INVESTIGATION OF PHOTOPLETHYSMOGRAPHIC SIGNALS AND BLOOD OXYGEN SATURATION VALUES OBTAINED FROM HUMAN SPLANCHNIC ORGANS USING A FIBER OPTIC SENSOR

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Hickey M, Samuels N, Randive N, Langford RM, Kyriacou PA. Investigation of photoplethysmographic signals and blood oxygen saturation values obtained from human splanchnic organs using a fiber optic sensor.

ABSTRACT. Objective. A reliable, continuous method of monitoring splanchnic organ oxygen saturation could allow for the early detection of malperfusion, and may prevent the onset of multiple organ failure. Current monitoring techniques have not been widely accepted in critical care monitoring. As a preliminary to developing a continuous indwelling device, this study evaluates a new handheld fiber optic photoplethysmographic (PPG) sensor for estimating the blood oxygen saturation (SpO_2) of splanchnic organs during surgery. **Methods.** A fiber optic splanchnic PPG sensor, instrumentation system and virtual instrument were developed to facilitate PPG and SpO_2 measurement from splanchnic organs. Following Local Research Ethics Committee approval, the sensor was evaluated on seventeen ASA 1 and 2 patients undergoing open laparotomy. PPG signals were obtained from the large bowel, small bowel, liver and stomach. Simultaneous PPG signals from the finger were also obtained using an identical fiber optic sensor. **Results.** Good quality PPG signals with high signal-to-noise (SNR) ratios were obtained from all splanchnic sites under investigation. Analysis of the ac and dc amplitudes of the red and infrared PPG signals showed there to be a statistically significant difference between PPG signals obtained from splanchnic organs with those obtained from the finger (using fiber optic sensors). Estimated SpO_2 values from the splanchnic organs show good agreement with those obtained from the finger using both a fiber optic sensor and a commercial device. Furthermore, the results of a Bland and Altman analysis indicate that fiber optic splanchnic pulse oximetry, particularly of the bowel, may provide a suitable method for monitoring splanchnic organ perfusion. **Conclusion.** The evaluation of a new fiber optic sensor on anaesthetized patients undergoing laparotomy demonstrated that good quality PPG signals and SpO_2 estimates can be obtained from splanchnic organs. Such a sensor may provide a useful tool for the intraoperative assessment of splanchnic perfusion.

KEY WORDS. photoplethysmography, pulse oximetry, optical fibers, splanchnic perfusion.

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INTRODUCTION

Splanchnic organs are particularly vulnerable to hypoperfusion, and if undetected, organ dysfunction can ensue. Furthermore, tissue hypoxia of one organ may lead indirectly to dysfunction or failure of distant organs through the release of mediators and various toxins [1]. In the case of bowel ischemia, 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 [2, 3]. This may ultimately contribute to the development of multiple organ failure, which remains a common cause of death and morbidity following major surgery.

Previous studies have indicated that the accurate monitoring of the gastrointestinal tract could allow for the early detection of inadequate tissue oxygenation [4]. Currently, there is no widely accepted and readily available monitoring technique to assess splanchnic perfusion [5]. Polarographic oxygen electrodes have been used to monitor splanchnic tissue oxygenation, but predominately remain as research tools [1]. MRI and PET allow regional cellular metabolism to be characterized and results have shown these techniques to be suitable for the diagnosis of mesenteric ischemia in humans [6]. However, practical considerations limit their usefulness in the intensive care setting. Gastric tonometry has been used in many clinical settings to estimate intestinal perfusion in both animals [7] and humans [8]. 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 [9]. Many of these techniques are complex and expensive and none of them directly measures oxygenation.

Pulse oximetry is a non-invasive optical technique used to estimate arterial blood oxygen saturation (SpO_2). Studies in animals have found it to be a rapid, reproducible, as well as a highly sensitive and specific technique for detecting small bowel ischemia [10]. More recently an electro-optical pulse oximetry sensor has been used for the first time in humans to measure photoplethysmographic (PPG) signals from various abdominal organs [5]. However, none of these sensors are suitable for prolonged monitoring in the abdomen.

As a preliminary to developing such a sensor, a hand-held fiber optic PPG sensor was developed. Such a sensor would facilitate the investigation of PPG signals and the estimation of blood oxygen saturation from various splanchnic organs operatively by the surgeon. In this paper, the development of the sensor and processing system are outlined first, before focusing on results obtained during clinical trials.

METHODS AND MATERIALS

Fiber optics sensors

Two identical reflectance fiber optic PPG sensors, one for the splanchnic area and one for the finger, were developed utilizing two 600 μm core silica glass fibers with numerical apertures (NA) of 0.37 as a means of transmitting and receiving the light from the splanchnic tissue. Figure 1 illustrates the configuration and optical components of one of the two fiber optic sensors. Red and infrared emitters, with peak emission wavelengths at 660 and 850 nm respectively, were mounted in SMA (SubMinature version A) packages. In order to facilitate the multiplexing of the red and infrared light into the single transmitting fiber, a custom-made Y-piece assembly (Ocean Optics) was utilized. Two ends of the Y-piece are SMA coupled to the red and infrared emitters, and the other end is coupled to the single transmitting fiber optic cable. The transmitting fiber is SMA terminated at one end (to facilitate coupling with the Y-piece). At the other end, the protective jacket was stripped away to expose 10 mm of bare fiber optic, which was then cleaved and polished flat. The single receiving fiber optic cable also has a bare fiber exposed at one end and is SMA terminated at the other end in order to facilitate coupling with the SMA mounted photodiode (active area 1 mm^2). Light backscattered from the tissue is collected by the receiving fiber which is coupled to the photodetector.

To enable ease of placement of the sensor on the surface of splanchnic organs, the exposed ends of the transmitting and receiving fiber optic cables were accommodated in a custom-made Perspex rod (Figure 1). The Perspex rod was precisely drilled to house the 10 mm of exposed fiber and a further 10 mm of the protected fiber. Also, as a previous investigation [11] indicated that the optimum distance between the transmitting and receiving fibers should be within the range of 3–6 mm, the Perspex rod was designed to ensure a separation distance of 3 mm. The fibers were then secured within the Perspex rod using medical UV curing adhesive (epoxy). The footprint of the sensor was covered with a 1 mm layer of the epoxy, and polished so as to give a plane surface.

In its current design, the footprint size of the sensor is defined by the 13 mcm diameter of the Perspex rod. However, the active optical footprint of the sensor is only 3.6 mm long and 0.6 mm wide—corresponding to the endfaces of both transmitting and receiving fibres and the separation distance between them (Figure 1).

The finger fiber optic sensor was also developed to allow for the comparison of photoplethysmographic signals from the splanchnic region with those from the finger. The optical components and configuration of the finger sensor are identical to those of the splanchnic sensor (Figure 1). For this sensor, the fibers were secured within a modified finger pulse oximetry clip probe.

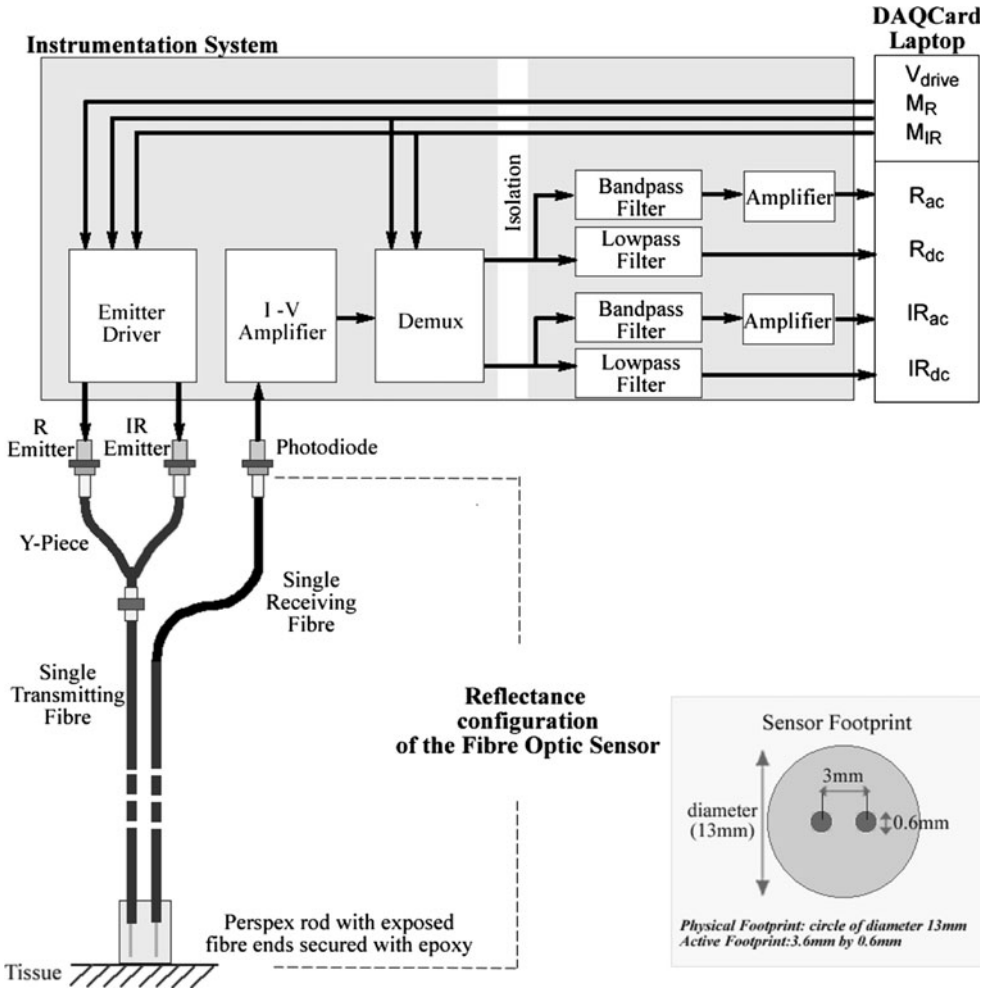

Fig. 1. Fiber optic sensor configuration and block diagram of the instrumentation system.

Instrumentation system and virtual instrument

An electrically isolated instrumentation system was constructed to drive the optical components of the sensors and to pre-process the red and infrared PPG signals from both the splanchnic site and the finger. As the channels for the splanchnic and finger fiber optic sensors were identical, only one channel is illustrated in the block diagram of Figure 1. The red and infrared emitters were driven by a software controlled constant current source. Two multiplexing signals (M_R and M_{IR}) and a drive voltage (V_{drive}), which were specified by the user in LabVIEW (National Instruments, USA), were supplied to the current sources from the interfaced data acquisition card (12-bit DAQCard-6024E, National Instruments, USA). The M_R and M_{IR} signals were used to switch on and off the red and infrared emitters at a duty cycle of 25%, ensuring that both emitters were never on at the same time. The drive voltage (V_{drive}) signal allowed the drive current through the emitters to be controlled.

The photodiode was connected to a differential transimpedance amplifier in order to produce a voltage proportional to the detected light intensity. The output of the transimpedance amplifier was then demultiplexed into its red (R) and infrared (IR) PPG components before passing through an isolation amplifier included for increased patient electrical safety.

The infrared and red PPG signals each contained a dc component and a much smaller ac component (usually less than 2% of the dc). The ac PPG components were separated from the red and infrared signals using second-order bandpass filters (0.1–10 Hz) and the dc components were separated using second order low-pass filters (0.1 Hz). The ac PPGs were then amplified with a non-inverting amplifier with a gain of 100.

All red and infrared signals were then digitized by the data acquisition card, where they were displayed analyzed and saved by a virtual instrument (VI) implemented in LabVIEW.

Patients and measurements

Local Research Ethics Committee approval was obtained to recruit ASA 1 and 2 adult patients undergoing elective laparotomy following informed, written consent. Patients who where undergoing acute emergency operations, or where unwilling or unable to conform to the protocol were excluded from the study.

Photoplethysmographic measurements were made in seventeen patients (three male and fourteen female, mean age (±SD): 54 ± 9.7) under general anesthesia. None of the patients recruited had a previous history of peripheral vascular disease (PVD) or diabetes. One of the patients recruited to the study had a previous medical history of hypertension, and another had previously undergone heart failure surgery. The study was observational and patients' surgical, anesthetic and monitoring management were as per routine. All patients were intubated and mechanically ventilated with FiO_2 of approximately 0.4, and $ETCO_2$ of approximately 4–4.5 kPa. All patients were induced with propofol, 2 mg/kg IV, and anesthesia was maintained with either 1–3% isoflurane or sevoflurane in a 50–70% air/oxygen or N_2O/oxygen mixture. The inspired concentration of the volatile anesthetic was varied to maintain hemodynamic stability. The fiber optic splanchnic sensor was placed in a transparent sterile medical ultrasound cover, so as to allow its use in the sterile surgical site. The identical fiber optic PPG finger sensor was also placed on the patients' index finger.

At an appropriate time during the surgery, the surgeon placed the abdominal PPG sensor on the surface of each accessible organ and all signals were acquired simultaneously for approximately two minutes per abdominal site (Figure 2). Blood oxygen saturation values from a commercial finger pulse oximeter (GE Healthcare) were also simultaneously monitored and recorded in a notebook.

Data analysis and statistics

Data files recorded by the LabVIEW virtual instrument were analyzed offline. The quality of the obtained ac PPG signals was assessed by measuring the signal-to-noise ratio (SNR). This was performed using measurements of pulse power against background noise in the frequency domain, achieved using the *pwelch* method.

For each patient data, the amplitudes of the red and infrared ac and dc PPG signals were calculated over two consecutive PPG cycles. Although this is an uncalibrated system, preliminary SpO_2 values were also estimated for each splanchnic site under investigation in order to provide an indication of the system's ability to estimate arterial blood oxygen saturation. This was achieved using a typical linear equation utilized in pulse oximetry (see equation 1) [12]. R is known as the ratio of ratios and is given in Equation 2.

Fig. 2. Fiber optic splanchnic PPG sensor being held on the small bowel by the surgeon during open laparotomy.

$$SpO_2 = 110 - 25 \times R \tag{1}$$

$$R = \frac{Rac/Rdc}{IRac/IRdc} \tag{2}$$

For each patient data, mean ac and dc amplitudes and mean SpO_2 values were obtained by averaging the calculated amplitude and SpO_2 values over the duration of the monitoring period (approximately 2 min).

In order to further quantify the measurement results, statistical tests were carried out on the calculated PPG amplitude and SpO_2 data for all measurement sites using SigmaStat (Systat, USA). As the data was normally distributed, a paired *t* test was used to analyze the statistical significance of the differences between infrared and red PPG amplitudes (both ac and dc) obtained at different measurement sites. The analysis was repeated for the SpO_2 data. A value of $P < 0.05$ was considered statistically significant.

The Bland and Altman between-method-differences analysis was utilized to investigate the level of agreement between the fiber optic finger and commercial finger SpO_2 values, as well as between the splanchnic and finger fiber optic SpO_2 values [13]. The Bland and Altman method suggests that the best way to look for an association between two methods is to plot the difference between the methods against their mean. If there is no obvious relation between the difference and the mean

then the lack of agreement can be summarized by calculating the bias, estimated by the mean difference (d) and the standard deviation of the differences (s). Provided differences within $d \pm 2$ s would not be clinically important the two measurement methods or instruments could be used interchangeably [13].

RESULTS

Good quality photoplethysmographic signals have been obtained from the small bowel (n = 17), large bowel (n = 14), liver (n = 5) and stomach (n = 5). Figure 3 shows typical ac infrared PPG signals obtained from these sites and the finger using the fiber optic sensor.

From Figure 3 it is observed that the splanchnic infrared PPG signals are larger in amplitude that the infrared PPG signals from the finger. Furthermore, there is a low frequency artifact present on the splanchnic PPG traces. This is possibly due to the mechanical ventilator and some slight movement of the handheld sensor by the surgeon, especially when monitoring at areas where access was difficult, such as the liver.

There was no significant difference between the SNRs calculated for both the infrared and red ac splanchnic signals and those obtained simultaneously from the finger (Table 1). The high SNR values for all signals suggest that the signals are of sufficient quality for use in the estimation of arterial blood oxygen saturation.

For each patient, the mean red and infrared ac and dc values obtained from each site were calculated over the two minute monitoring interval. In order to provide an indication of how PPG amplitudes differ between sites, the mean of the means ac and dc PPG amplitudes for each site were calculated by averaging the mean ac or dc amplitudes for each patient (Figure 4). A predominant difference was observed between the mean of the means ac and dc PPG amplitudes from splanchnic sites compared with those from the finger.

Statistical analysis performed on the ac and dc PPG amplitude data using paired *t* tests (Table 2) also indicated a difference between splanchnic and finger PPG amplitudes. Table 2 shows that for the large and small bowel there is a statistically significant difference between the splanchnic ac and dc PPG signals and those obtained from the finger at both wavelengths. However, there was no significant difference between the signals from the large and the small bowel.

Both ac PPG signals from the liver show no significant difference to the red and infrared ac signals from the finger and other splanchnic organs. However, for the red and infrared dc PPG signals, the values from the liver demonstrate a statistically significant change to those from the finger. Although the red ac PPG signal and both dc signals from the stomach were found to be significantly different from the signals from the finger, the analysis on the infrared ac signals showed no statistical difference. However, it must be stressed that due to the small sample size of both the liver (n = 5) and stomach (n = 5) data, these results must be considered cautiously and were included as a preliminary indication.

Figure 5 shows the mean of the means SpO_2 values for all four splanchnic sites (large bowel, small bowel, liver and stomach) and the finger estimated using the fiber optic sensors. The mean of the means SpO_2 values from

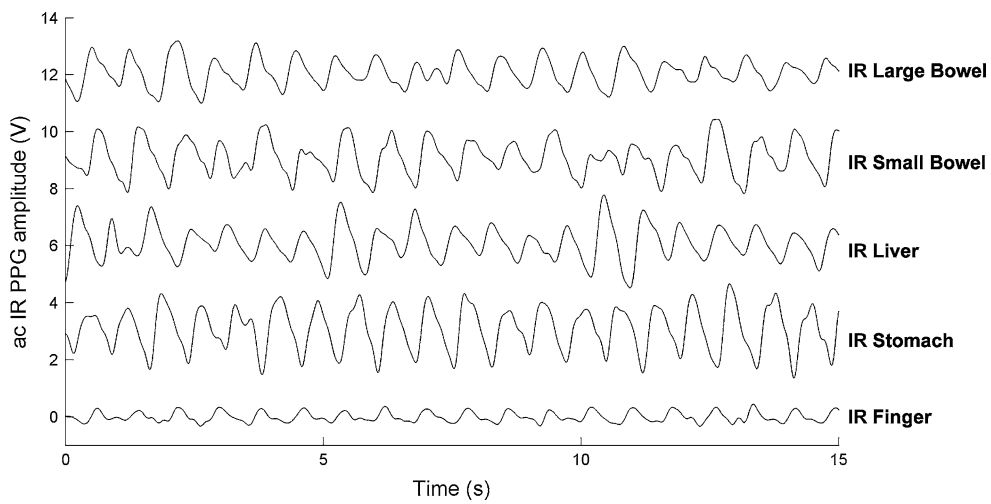

Fig. 3. Infrared (IR) ac PPG signals from the large bowel, small bowel, liver, stomach and finger. The splanchnic PPG signals are modulated by a low frequency artifact, possibly caused by mechanical ventilation or movement of the handheld sensor.

Table 1. Mean (±SD) signal-to-noise ratio (dB) of the acquired ac infrared and red PPG signals for all monitoring sites

Site	IRac SNR (dB)	Rac SNR (dB)
Large bowel (n = 14)	83.21 ± 4.17	81.71 ± 5.51
Small bowel (n = 17)	82.47 ± 6.39	80.73 ± 6.83
Liver (n = 5)	83.00 ± 5.02	83.00 ± 6.24
Stomach (n = 5)	81.00 ± 6.44	79.00 ± 9.35
Finger (n = 17)	83.02 ± 6.03	82.63 ± 6.98

the commercial pulse oximeter are also included for comparison purposes.

The mean of the means SpO_2 value estimated from the finger using the fiber optic PPG sensor (97.94%) is in good agreement with that obtained from the commercial pulse oximeter (97.88%). The SpO_2 values obtained from the small and large bowel (97.41 and 97.14% respectively) are almost identical and are also in good agreement with the SpO_2 values from the finger (both fiber optic and commercial sensors).

However, the mean of the means SpO_2 estimated from the stomach and liver are shown to either underestimate or overestimate arterial blood oxygen saturation when compared with the finger fiber optic and commercial SpO_2 values. The mean SpO_2 obtained from the stomach is 95.80%, which is underestimating by approximately 2% when compared to the mean commercial SpO_2. While the mean SpO_2 value estimated at the liver is 100.60% which is overestimating the arterial blood oxygen saturation by approximately 3%.

Results of paired *t* tests comparisons on all SpO_2 data sets can be seen in Table 3. Estimated SpO_2 values from the large bowel, small bowel, stomach, and finger (both fiber optic and commercial) showed no statistically significant differences between different sites. However, paired *t* tests performed on the liver SpO_2 values showed significant differences between the liver and both the large and small bowel in the estimation of arterial blood oxygen saturation. Also, a statistically significant difference was found between SpO_2 estimated from the liver SpO_2 estimated from the commercial pulse oximeter.

Figures 6, 7, 8, 9 and 10 summarize the results of the Bland and Altman between-methods-difference analysis. Figure 6 is a plot of the difference between the fiber optic and commercial finger SpO_2 values against their mean, from which it can be concluded that there is no obvious relation between the difference and the mean. Therefore, the limits of agreement for the finger SpO_2 data (fiber optic and commercial finger measurements) were calculated and found to be −2.6 and 2.4% and are indicated in Figure 6. These limits of agreement are within the ±3% accuracy of commercial pulse oximeters as given by the manufacturers. Therefore, it can be reasonably argued that these levels of difference are sufficiently small enough to be considered as clinically irrelevant.

Figures 7 and 8 show the plots of the difference between finger and splanchnic SpO_2 values against the mean for the large bowel and small bowel respectively. The limits of agreement were calculated as described above and were found to be −3.4 and 4.3% for the large bowel, and −3.8 and 4.2% for the small bowel data. The limits of agreement in the case of small bowel monitoring and large bowel monitoring are almost identical, indicating that splanchnic monitoring from the bowel provides SpO_2 values that are either 4.2% above or 3.8% below those obtained from the finger.

Figures 9 and 10 show the plots of the difference between finger and splanchnic SpO_2 values against the

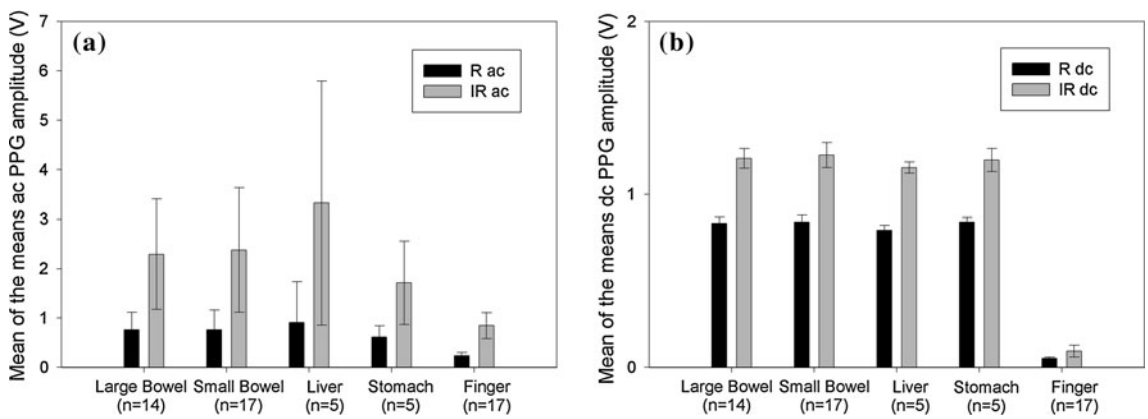

Fig. 4. **a** *Mean (±SD) ac PPG amplitudes and* **b** *mean (±SD) dc PPG amplitudes for the large bowel (n = 14), small bowel (n = 17), liver (n = 5), stomach (n = 5) and the finger (n = 17).*

Table 2. Results of paired t test comparisons on all PPG signals from all sites

	Large bowel (n = 14)	Small bowel (n = 17)	Liver (n = 5)	Stomach (n = 5)	Finger (n = 17)
Large bowel (n = 14)	–	NS	NS	NS	Rac ($P = 0.001$) IRac ($P = <0.001$) Rdc ($P = <0.001$) IRdc ($P = 0.001$)
Small bowel (n = 17)	NS	–	Rdc ($P = 0.049$)	NS	Rac ($P = <0.001$) IRac ($P = <0.001$) Rdc ($P = <0.001$) IRdc ($P = <0.001$)
Liver (n = 5)	NS	Rdc ($P = 0.049$)	–	Rdc ($P = 0.023$)	Rdc ($P = < 0.001$) IRdc ($P = <0.001$)
Stomach (n = 5)	NS	NS	Rdc ($P = 0.023$)	–	Rac ($P = 0.008$) Rdc ($P = <0.001$) IRdc ($P = <0.001$)
Finger (n = 17)	Rac ($P = <0.001$) IRac ($P = <0.001$) Rdc ($P = <0.001$) IRdc ($P = <0.001$)	Rac ($P = <0.001$) IRac ($P = <0.001$) Rdc ($P = <0.001$) IRdc ($P = <0.001$)	Rdc ($P = <0.001$) IRdc ($P = <0.001$)	Rac ($P = 0.008$) Rdc ($P = <0.001$) IRdc ($P = <0.001$)	–

Signals include red ac and dc (Rac and Rdc) and infrared ac and dc (IRac and IRdc) PPGs.

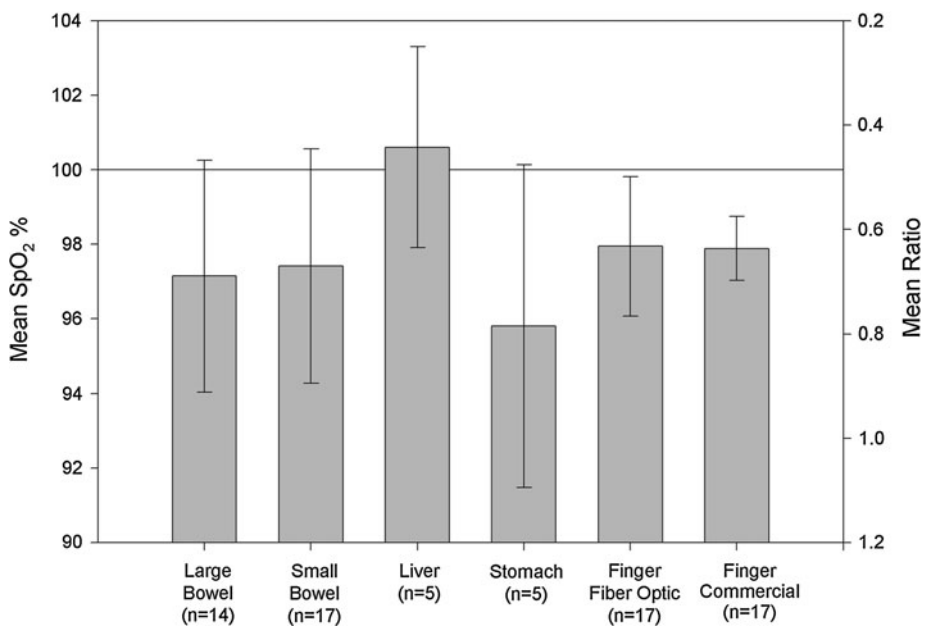

Fig. 5. Mean of the means SpO_2 (±SD) values for the large, small bowel, liver, stomach, and finger using the fiber optic sensors. The mean of the means SpO_2 (±SD) value from the commercial finger pulse oximeter (GE Healthcare) is also indicated for comparison.

Table 3. Results of paired t test comparisons on estimated SpO_2 values from all sites

	Large bowel (n = 14)	Small bowel (n = 17)	Liver (n = 5)	Stomach (n = 5)	Finger fiber optic (n = 17)	Finger commercial (n = 17)
Large bowel (n = 14)	–	NS	$P = < 0.001$	NS	NS	NS
Small bowel (n = 15)	NS	–	$P = 0.023$	NS	NS	NS
Liver (n = 5)	$P = < 0.001$	$P = 0.023$	–	NS	NS	$P = 0.038$
Stomach (n = 5)	NS	NS	NS	–	NS	NS
Finger fiber optic (n = 17)	NS	NS	NS	NS	–	NS
Finger commercial (n = 17)	NS	NS	$P = 0.038$	NS	NS	–

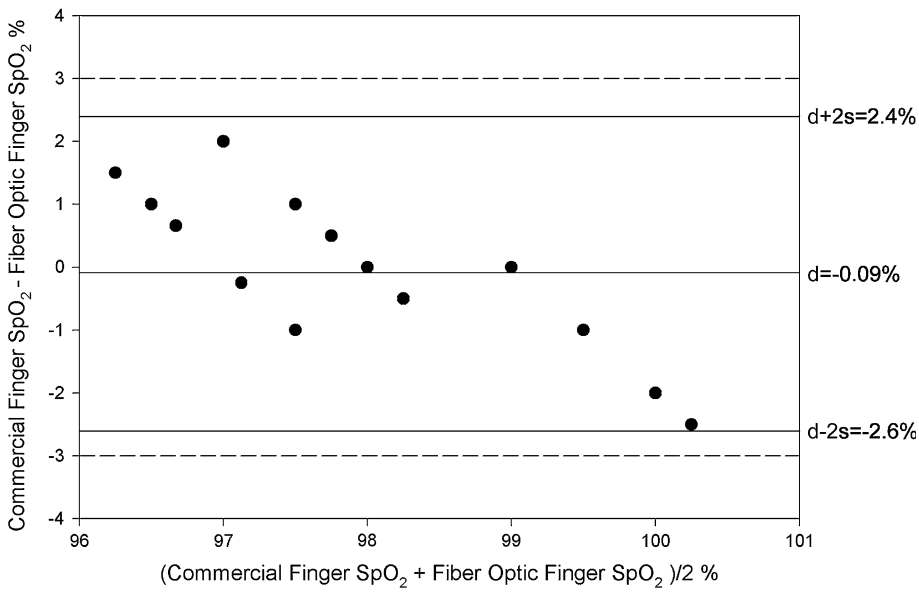

Fig. 6. Difference against the mean for SpO_2 data obtained from the finger when using the commercial pulse oximeter and the fiber optic PPG sensor (d:mean; s: standard deviation). The dotted lines indicate the ±3% accuracy of commercial pulse oximeters.

mean for the liver and stomach respectively. The limits of agreement were found to be −9.7 and 6.1% for the liver, and −6.6 and 8.2% for the stomach. These limits of agreement are too wide to be considered clinically insignificant.

CONCLUSION

A new prototype splanchnic fiber optic PPG sensor and instrumentation system were successfully developed and evaluated on seventeen patients during open laparotomy. Good quality PPG signals with large amplitudes were obtained from the large bowel, small bowel, liver and stomach.

As shown in Figure 4, there was an obvious difference in the amplitudes of the red and infrared (ac and dc) PPG signals obtained from splanchnic sites, such as the large bowel, when compared with those obtained from the finger. Also, statistical analysis showed a significant difference between the splanchnic and finger PPG amplitudes. It is thought that this could be due to differences in tissue type and vasculature amongst the various sites investigated. It is possible that the arteries are closer to the surface of the tissue in splanchnic organs when compared to a peripheral site such as the finger. Therefore, the light travelling through the splanchnic tissue may possibly encounter more pulsatile arterial blood along its path. This may explain the larger red and infrared ac PPG signals obtained from the various

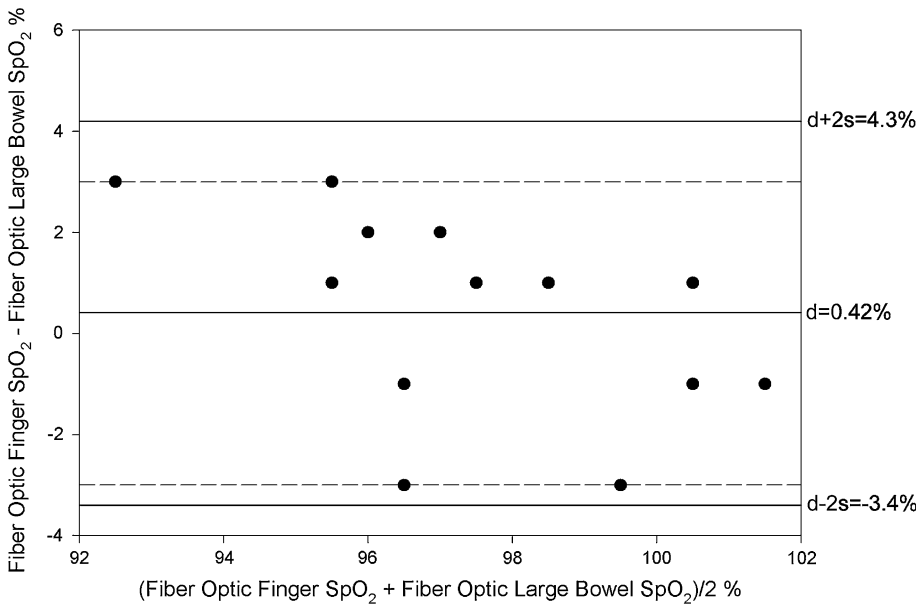

Fig. 7. Difference against the mean for SpO_2 data obtained from the large bowel using the splanchnic fiber optic PPG sensor and the corresponding finger SpO_2 values obtained using the finger fiber optic PPG sensor (d: mean; s: standard deviation). The dotted lines indicate the ±3% accuracy of commercial pulse oximeters.

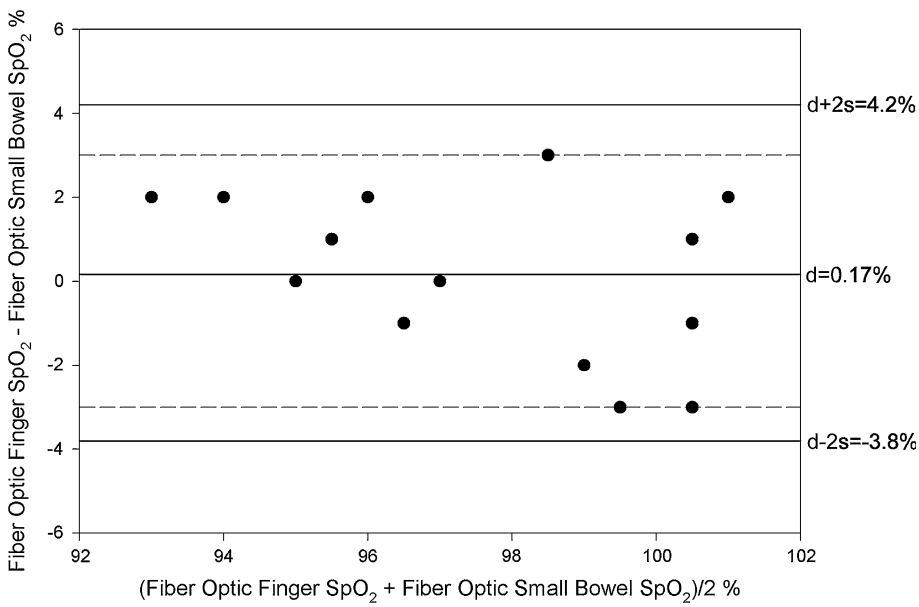

Fig. 8. Difference against the mean for SpO_2 data obtained from the small bowel using the splanchnic fiber optic PPG sensor and the corresponding finger SpO_2 values obtained using the finger fiber optic PPG sensor (d: mean; s: standard deviation). The dotted lines indicate the ±3% accuracy of commercial pulse oximeters.

abdominal organs in comparison with those obtained from the finger. Furthermore, the thick epidermis layer present in the tissue of the finger may cause the light travelling in the finger to undergo increased absorption due to non-pulsatile tissue than the light travelling in the splanchnic organ tissue. This may explain the smaller red and infrared dc PPG amplitudes obtained from the finger.

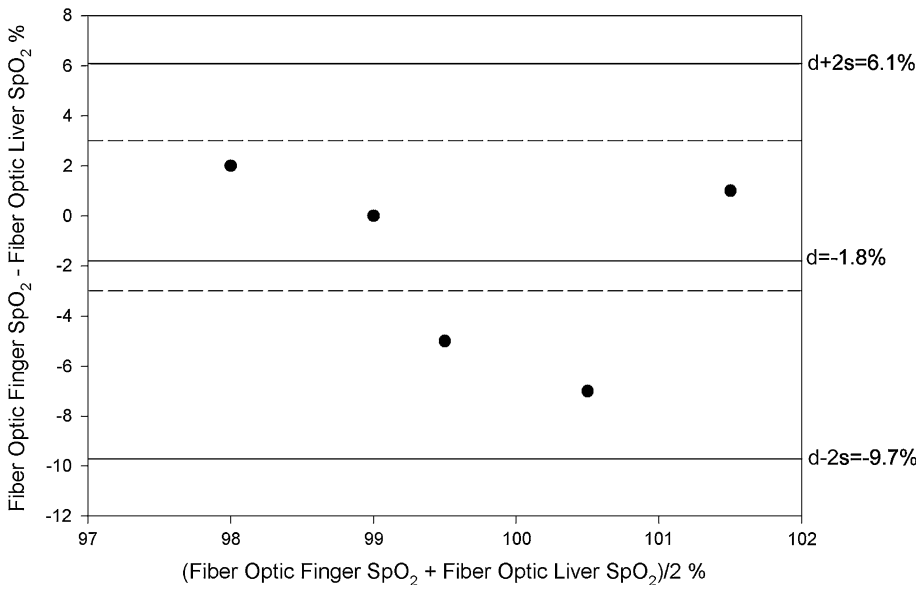

Fig. 9. Difference against the mean for SpO_2 data obtained from the liver using the splanchnic fiber optic PPG sensor and the corresponding finger SpO_2 values obtained using the finger fiber optic PPG sensor (d: mean; s: standard deviation). The dotted lines indicate the ±3% accuracy of commercial pulse oximeters.

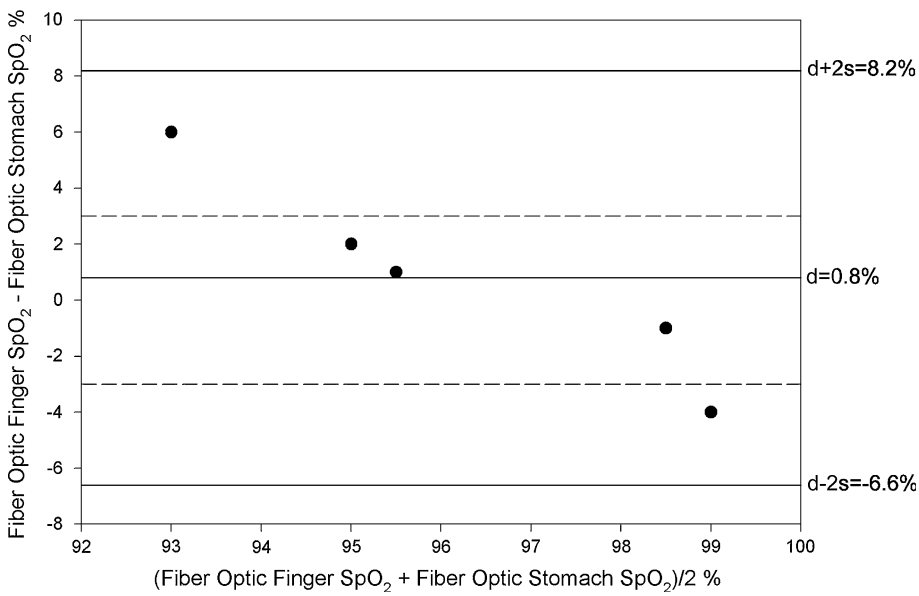

Fig. 10. Difference against the mean for SpO_2 data obtained from the stomach using the splanchnic fiber optic PPG sensor and the corresponding finger SpO_2 values obtained using the finger fiber optic PPG sensor (d: mean; s: standard deviation). The dotted lines indicate the ±3% accuracy of commercial pulse oximeters.

Despite these differences in PPG ac and dc amplitudes, the mean of the means splanchnic and finger SpO_2 values (Figure 5) showed good agreement. The small and large bowel showed almost identical SpO_2 estimations which were in close agreement with those obtained from the finger using both the commercial and fiber optic sensors. Furthermore, statistical analysis showed there to be no significant difference between SpO_2 values estimated at these sites. The results of the Bland and Altman analysis showed good agreement between both the fiber optic

finger sensors and the commercial finger pulse oximeter. Furthermore, the results of the Bland and Altman test on the large and small bowel data have indicated that large and small bowel fiber optic pulse oximetry may be feasible.

The SpO_2 measurements from the liver and stomach showed an overestimation and underestimation in comparison to those from both the commercial and fiber optic finger sensors. While these differences may not be alarming in an uncalibrated system, statistical analysis also showed there to be a significant difference between SpO_2 estimated at the liver and SpO_2 estimated at other sites. Furthermore, the limits of agreement calculated for both stomach and liver data during the Bland and Altman analysis are too wide to be considered clinically insignificant. As the sample size for both the stomach and liver data is small ($n = 5$) further PPG measurements from these sites need to be obtained before more concrete conclusions can be made as to the feasibility of fiber optic pulse oximetry from these sites.

Overall, these preliminary clinical results are positive and suggest that a splanchnic fiber optic PPG sensor may prove a useful tool for the intraoperative assessment of splanchnic perfusion. Future improvements in the accuracy of the system, such as calibration, would allow for more robust conclusions to be drawn.

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