An In Vivo Investigation of Photoplethysmographic Signals and Preliminary Pulse Oximetry Estimation from the Bowel Using a New Fiberoptic Sensor

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BACKGROUND: The continuous monitoring of splanchnic organ oxygen saturation could make the early detection of inadequate tissue oxygenation feasible, reducing the risk of hypoperfusion, severe ischemia, multiple organ failure, and, ultimately, death. Current methods for assessing splanchnic perfusion have not been widely accepted for use in the clinical care environment. In an attempt to overcome the limitations of the current techniques, a new fiberoptic photoplethysmographic (PPG)/pulse oximetry sensor was developed as a means of assessing splanchnic organ perfusion during surgery in humans.

METHODS: A new fiberoptic splanchnic pulse oximeter and an optically identical fiberoptic finger pulse oximeter have been developed. Simultaneous PPG signals and preliminary estimates of arterial oxygen saturation from the bowel (small and large) and finger were obtained in 17 patients (3 men and 14 women) undergoing open laparotomy.

RESULTS: Good quality PPG signals were obtained from the small and large bowel and from the finger in all patients (lower 95% confidence limit for the proportion was 0.64). Comparisons of blood oxygen saturation values acquired when using the splanchnic and the finger fiberoptic sensors and a commercial finger pulse oximeter indicated that there was no statistically significant difference between them (all $P > 0.454$). A Bland and Altman plot of the difference between blood oxygen saturation values from the bowel fiberoptic pulse oximeter and the fiberoptic finger pulse oximeter against their mean showed that the limits of agreement between the 2 pulse oximeters were −3.8% and 4.2% for small bowel measurements, and −3.4% and 4.3% for large bowel measurements. The 95% prediction interval for the difference between the 2 devices was between −4.2% and 4.7%.

CONCLUSION: This study demonstrated that good quality PPG signals can be obtained from the bowel using a new fiberoptic sensor. Further evaluation is required to determine whether fiberoptic pulse oximetry of the bowel may provide a suitable method for monitoring splanchnic perfusion.

Splanchnic ischemia can ultimately lead to cellular hypoxia and necrosis, and may contribute to the development of multiple organ failure and increased mortality.[1–3] Many techniques, such as laser Doppler and gastric tonometry, have been investigated as a means of monitoring the perfusion of splanchnic organs.[4–7] However, none of these methods has been widely accepted as a routine method of assessing splanchnic perfusion.[3] Pulse oximetry has been widely accepted as a reliable method for monitoring oxygen saturation of arterial blood (Spo_2).[8–10] However, the reliable estimation of Spo_2 depends on the presence of good quality photoplethysmographic (PPG) signals. Restricted arterial flow may result in diminished PPG signals, and, therefore, it has been suggested that unmeasurable Spo_2 due to the loss of pulsatility, or the amplitude and morphology of PPG signals, may reflect intestinal ischemia.[11,12] Animal studies have shown that surface pulse oximetry was rapid, reproducible, and a highly sensitive and specific technique for detecting small bowel ischemia.[12–15] However, in smaller-animal models, such as rabbits, whose intestinal diameters approach that of infants, it has been found that pulse oximetry results in a high number of false-negative results.[16] The feasibility of estimating splanchnic blood oxygen saturation in humans has also been demonstrated in a study of 30 patients using commercial transmission pulse oximeters on the intestine[11] and in a single case study of a 12-month-old girl.[17] However, there are difficulties in applying commercial pulse oximeters in abdominal human organs because available probes are unsuitable and are not easily sterilizable.[18] A preliminary

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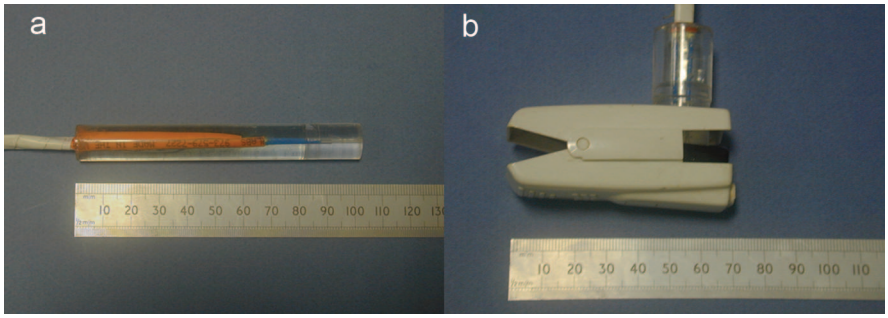

Figure 1. Photographs of (a) the developed reflectance fiberoptic splanchnic pulse oximetry sensor, and (b) the reflectance fiberoptic finger pulse oximetry sensor.

study using a prototype electrooptical system showed that measurable PPG signals with large amplitudes and good signal-to-noise ratio at 2 wavelengths (red and infrared) could be detected from various abdominal organs such as the liver and bowel.[19] The limitation of this device was that it was difficult to be held on the surface of the investigated organ.

In an attempt to overcome the limitations of previous attempts, a new sensor technology to facilitate direct measurements of splanchnic blood oxygen saturation, using fiberoptic technology, is suggested. The main advantages of fiberoptic technologies for such applications are characterized mainly by their flexibility in size, their electrical and thermal safety when placed in the body (compared with optoelectronic components attached on the body or organ), and their ease in sterilization using conventional medical sterilization techniques.[18]

A new handheld fiberoptic reflectance pulse oximetry sensor and processing system have been developed with the main aim of investigating PPG signals from the bowel. The fiberoptic sensor and its associated instrumentation and software are described before presenting results from a clinical investigation.

METHODS

Fiberoptic Pulse Oximetry Sensors

A new reflectance fiberoptic splanchnic pulse oximetry sensor was developed that comprises 2 emitters (660 and 850 nm, FFT 2000 BHR and H22E4020IR; the Optoelectronic Manufacturing Corporation, Cornwall, UK), a 1 mm^2 photodiode, a custom-made Y piece (Ocean Optics, Dunedin, FL), and 600-μm optical fiber cables (Fig. 1a).[18] The sensor was designed in a handheld configuration (pencil probe) to enable the ease of application of the sensor on the investigated organs by the clinical expert during the pilot clinical trials. This was achieved by inserting the light-transmitting and light-receiving fibers into a precision-drilled Perspex rod (diameter, 13 mm; height, 100 mm). To facilitate comparisons of the acquired Spo_2 values from splanchnic organs with those from the finger, an optically identical fiberoptic finger pulse oximetry sensor was also developed. This sensor was inserted into a modified pulse oximetry finger clip (Fig. 1b).

Instrumentation and Software

An isolated 3-channel battery-powered instrumentation system was designed to drive the optical components of both the splanchnic and finger sensors and to preprocess all AC and DC PPG signals at both wavelengths.[18] All PPG signals were digitized by a 12-bit data acquisition card (DAQCard-6024E; National Instruments, Austin, TX) in the laptop computer and displayed and analyzed by a Virtual Instrument running in LabVIEW (National Instruments). All signals were electronically archived for further offline analysis.

Patients and Measurements

After obtaining local research ethics committee approval, informed written consent was obtained from ASA physical status I or II, male or female (nonpregnant) adult patients (aged between 18 and 65 years) who were due for elective surgery involving laparotomy. Patients who were undergoing acute emergency operations or had abnormal laboratory results that were considered clinically significant to this study, or patients who were unwilling or unable to conform to the protocol, were excluded from the study.

Seventeen patients (3 men and 14 women; mean age ± SD: 54 ± 9.7 years), undergoing general anesthesia, were studied. None of the patients had a history of peripheral vascular disease or diabetes. One of the patients had a medical history of hypertension, and another had previously undergone heart failure surgery. None of the patients was receiving medication that would affect the objectives of this preliminary investigation. The study was observational and patients' surgical, anesthetic, and monitoring management were as per routine. All patients were induced with propofol 2 mg/kg IV, and after placement of an endotracheal tube, anesthesia was maintained with either 1% to 3% isoflurane or sevoflurane in a 50% to 70% air/oxygen or N_2O/oxygen mixture. The inspired concentration of the volatile anesthetic was varied to maintain hemodynamic stability. All patients were tracheally intubated and their lungs ventilated using volume-controlled intermittent positive pressure ventilation set at 12 breaths per minute (Datex-Ohmeda Aestiva/5; GE Healthcare, Hertfordshire, UK). Patient temperature was measured using temperature probes (Temprecise; Arizant, Wakefield, UK) sited in the esophagus. Arterial blood pressure was measured noninvasively from the arm every 5 minutes. The blood pressure cuff was placed on the opposite arm to the finger pulse oximetry sensor.

After the attachment of all operating room monitoring devices (electrocardiographic leads, commercial pulse oximeter, etc.), the custom-made fiberoptic finger pulse oximetry sensor was placed on the index finger of the patient. Before any splanchnic PPG measurements were taken, the fiberoptic splanchnic pulse oximetry sensor was inserted into a sterile medical ultrasound probe cover (Cory Medical, Taunton, UK) and was secured in place using 2 sterile fixation bands. At an appropriate time during the surgery (decided by the surgeon), the sensor was passed to the surgeon and it was applied gently to the surface of accessible bowel (small or large) so

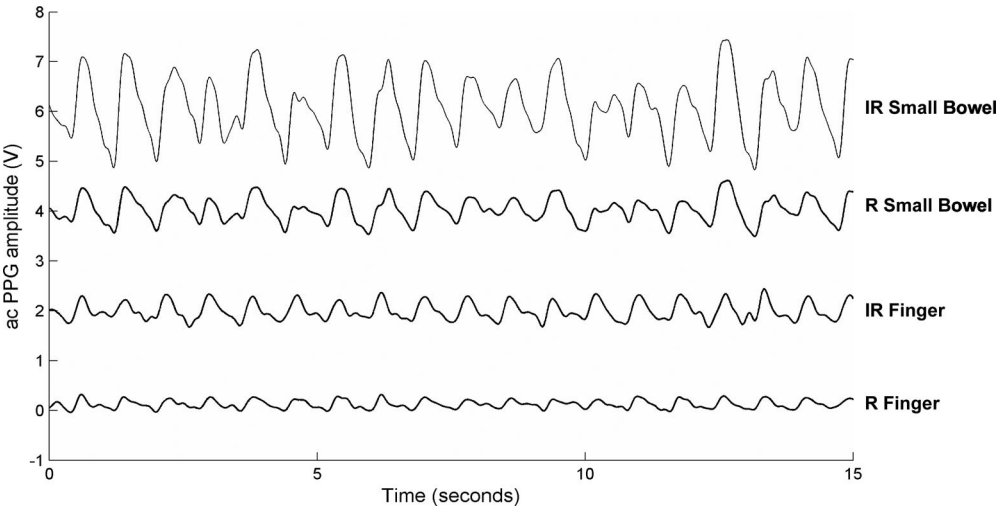

Figure 2. Typical infrared (IR) and red (R) photoplethysmographic (PPG) traces from the small bowel and their corresponding finger signals.

that the emitted light was reflected from its surface. Simultaneous AC and DC splanchnic PPG signals, and AC and DC peripheral PPG signals were recorded for approximately 2 minutes for each site under investigation. During the splanchnic PPG measurements, values of Spo_2 from a commercial finger transmission pulse oximeter (OxyTip+; GE Healthcare, UK) were also manually recorded in a notebook. The researcher recording all PPG signals and Spo_2 values was not blinded to the results from different measurement sites (splanchnic or peripheral) or different measurement devices (fiberoptic sensors or commercial finger pulse oximeter).

Data Analysis and Statistics

Although this is an uncalibrated system, preliminary Spo_2 values were estimated for each splanchnic site under investigation to provide an indication of the system's ability to estimate Spo_2. The Spo_2 values were estimated by using a typical linear equation used in pulse oximetry[18]:

$$Spo_2 = 110 - 25 \times R$$

R is known as the ratio of ratios and is given by:

$$R = \frac{r_{ac}/r_{dc}}{ir_{ac}/ir_{dc}}$$

where r_{ac} and ir_{ac} are the amplitudes of the AC red and infrared signals, respectively, and r_{dc} and ir_{dc} are the amplitudes of the DC red and infrared signals, respectively.

Mean splanchnic and finger Spo_2 values were estimated by averaging the Spo_2 values over the 2-minute monitoring period. The values recorded from the commercial device during the same monitoring period were also averaged to obtain a mean commercial Spo_2 value.

Paired *t* tests were performed using SigmaStat software (Systat Software, Inc., San Jose, CA) on all Spo_2 datasets to determine whether there was a statistically significant difference between Spo_2 estimation from the finger and the bowel (small and large). The limits of agreement between the finger fiberoptic Spo_2 values and those from the commercial pulse oximeter were calculated using the between-method differences analysis outlined by Bland and Altman.[20] The Bland and Altman method was also used to determine the limits of agreement between the finger and splanchnic fiberoptic Spo_2 datasets.

RESULTS

Good quality, easily recognizable PPG signals with large amplitudes were recorded in all attempts from the small bowel (n = 17) and large bowel (n = 14) (lower 95% confidence limit for the proportion was 0.64). In 3 cases, the large bowel was not accessible by the surgeon and as a result only PPG signals from the small bowel were obtained. During the clinical measurements, the heart rate, core temperature, mean arterial blood pressure, end-tidal CO_2, and arterial blood pressure were recorded from all patients. The mean (range) of these variables were as follows: heart rate 75.94 bpm (60–104 bpm), temperature 36.38°C (35.9°C–36.9°C), mean arterial blood pressure 78.24 mm Hg (55–98 mm Hg), end-tidal CO_2 4.46 kPa (3.9–5 kPa), and arterial blood pressure 108/64 mm Hg (90/50–144/85 mm Hg).

Figure 2 depicts typical AC PPG traces from the small bowel and the corresponding peripheral signals. The recorded PPG signals from the bowel displayed larger amplitudes than the corresponding peripheral signals obtained from the identical fiberoptic sensor. It is believed that this is attributable to the underlying difference in tissue and vasculature between the peripheral and splanchnic sites. The low-frequency artifact present on the PPG traces from the small bowel (Fig. 2) was caused by the mechanical ventilator and also, perhaps, movement of the handheld sensor.

The mean of the mean Spo_2 value estimated from the finger using the fiberoptic finger pulse oximeter sensor (97.94% ± 1.86%) was in good agreement with that obtained from the commercial pulse oximeter (97.88% ± 0.86%). The mean Spo_2 values obtained from the small and

Table 1. Results of Paired *t* Tests on the Arterial Blood Pressure Saturation (Spo_2) Data for the Small Bowel, Large Bowel, and Finger

Treatment name	Mean (%)	Standard deviation (%)	Standard error of the mean (%)
Small bowel Spo_2 (n = 17)	97.472	3.231	0.784
Large bowel Spo_2 (n = 14)	97.14	3.091	0.826
Difference	−0.19	1.861	0.497
	95% confidence interval for difference of means: −1.264% to 0.884%		
	No significant difference, P = 0.708		
Small bowel Spo_2 (n = 17)	97.472	3.231	0.784
Finger Spo_2 (n = 17)	97.681	2.355	0.571
Difference	−0.21	2.15	0.521
	95% confidence interval for difference of means: −1.315% to 0.896%		
	No significant difference, P = 0.693		
Large bowel Spo_2 (n = 14)	97.14	3.091	0.826
Finger Spo_2 (n = 14)	97.573	2.168	0.579
Difference	−0.433	2.1	0.561
	95% confidence interval for difference of means: −1.646% to 0.779%		
	No significant difference, P = 0.454		

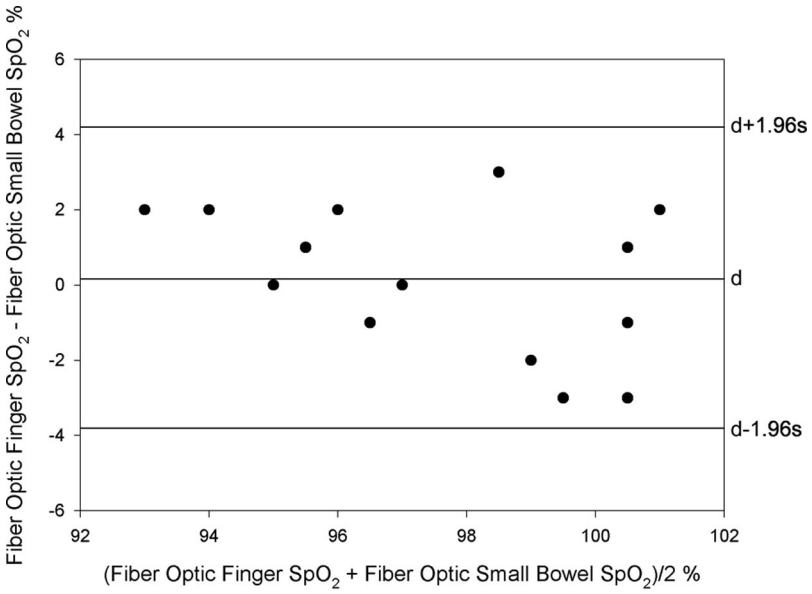

Figure 3. Difference against mean for arterial blood pressure saturation (Spo_2) data obtained from the small bowel using the splanchnic pulse oximetry sensor and the corresponding finger values obtained using the fiberoptic pulse oximetry sensor. d = mean; s = standard deviation.

large bowel (97.41% ± 3.14% and 97.14% ± 3.10%, respectively) were almost identical and are also in good agreement with the Spo_2 values from the finger (both fiberoptic and commercial sensors).

Paired t tests ($P < 0.05$) were performed on the Spo_2 data from the small bowel, large bowel, and periphery (Table 1). The mean absolute pairwise differences were <0.4%, and no significant difference was found between different sites (all $P > 0.454$).

The Bland and Altman method was used to compare Spo_2 values obtained from the small bowel and large bowel with their corresponding Spo_2 values from the finger using the fiberoptic sensor. Figures 3 and 4 show the plots of the difference between finger and splanchnic Spo_2 values against the mean for the small bowel and large bowel data, respectively. Because no obvious relation was observed between the difference and the mean in both cases, the limits of agreement were calculated as described above. The limits of agreement were found to be −3.8% and 4.2% for the small bowel data, and −3.4% and 4.3% for the large bowel. The 95% prediction intervals for the small and large bowel data were calculated to be −4.2% to 4.6% and −3.8% to 4.7%, respectively.

DISCUSSION

A new handheld fiberoptic pulse oximeter system recorded good quality PPG signals and provided Spo_2 estimates with ±4% accuracy from the small bowel (n = 17) or large bowel (n = 14) in all of the 17 patients studied. The fiberoptic pulse oximetry system in its current handheld design could be a useful tool for surgeons, enabling the assessment of some surgical outcomes early, such as the quality of surgical anastomosis.

However, the main limitation of the study was that it did not allow for the assessment of the device on patients with compromised bowel perfusion. As a result, all Spo_2 values were within the normal range. The data range of the results presented may be too narrow for Bland and Altman analysis to be helpful in assessing interchangeability of

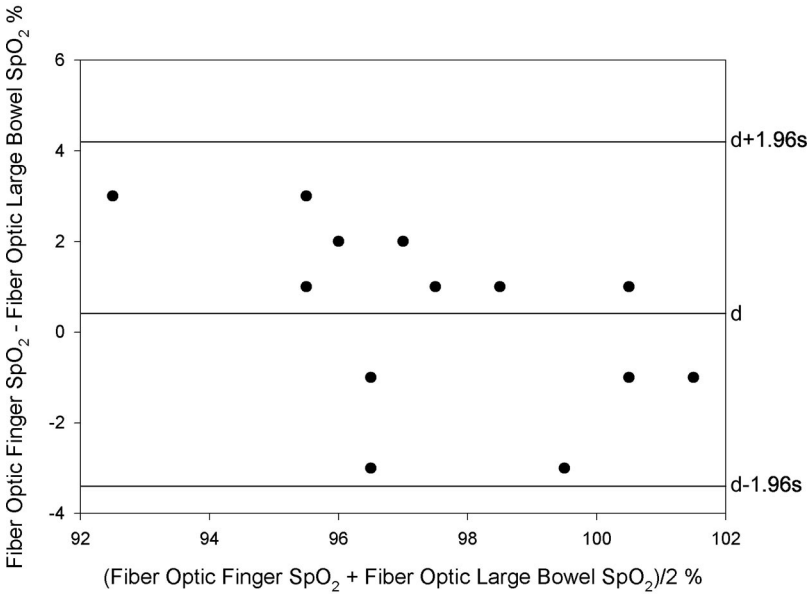

Figure 4. Difference against mean for arterial blood pressure saturation (Spo_2) data obtained from the large bowel using the splanchnic pulse oximetry sensor and the corresponding finger values obtained using the fiberoptic pulse oximetry sensor. d = mean; s = standard deviation.

methods. Therefore, the next step in evaluating the system as a potential method for detecting splanchnic ischemia would be to conduct more rigorous clinical investigations on a group of patients in which splanchnic perfusion is compromised. Also, it would be desirable to develop an experimental model (perhaps an animal study) to induce abnormally low splanchnic (bowel) Spo_2 values.

To provide a better understanding of the perfusion of the bowel, future work should include the comparison of the splanchnic Spo_2 results against other indicators of microvasculature perfusion (Doppler techniques). This may provide valuable information regarding the sensitivity of the fiberoptic sensor to changes in perfusion states.

In its current state, the developed technology is only capable of assessing PPG signals from the bowel during open laparotomy. Further probe miniaturization may enable its use in a postoperative environment. Further work needs to be performed to validate this hypothesis.

CONCLUSION

Good quality PPG signals have been obtained from the small and large bowel using a new splanchnic fiberoptic sensor. Preliminary clinical results are positive and suggest that such a sensor may prove a useful tool for the intraoperative assessment of splanchnic perfusion. Future work will assess the performance of the sensor in cases of poor bowel perfusion.

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