signal) AC PPG waveforms and the obtained from brain tissue that was recorded while the patient was lightly sedated and breathing spontaneously.

Table 5 shows the mean cerebral arterial oxygen saturations (ScaO₂) from all six patients estimated using frequency-domain analysis. The low saturation observed for patient five is unexplained. During these measurements the SpO₂ values acquired from commercial finger probe were between 98-100%.

Results from the Investigation of PPG Signals and SpO₂s from Rat Spinal Cord Tissue: Prior to commencing spinal compression good quality PPG signals with large amplitudes and high signal to noise ratio were recorded from all six animals. Figure 15 shows a ten second trace of a PPG signal from the spinal cord dura of one subject.

Figure 16 depicts a complete waveform for the entire 15 minutes measurement. The amplitude of the PPG signal decreased dramatically on compression. Upon release of the compression the PPG amplitudes increased to approximately two-thirds of its baseline value and then gradually increased. The PPGs reached the baseline value in approximately five minutes. This PPGs behavior was similar in all six animals.

Results from the Preliminary Investigation of PPG Signals and SpO₂s from the Anterior Fontanelle (AF) of Critically ill Neonates: Fontanelle and toe PPGs

<table>
<thead>
<tr>
<th>Patient #</th>
<th>Peak frequency f̄ (Hz)</th>
<th>Ratio-of-ratios</th>
<th>ScaO₂ (%)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.06</td>
<td>0.474</td>
<td>98.2</td>
</tr>
<tr>
<td>2</td>
<td>1.08</td>
<td>0.380</td>
<td>100.5</td>
</tr>
<tr>
<td>3</td>
<td>0.94</td>
<td>0.608</td>
<td>94.8</td>
</tr>
<tr>
<td>4</td>
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<td>0.784</td>
<td>90.4</td>
</tr>
<tr>
<td>5</td>
<td>1.10</td>
<td>2.32</td>
<td>52.0</td>
</tr>
<tr>
<td>6</td>
<td>0.86</td>
<td>0.694</td>
<td>92.6</td>
</tr>
</tbody>
</table>

Mean ± SD 88.1 ± 18.1

TABLE 5. Mean cerebral arterial oxygen saturations (ScaO₂) (n = 6)

Figure 15. Ten-second recordings of infrared PPGs from the spinal cord of a rat before compression

Figure 16. Recording of infrared PPGs from the spinal cord before, during and after compression.
obtained simultaneously from the fontanelle and foot of a neonate using the custom made pulse oximetry probes are shown in Figure 17. The modulations in the PPG traces were due to the mechanical ventilator.

Similar signals were obtained from all neonates. Figure 18 shows a preliminary PPG amplitude analysis of all eight subjects.

Preliminary SpO\textsubscript{2} values from both custom made probes (fontanelle and foot) were calculated. Figure 19 shows the mean SpO\textsubscript{2} values from all three pulse oximeters.

**Results from the Investigation of PPG Signals and SpO\textsubscript{2}s in DIEP Free Flaps**

PPG signals at all three wavelengths were recorded in the postoperative period from the majority of patients. Figure 20 depicts typical PPG signals from one of the DIEP flaps, together with simultaneous PPG recordings from an identical finger probe, obtained 2 hours in the postoperative period.

Figure 21 shows a preliminary PPG amplitude analysis of all ten subjects. In this figure the mean (±SD) PPG amplitudes, at three wavelengths as recorded in the different monitoring times are presented.

Preliminary estimation of blood oxygen saturation values estimated from the free flap PPGs during the postoperative period were found to be in broad agreement with the commercial finger pulse oximeter used in this study. Figure 22 shows the mean SpO\textsubscript{2} values from the two pulse oximeters for all patients.

![Figure 17](image1.png) **Figure 17.** AC PPGs at both wavelengths, red and infrared (IR) from the anterior fontanelle and the foot of a neonate.

![Figure 18](image2.png) **Figure 18.** Mean (±SD) AC PPG amplitudes at both wavelengths from the foot and the fontanelle of all eight neonates.

![Figure 19](image3.png) **Figure 19.** Mean (±SD) SpO\textsubscript{2}s from the commercial, the custom made foot and the custom made fontanelle pulse oximeters from all eight neonates.
Conclusions

Pulse oximetry is a non-invasive photometric technique that provides non-invasively information about the global arterial blood oxygen saturation (SpO₂), and has widespread clinical applications. Currently pulse oximetry utilizes peripheral probes which are mainly attached to the finger, toe or earlobe. Despite its success as an indicator of global perfusion there is a need to explore pulse oximetry as a technique for monitoring regional perfusion. This could be made possible with the design on new pulse oximetry probes with the capability of placement or attunement to specific organs or tissues. Such new application will perhaps enhance our knowledge of organ perfusion and will also aid in the direct monitoring of perfusion of transplanted tissues (such as free flaps) and organs. This paper presented new custom made pulse oximetry probes which were designed and fabricated for placement on various organs and tissues. The clinical studies successfully demonstrated the feasibility in acquiring PPGs and estimating blood oxygen saturation values from a variety of organs and tissues. The technological developments and the measurements presented in this work pave the way in a new era of pulse oximetry where direct and continuous monitoring of blood oxygen saturation of internal organs and tissues could be made possible.

References