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Optimal spacing between transmitting and receiving optical fibres in reflectance pulse oximetry

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Abstract. Splanchnic ischaemia can ultimately lead to cellular hypoxia and necrosis, and may well contribute to the development of multiple organ failures and increased mortality. Therefore, it is of utmost importance to monitor abdominal organ blood oxygen saturation (SpO$_2$). Pulse oximetry has been widely accepted as a reliable method for monitoring oxygen saturation of arterial blood. Animal studies have also shown it to be effective in the monitoring of blood oxygen saturation in the splanchnic region. However, commercially available pulse oximeter probes are not suitable for the continuous assessment of SpO$_2$ in the splanchnic region. Therefore, there is a need for a new sensor technology that will allow the continuous measurement of SpO$_2$ in the splanchnic area pre-operatively, operatively and post-operatively. For this purpose, a new fibre optic sensor and processing system utilising the principle of reflectance pulse oximetry has been developed. The accuracy in the estimation of SpO$_2$ in pulse oximetry depends on the quality and amplitude of the photoplethysmographic (PPG) signal and for this reason an experimental procedure was carried out to examine the effect of the source-detector separation distance on the acquired PPG signals, and to ultimately select an optimal separation for the final design of the fibre-optic probe. PPG signals were obtained from the finger for different separation distances between the emitting and detecting fibres. Good quality PPG signals with large amplitudes and high signal-to-noise ratio were detected in the range of 3mm to 6mm. At separation distances between 1 mm and 2 mm, PPG signals were erratic with no resemblance to a conventional PPG signal. At separation distances greater than 6mm, the amplitudes of PPG signals were very small and not appropriate for processing. This investigation indicates the suitability of optical fibres as a new pulse oximetry sensor for estimating blood oxygen saturation (SpO$_2$) in the splanchnic region.

1. Introduction

Monitoring of abdominal organ oxygen saturation (SpO$_2$) is of paramount importance in anaesthesia, intensive care and surgery[1]. The organs and tissues must be sufficiently perfused with oxygenated blood in order to survive. When an organ or tissue suffers severe hypoperfusion or extreme hypoxia, organ dysfunction ensues. Tissue hypoxia of one organ may lead indirectly to dysfunction or failure of distant organs through the release of mediators and various toxins [2]. In the case of bowel ischaemia, the loss of mucosal barrier function results in bacterial translocation and endotoxin absorption into portal blood which can amplify the systemic inflammatory response following surgery [3, 4]. This may ultimately contribute to the development of multiple organ failure, which remains a common

cause of death and morbidity following major surgery despite advances in intensive care management [2].

Previous studies have indicated that the gastrointestinal tract might be the canary of the body, and, if monitored accurately, could allow for the early detection of inadequate tissue oxygenation [5]. Current monitoring techniques have not been widely accepted for use in the clinical setting, and do not provide a readily available monitoring technique to measure splanchnic perfusion and, most importantly, to quantitatively measure splanchnic oxygen saturation [1,2]. Techniques used to measure tissue oxygenation such as polarographic oxygen electrodes remain research tools and are used as a basis to compare emerging technologies [2]. Gastric tonometry, one of the few techniques currently used in clinical practice for estimating intestinal hypoxia, has been shown to be useful as a prognostic tool in detecting hypovolaemia [6]. However, due to the intermittent, heavily operator dependent and time consuming nature of the device, as well as its expense, it has not been widely accepted [7, 8]. Methods such as laser Doppler, Doppler ultrasound, and intravenous fluorescein have also been previously explored to assess intestinal ischaemia in animals [9, 10]. Many of these techniques are complex and expensive and none of them directly measures oxygenation. Therefore, there is a need for a simple, reliable, and continuous method for estimating abdominal organ blood oxygen saturation (SpO_2).

Pulse oximetry is a non-invasive optical technique used to estimate arterial blood oxygen saturation by shining light at two wavelengths, red and infrared, through vascular tissue [11]. The intensity of the backscattered light which reaches the photodetector is measured and the variations in the photodetector current are assumed to be related to blood volume changes underneath the probe. These variations are electronically amplified and recorded as a voltage signal called the photoplethysmograph (PPG). The pulsatile nature of arterial blood results in a waveform in the received signal that allows the absorbance effects of arterial blood (ac component) to be identified from those of non-pulsatile venous blood and other body tissue (dc component). The light absorbance of oxygenated haemoglobin and deoxygenated haemoglobin at these two wavelengths is different and therefore the amplitudes of the red and infrared ac PPG signals are sensitive to changes in arterial oxygen saturation. From the ratios of these amplitudes, and the corresponding dc photoplethysmographic components, arterial blood oxygen saturation (SpO_2) is estimated [12]. The technique of pulse oximetry relies on the presence of adequate peripheral arterial pulsations, which are detected as photoplethysmographic signals. Therefore, in order to accurately estimate SpO_2 PPG signals of good quality and high signal to noise ratio are required.

Pulse oximetry has been used experimentally in the detection of intestinal oxygenation in animals [13, 14]. In these studies it was found to be a rapid, reproducible, as well as a highly sensitive and specific technique for detecting small bowel ischaemia. More recently a custom made reflectance pulse oximeter has been used for the first time in humans to measure PPGs from various abdominal organs such as the liver, the kidney and the bowel. The use of commercial pulse oximeters for estimating splanchnic perfusion in humans has been found to be impractical (bulky, cannot be sterilized etc). There remains a need for a new sensor technology that is suitable for use in the human abdomen, which will allow the continuous measurement of SpO_2 in the splanchnic area pre-operatively, operatively and post-operatively.

To overcome the limitations of the above described technologies, a new fibre optic sensor utilising the principle of reflectance pulse oximetry and processing system has been developed for the continuous estimation of splanchnic blood oxygen saturation. In the design of a reflectance pulse oximeter probe the distance between the transmitting and receiving optical components have a significant impact on the quality and amplitude of the photoplethysmographic signal, and consequently in the estimation of blood oxygen saturation. This paper describes the technical developments of the fibre optic sensor and processing system, and explores in detail the effects of fibre (transmitting and receiving) separation on the PPG signal.

2. Reflectance Pulse Oximeter Development

A new reflectance, pulse oximeter probe was developed, comprising of optical fibres coupled to infrared and red subminiature version A (SMA) mounted emitters (peak emission wavelengths at 850 nm and 650 nm respectively) and a photodiode (single photodiode with an active area of 1 mm^2). A PPG processing system was developed for the detection and pre-processing of the red and infrared ac and dc PPG signals before digitization by a 16-bit data acquisition card (National instruments, DAQPad-6015). The digitized PPG signals were further processed, analysed and displayed by a *Virtual Instrument* (VI) implemented in *LabView*.

2.1. *Fibre Optic Probe.* Silica glass step index fibres with a core of 600 μm were chosen for the transmission and reception of light to the tissue. The fibres were protected with a hard polymer buffer, Kevlar strands, and an outer Tefzel jacket. Bare fibre was exposed at the end of each fibre cable. The fibre was cleaved to achieve a flat surface at 90 degrees to the emitting light. The tip of each fibre was polished with a 5 μm, 3 μm, 1 μm, and 0.3 μm polishing film to ensure that the fibre region was free from large scratches and that there were no chips in the edges of the fibre that extended into the core of the fibre.

In order to facilitate multiplexing of the red and infrared light into a single fibre, a 400 nm bifurcated fibre (Y-piece) is used (Ocean Optics, Netherlands). Two ends of the Y-piece are coupled to SMA mounted emitters, while the other end is attached to a prepared 600 μm fibre (Figure 1). This allows for the two wavelengths to be transmitted down a single fibre. A single prepared 600 μm fibre is used to detect the backscattered light.
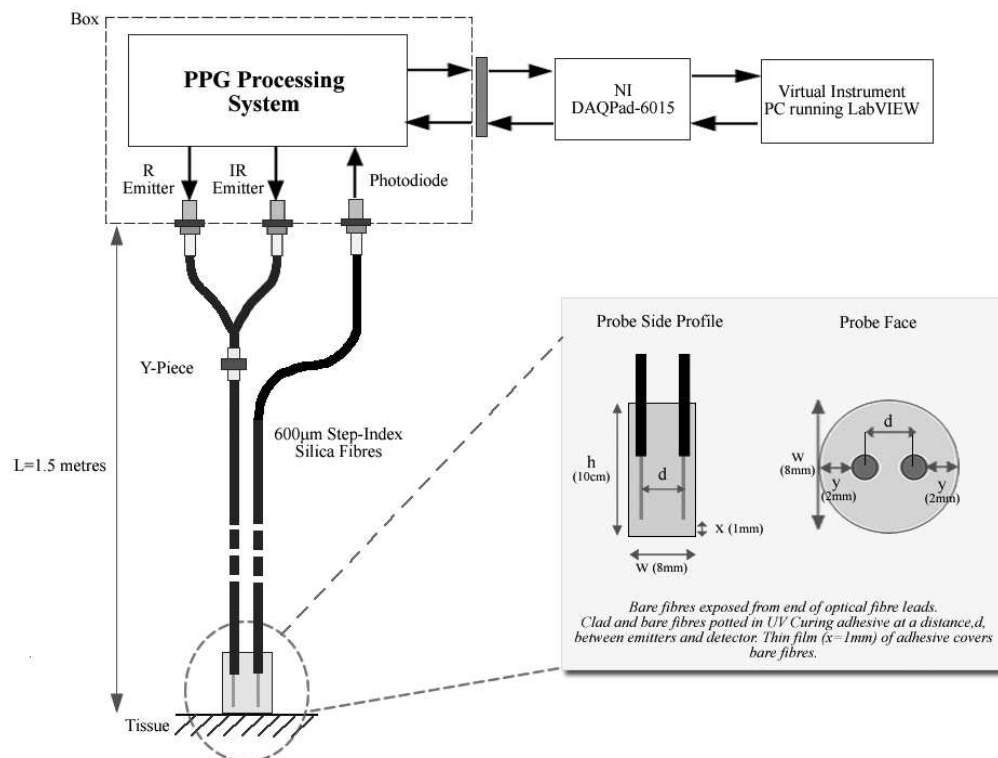

Figure 1. Reflectance configuration of fibre-optic pulse oximeter probe including desired probe dimensions

2.2. *PPG Processing and Acquisition System.* An electrically isolated acquisition and processing system has been designed and developed to drive the optical components of the fibre probe and also to detect and pre-process the red and infrared ac and dc PPG signals. A virtual instrument (VI) implemented in LabView was also developed. The VI is used for driving various hardware parts in the processing system and also for the acquisition, displaying, analysis and storing of all acquired PPG signals. A block diagram of the processing system is shown in Figure 2. The emitters, red (R) and infrared (IR), are driven by software controlled constant current sources. Output signals generated in the Virtual Instrument drive the current sources via the outputs ports of the 16-bit analogue-to-digital card. These output signals are shown in Figure 3. The two multiplexing signals allow for the red and infrared emitters to be turned on and off at a rate of 500 Hz, ensuring that both emitters are never on at the same time. The intensity signal allows the user to control the intensities of the emitters at all times during use. The photodetector detects the energy backscattered by the tissue and gives an output current proportional to the detected light intensity. The output of the current-to-voltage (I-V) differential amplifier contains multiplexed PPG signals corresponding to red and infrared wavelengths. The signal from the current-to-voltage differential amplifier passes to a demultiplexer synchronised to the multiplexing signals from the VI, which separate the red and infrared signals. The two signals (R and IR) are then filtered to extract the ac and dc PPG components for each wavelength. The output PPG signals are digitised and further analysed by the Virtual Instrument. PPG traces corresponding to infrared and red wavelengths are obtained simultaneously and displayed on the personal computer screen. All acquired signals are also saved in spreadsheet format for further post processing and analysis.
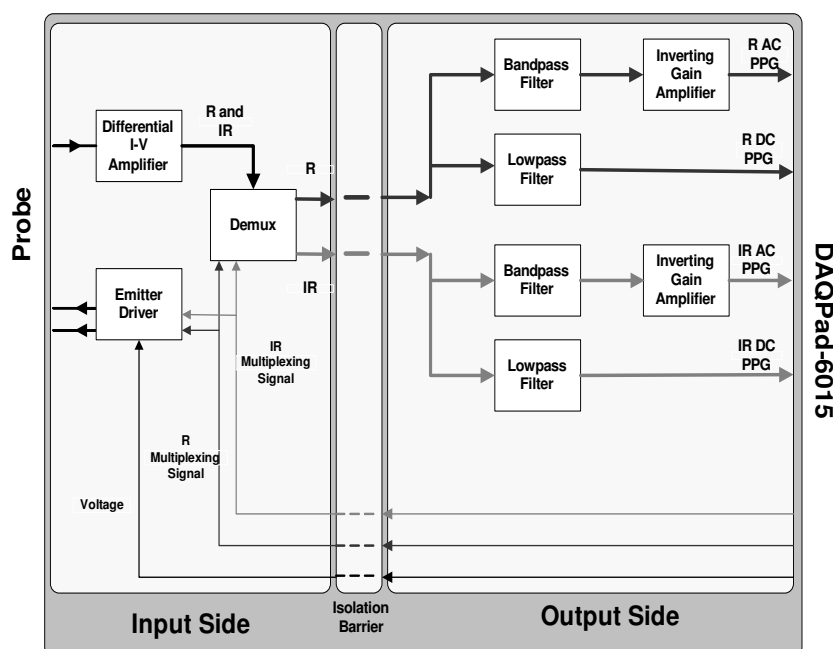

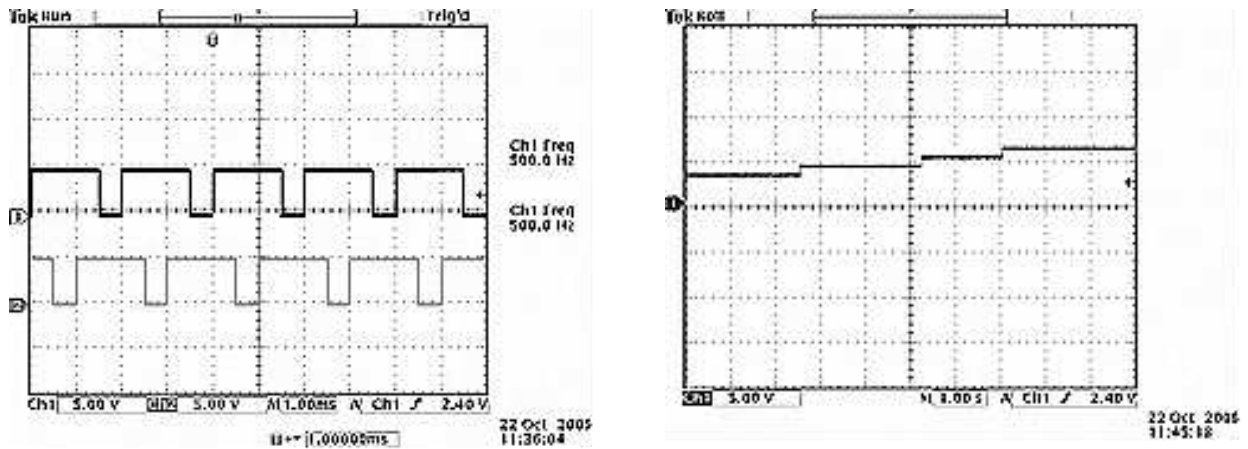Figure 2. Block diagram illustrating the various stages of the PPG Processing system

Figure 3. (a) Multiplexing signals from VI, used to control the multiplexing of the two emitters, and (b) Intensity signal from VI, which allows the intensity of the emitters to be varied. Each volt corresponds to 10mA of a drive current. The signal can be changed at anytime during use.

3. Optimal Source-Detector Separation Study

Source-detector separation is of great importance and significance in designing a reflectance pulse oximeter probe as it bears a direct impact on the quality of the PPG signal and the accurate estimation of SpO$_2$ [15]. Prior to finalising the probe design and setting the fibres in epoxy, a detailed investigation was conducted to examine the effect of source detector separation on PPG signals and to ultimately establish the optimum separation distance between the light emitting and receiving fibre.

In order to conduct this experiment, a precision drilled perspex finger piece was designed to allow for the placement of the fibres at various distances (Figure 4). All separation distances given are from the centre of the emitting fibre to the centre of the detecting fibre. During the experiment, PPG signals obtained from the finger at both wavelengths were recorded simultaneously while varying the separation between emitter and detector at 1 mm increments (range: 1-8 mm). During the experiment the emitter current was maintained constant at 40 mA. Any overhead fluorescent lights were switched off to minimise artefacts.
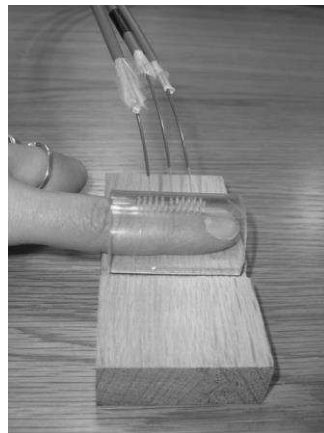

Figure 4. Illustrating the use of a precision drilled perspex piece for the placement of fibres during the source-detector separation experiment

4. Results

Photoplethysmographic signals of good quality were recorded at both wavelengths at all separation distances between the transmitting and receiving fibres. Figure 5 depicts typical finger ac PPG traces at various separation distances.

   Although PPG traces were detected at almost all separation distances, there were significant differences in signal amplitude, and morphology at the various monitoring separations. Large amplitude PPG signals were acquired at 1 mm separation. However, these signals were of very poor quality (very noisy) and erratic with little resemblance of a conventional PPG signal. Signals within the range of 2 mm to 6 mm produced PPGs of good quality with large amplitudes and high signal-to-noise ratio (SNR). Over 6 mm separation distance the resulted ac PPGs were of poor quality and very low amplitude (Figure 5).
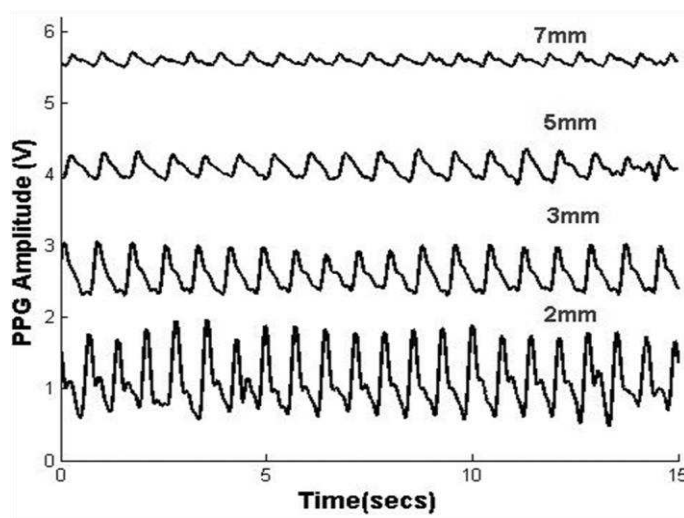

Figure 5. Typical photoplethysmographic (PPG) traces from the finger at various fibre separation distances
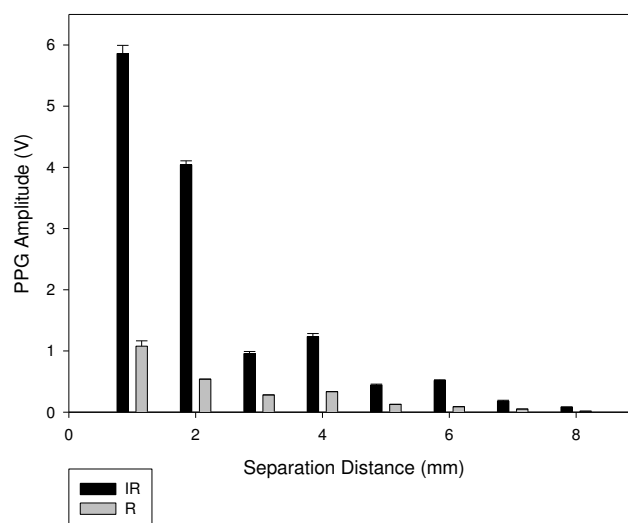

Figure 6. Mean PPG, red (R) and infrared (IR), ac amplitudes and Standard Deviation at all investigating separation distances (drive current at 40mA)

Figure 6 shows the mean ac red and infrared PPG amplitudes for all separation distances. It can be seen that the PPG amplitudes decrease as the separation distance increases. Such a phenomenon is well explained as the transfer of photons to the emitter via the tissue bed decreases as the distance between the emitting source and the receiving source increases. Figure 7 shows the mean dc red and infrared PPG signals (Standard Deviation) for all separation distances. The dc signals at 1-2 mm separation were predominately larger than at other separation distances. This suggests that the source and detecting fibres are too close, and therefore saturating the photodetector.
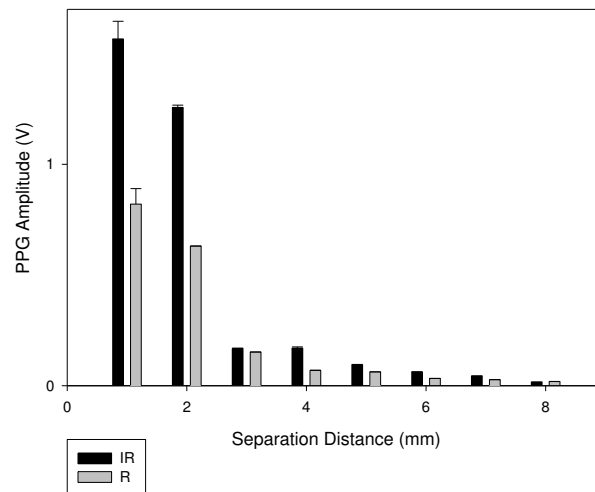

Figure 7: Mean PPG, red (R) and infrared (IR), dc amplitudes and Standard Deviation at all investigating separation distances (drive current at 40mA)

5. Conclusion

The development of a real-time blood oxygen saturation monitoring system for the splanchnic area would greatly aid in the timely assessment of the patient medical condition. Quick detection of changes in tissue oxygenation in the viscera could allow for earlier intervention to restore splanchnic perfusion, and improve survival in critically ill patients.

In an attempt to develop a new pulse oximetry probe for estimating splanchnic oxygen saturation pre-operatively, operatively and postoperatively a new fibre-optic based pulse oximeter system has been successfully designed and developed. Detailed experiments to determine the optimum separation distance between the receiving and the transmitting fibres of the probe have been conducted in the laboratory.

Photoplethysmographic signals acquired at 1 mm distance between the transmitting and receiving fibres are found to be unsuitable as the resulted PPG signals, both ac and dc, were noisy, erratic, and of extremely large amplitudes. This is possibly due to saturation of the photodetector. PPG signals from such separation distance will ultimately result in the erroneous estimation of blood oxygen saturation. At 2 mm separation the ac PPG signal was of better quality than the 1 mm separation. However, the dc level produced at this separation was clearly unsuitable for estimation of SpO_2 as they caused the photodetector to saturate again. Both ac and dc PPG signals in the range of separation between 3 and 6 mm were of good quality with large ac amplitudes and dc values within the expected range. Such signals will be most suited for the accurate estimation of blood oxygen saturation. PPG signals above 6 mm separation produced weak signals of low amplitude and very poor signal to noise

ratio. Such signals will be unreliable in the estimation of blood oxygen saturation and, therefore, such distances between transmitting and receiving fibres should be avoided.

In conclusion this work has demonstrated that the optimum separation distance between the emitting optical fibre and the receiving fibre in the development of a fibre-optic splanchnic pulse oximetry probe should be within the range of 3 to 6 mm. These results, although preliminary, suggest that it might be feasible to develop a fibre-optic pulse oximeter that will be used for the estimation of splanchnic blood oxygen saturation pre-operatively, operatively and post-operatively. Further studies will be conducted to verify the use and ability of this probe in a clinical setting.

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