Development and evaluation of a photometric fibre-optic sensor for monitoring abdominal organ photoplethysmographs and blood oxygen saturation

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ABSTRACT

A two wavelength photometric fibre-optic reflectance sensor was developed for assessing abdominal organ perfusion. In vitro tests showed that reliable photoplethysmographic (PPG) signals and blood oxygen saturation (SpO_2) values were recorded when the separation between emitting and receiving fibres was at 3mm and the emitting current was between 20mA-40mA. In a clinical study, good quality PPG signals were obtained from the small and large bowel of a patient undergoing laparotomy. Abdominal organ SpO_2 were in good agreement with those obtained from a commercial device. These observations suggest that the fibre-optic sensor may be suitable for monitoring abdominal organ perfusion.

Keyword: biomedical sensor, photoplethysmography, tissue optics

1. INTRODUCTION

The organs and tissues of the abdominal region must be sufficiently perfused with oxygenated blood in order to survive[1]. When an organ or tissue suffers severe hypoperfusion, organ dysfunction ensues. If undetected this may ultimately contribute to the development of multiple organ failure. Previous studies have indicated that monitoring of the gastrointestinal tract could allow for the early detection of inadequate tissue oxygenation[2]. However, there remains a need for a simple, reliable, continuous method for estimating abdominal blood oxygen saturation (SpO_2). Current available monitoring techniques such as laser Doppler, and intravenous fluorescein have been explored to assess intestinal ischemia in animals[3], while gastric tonometry has been shown to be a useful tool in detecting hypovolaemia[4]. However, due to the intermittent, heavily operator dependent, and time consuming nature of these devices, as well as their expense, they have not been widely accepted in clinical care[1]. Moreover, none of them directly measures oxygenation.

Pulse oximetry has been used experimentally in the detection of intestinal oxygenation in animals[5]. More recently a custom made reflectance pulse oximeter has been used in humans to measure photoplethysmographic (PPG) signals from various abdominal organs[1]. The use of commercial pulse oximeters for estimating abdominal perfusion in humans has been found to be impractical[6], and does not allow for prolonged continuous measurement of SpO_2 in the abdominal area.

To overcome these limitations, a photometric fibre optic reflectance sensor utilising and processing system have been developed for the continuous estimation of abdominal blood oxygen saturation. This paper describes the technical

developments of the fibre optic sensor, and presents preliminary PPG measurements taken from various abdominal organs during open laparotomy.

2. METHODS

2.1 Fibre Optic Sensor and Processing System

For the prototype fibre-optic sensor, it was suggested by clinical partners that a handheld reflectance pulse oximeter sensor be developed to be used by clinicians for intraoperative assessment. A sensor was designed using 600 μm core silica glass step index fibres, infrared (850nm) and red (650nm) emitters, and a $1mm^2$ active area photodiode. Figure 1 illustrates the configuration of the fibre optic pulse oximeter sensor. A Y-piece was used to multiplex the red and infrared light into a single fibre which transmits the light to the tissue. Another fibre detects the backscattered light and returns it to a photodiode. An electrically isolated processing system was constructed to drive the optical components and to pre-process the PPG signals. Time multiplexed ac and dc PPG traces (obtained at red and infrared wavelengths) were processed by the system and digitized by a 12-bit data acquisition card (DAQCard-6024E, National Instruments, Texas, USA), where they were displayed analysed and saved on a Laptop computer running LabVIEW.

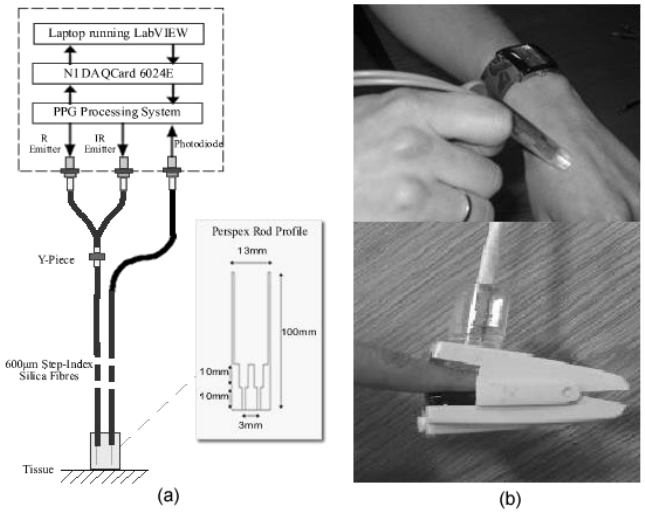


Figure 1: (a) Configuration of the fibre optic sensor and (b) abdominal fibre optic sensor (top) and finger fibre optic sensor (bottom)

For the construction of the sensor, a custom-made Perspex rod accommodating the fibres was designed. The fibre cables used had 10mm bare fibre exposed at the end, followed by 10mm of fibre coated by a hard polymer jacket, and finally the rest of the fibres were further protected by Kevlar strands and furcation tubing. The Perspex rod was precisely drilled in order to facilitate these different diameters (Figure 1(a)). A previous investigation found the optimal spacing of the emitting and receiving fibres of this reflectance sensor to be within the range of 3mm to 6mm[6]. Hence, the fibre sensor was terminated at the end of the Perspex rod ensuring a separation distance of 3 mm between the emitting and receiving fibre. The fibres were then secured within the Perspex rod using medical UV curing adhesive. The footprint of the sensor was covered with a 1mm layer of the epoxy, and polished so as to give a plane surface. An identical finger sensor was also developed to facilitate comparison of PPG signals from the abdominal organ with those from the periphery. Fig.1 (b) shows the finished abdominal sensor and identical finger sensor.

2.2 Laboratory evaluation of instrumental developments

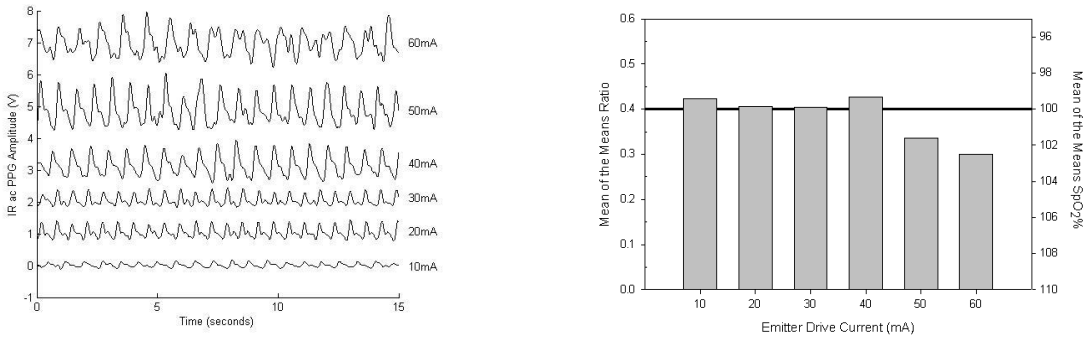
Before undertaking clinical trials all hardware and software parts of the developed system were evaluated in the laboratory. More specifically the effect of the emitter drive current on the amplitude and morphology of the acquired photoplethysmographic signals using the developed sensor was investigated. The sensor was placed on the finger of a healthy volunteer. The current was increased from 10 mA to 60 mA in steps of 10mA. A thermocouple was used to monitor finger temperature during the experiment. PPG signals were recorded and analyzed for all current values.

2.3 Preliminary Investigation of Fibre-Optic Sensor during Open Laparotomy

Ethics Committee approval was obtained to study patients undergoing open laparotomy. The fibre-optic PPG sensor was placed in a sterile medical ultrasound cover which was transparent to the light being emitted. At an appropriate time during the surgery, the surgeon placed the abdominal PPG sensor on the surface of each accessible abdominal organ. Overhead lights were turned off, and signals were monitored and acquired for approximately two minutes on each site.

RESULTS

Photoplethysmographic signals were obtained for all values of emitter drive currents. Figure 2(a) shows typical ac IR PPG traces for each drive current value. It was found that both ac and dc amplitudes increase as emitter drive current is increased. This was to be expected as there are an increased number of photons reaching the photodetector when the emitter is driven at a higher intensity.

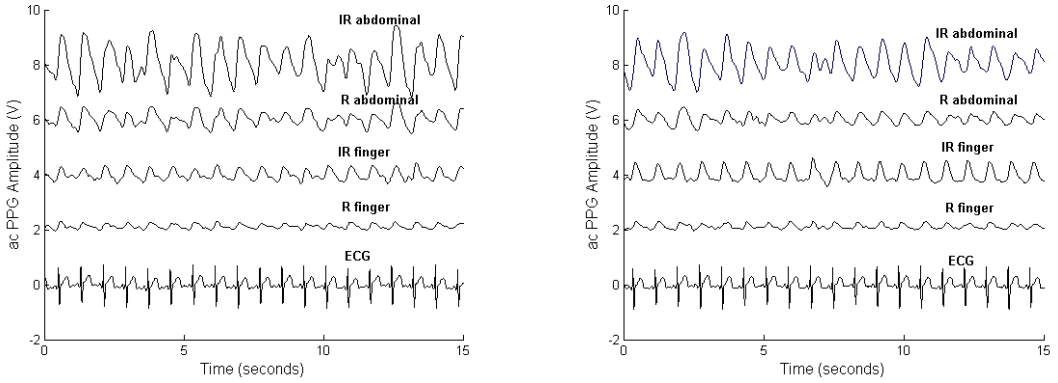


(a) (b)

Figure 2: (a) IR ac PPG signals for various emitter drive currents and (b) mean ratio and SpO_2 values for various emitter drive currents

However, it was needed to ensure that this increase in intensity has no effect on the estimation of SpO_2. Figure 2(b) shows the mean ratio of ratios and mean SpO_2 values for various currents. Temperature analysis also indicated that an increase in emitter drive current results in a very small thermal effect on the tissue.

In a preliminary evaluation of the fibre-optic sensor during open laparotomy, good quality PPG signals were taken from the small and large bowel of a single patient (Figure 3(a) and (b)). Preliminary SpO_2 values of 95% and 96% were estimated from the small bowel and the large bowel respectively. SpO_2 values monitored from a commercial device (GE Healthcare) indicated 97% during the procedure.



(a) (b)

Figure 3: ac red (R) and infrared (IR) PPG signals from (a) the small bowel and finger and (b) the large bowel and finger

CONCLUSION

A prototype fibre optic sensor, a processing system and a virtual instrument were successfully developed and evaluated. In an investigation into the effect of emitter drive current on PPG amplitudes and SpO_2 estimation, photoplethysmographic signals were acquired at all emitter drive currents. Even though the developed system is not yet formally calibrated, when the emitters were driven in the region of 10mA to 40mA, SpO_2 values in the region of 100% were estimated, which is within the normal range. Emitter currents above 50mA resulted in SpO_2 values slightly above 100%. Although this is not alarming for an uncalibrated system, such erroneous results of SpO_2 values might lead to the conclusion that at such emitting currents and at a separation distance of 3mm between the emitting and receiving fibres the photodetector might be driven near saturation. The PPG signals obtained at 10mm were of very low amplitude, and as accurate SpO_2 estimation depends on the presence of good quality PPG signals, it is suggested that the emitters should be driven within the range of 20mA-40mA in order to obtain reliable results.

Good quality PPG signals were obtained from the large and small bowel in a preliminary study on a patient undergoing open laparotomy. Even though this is an uncalibrated system, the preliminary estimated SpO_2 values of 95% for the small bowel and 96% for the large bowel show good agreement with those obtained from a commercial device. These results indicate that a fibre-optic sensor may be a valuable method for monitoring abdominal organ oxygen saturation. Clinical trials are being extended (n=20) in order to provide a complete evaluation of the system.

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