Preliminary assessment of abdominal organ perfusion utilizing a fiber optic photoplethysmographic sensor

M. Hickey, N. Samuels, N. Randive, R. Langford and P. A. Kyriacou, *Senior Member, IEEE*

Abstract— **In an attempt to overcome the limitations of current techniques for monitoring abdominal organ perfusion, a prototype reflectance fiber optic photoplethysmographic (PPG) sensor and processing system was evaluated on seventeen anaesthetized patients undergoing laparotomy. Good quality PPG signals were obtained from the large bowel, small bowel, liver and stomach. Simultaneous PPG signals from the finger were also obtained for comparison purposes using an identical fiber optic sensor. Analysis of the mean ac and dc PPG amplitudes of all acquired signals indicated larger amplitudes for those signals obtained from abdominal organs than those obtained from the finger. Mean estimated blood oxygen saturation (SpO_2) values from all abdominal sites showed good agreement with those obtained from the finger using both the finger fiber optic sensor and a commercial finger pulse oximeter. Furthermore, a Bland and Altman between-method-differences analysis on the estimated SpO_2 data suggests that a fiber optic abdominal sensor may be a suitable method for the evaluation of abdominal organ perfusion.**

I. Introduction

A continuous method for monitoring perfusion of the abdominal area would be invaluable in the early detection of inadequate tissue oxygenation, reducing the risk of severe hypoperfusion and multiple organ failure [1, 2]. Current techniques for assessing abdominal organ perfusion, such as Doppler ultrasound [3] and gastric tonometry [4, 5], have not been widely accepted in the clinical environment due to their intermittent and heavily operator dependent nature [1].

Pulse oximeters estimate arterial blood oxygen saturation by shining light at red and infrared wavelengths through vascular tissue [6]. In this method, the ac pulsatile PPG signal associated with cardiac contraction is assumed to be attributable solely to the arterial blood component. The amplitudes of the red and infrared ac PPG signals are sensitive to changes in arterial oxygen saturation because of differences in the light absorption of oxygenated and deoxygenated hemoglobin at these two wavelengths. From the ratios of these amplitudes, and the corresponding dc photoplethysmographic components, arterial blood oxygen saturation (SpO_2) is estimated [6]. Although pulse oximetry has been used experimentally in both animals and humans for assessing abdominal perfusion [7-9], the use of commercial pulse oximeters in the human abdomen has been found to be impractical [6]. A custom made reflectance electro-optical pulse oximeter has shown that good quality photoplethysmographic (PPG) signals can be detected from various human abdominal organs [6]. However, this probe is not suitable for prolonged continuous monitoring in the abdomen.

A prototype fiber optic PPG sensor and processing system utilizing the principle of reflectance pulse oximetry have been developed for the assessment of abdominal organ perfusion during open laparotomy [10, 11]. It is believed that the use of fiber optics may provide a safe method for prolonged continuous monitoring of oxygen saturation of abdominal organs due to their electrically safe nature and small cross-sectional area. In order to evaluate the developed technology, abdominal PPG measurements and preliminary abdominal SpO_2 estimation was performed on seventeen patients undergoing elective laparotomy.

This paper outlines the technology and the clinical methods by which the abdominal PPG signals were obtained, followed by a presentation and discussion of the results.

II. Methods

A. Fiber Optic PPG Sensor and Processing System

A reflectance fiber optic PPG sensor was developed using 600 μm core silica glass step index fibers, infrared (850 nm) and red (650 nm) emitters (OMC, UK), a 1mm^2 active area photodiode (OMC, UK), and a custom-made Y-Piece (Ocean

Manuscript received April 1 2010. This work was supported in full by the Engineering and Physical Sciences Research Council.

M. Hickey is with the School of Engineering and Mathematical Sciences, City University, London, UK (phone: +44(0)2070403878; e-mail: m.hickey@ city.ac.uk).

N. Samuels is with the Anaesthetic Laboratory and Department, St Bartholomew's Hospital, Barts and The London NHS Trust, London UK (email: nmsams@yahoo.co.uk)

N. Randive is with the Anaesthetic Laboratory and Department, St Bartholomew's Hospital, Barts and The London NHS Trust, London UK (email: drnilran@gmail.com)

R. Langford is with the Anaesthetic Laboratory and Department, St Bartholomew's Hospital, Barts and The London NHS Trust, London UK (email: r.m.langford@btconnect.com)

P. A. Kyriacou is with the School of Engineering and Mathematical Sciences, City University, London, UK (e-mail: p.kyriacou@city. ac.uk).

Optics, Netherlands). The fibers were Subminature version A (SMA) coupled to the emitters and detectors at one end, and the bare fibers at the other end were then accommodated in a custom-made Perspex rod in order to facilitate ease of placement on the abdominal organs during laparotomy (Fig.1(a)). An optically identical fiber optic sensor was also developed to enable monitoring of PPG signals from the finger, and therefore allow the comparison between abdominal and finger PPG signals (Fig. 1(b)). An electrically isolated processing system was constructed to drive the optical components of the sensors and to pre-process the red and infrared ac and dc PPG signals from both the abdominal site and the finger. The PPG signals were then digitized by a 12-bit data acquisition card (DAQCard-6024E, National Instruments, Texas, USA) at a sampling rate of 200Hz, where they were displayed, analyzed and saved on a laptop computer running LabVIEW.

The technical details of the sensors, the processing and data acquisition systems have been described in previous publications [10, 11].

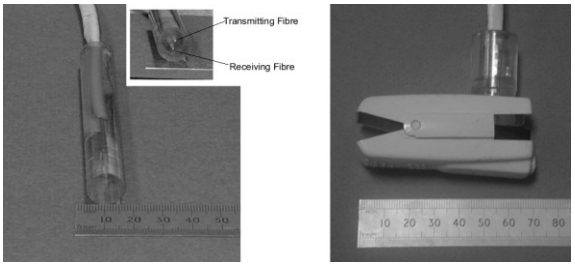

Fig.1. (a) The developed abdominal fiber optic PPG sensor and (b) the identical finger fiber optic PPG sensor

A. Evaluation of the Fiber-Optic Sensor during Open Laparotomy

Ethics Committee approval was obtained to study patients undergoing elective laparotomy. Photoplethysmographic measurements were made in seventeen anesthetized patients (three male and fourteen female, mean age (±SD): 54 ± 9.7). The study was observational and patients' surgical, anesthetic and monitoring management were as per routine. The fiber optic abdominal 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. Blood oxygen saturation values from a commercial finger pulse oximeter (GE Healthcare) were also simultaneously monitored and recorded in a notebook.

III. RESULTS

Good quality photoplethysmographic signals with high Signal to noise ratio (SNR) (approx. 80dB) were obtained from the small bowel (n=17), large bowel (n=17), liver (n=5) and stomach (n=5). Figures 2 and 3 show typical ac red and infrared PPG signals obtained from the small bowel and large bowel respectively.

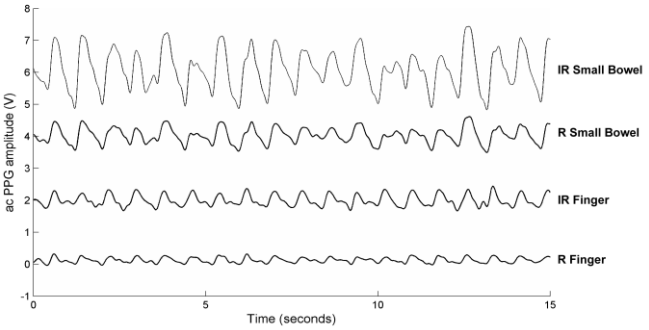

Fig.2. Red (R) and infrared (IR) ac PPG signals from the small bowel and finger when using the custom-made fiber optic abdominal and finger sensors. Signals have been offset for display purposes

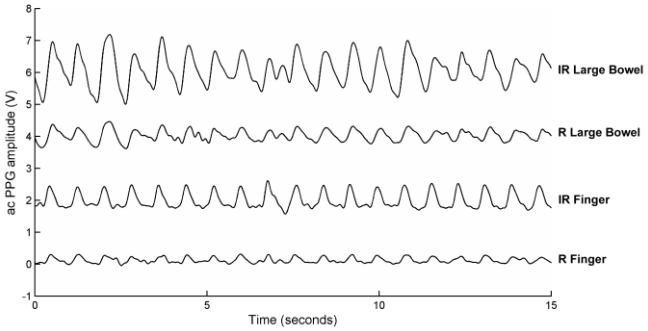

Fig.3. Red (R) and infrared (IR) ac PPG signals from the large bowel and finger when using the custom-made fiber-optic abdominal and finger sensors. Signals have been offset for display purposes

In order to provide an indication of how PPG amplitudes differ between sites, the mean abdominal red (R) and infrared (IR) ac and dc PPG amplitudes for each site were calculated. The mean ac and dc red and infrared PPG amplitudes from the finger were also calculated (Fig. 4 and 5).

Although the fiber optic sensors are not calibrated for pulse oximetry, preliminary mean SpO_2 values were calculated for the small bowel, large bowel, liver, stomach and finger (Fig. 6). The mean SpO_2 values from the commercial pulse oximeter are also included for comparison purposes.

Paired *t*-tests ($p<0.05$) were carried out (using SigmaStat, USA) on the estimated SpO_2 data sets (fiber optic abdominal sensor, fiber optic finger sensor and commercial finger pulse oximeter) to determine whether there was a statistically significant difference between SpO_2 values from the different monitoring sites. Due to the small sample size of both the liver and stomach data (n=5), these were omitted from the statistical analysis. There was no statistically significance difference amongst any of the combinations of comparisons between SpO_2 from the various abdominal organs and the

finger when using the fiber optic sensors.

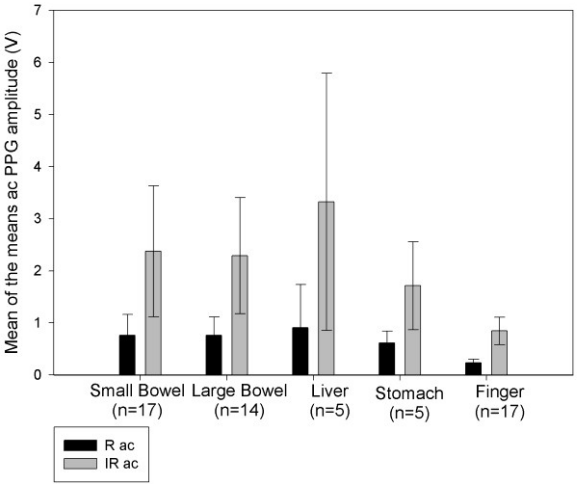

Fig.4. Mean (±SD) ac PPG amplitudes for the small bowel (n = 17), large bowel (n = 14), liver (n = 5), stomach (n = 5) and the finger (n = 17)

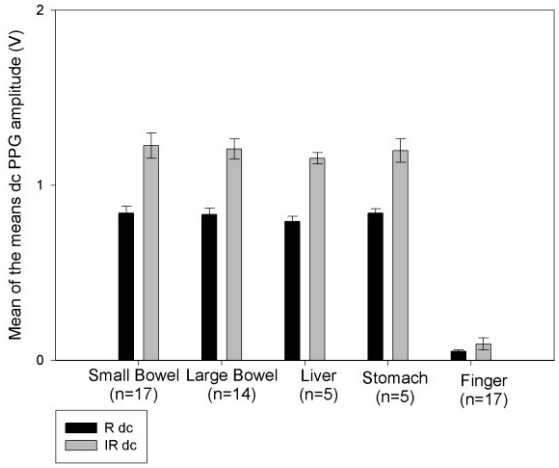

Fig.5. Mean (±SD) dc PPG amplitudes for the small bowel (n = 17), large bowel (n = 14), liver (n = 5), stomach (n = 5) and the finger (n = 17)

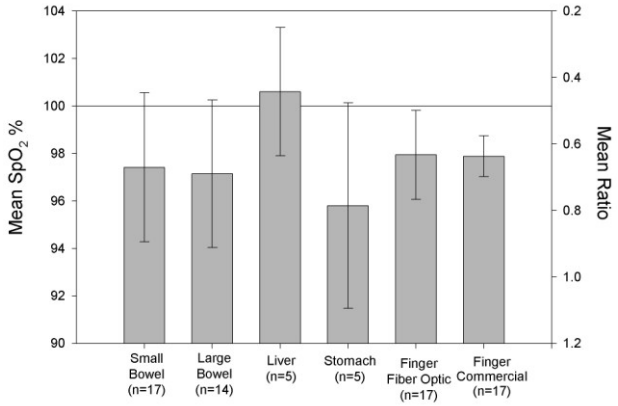

Fig.6. Mean SpO_2 (±SD) values for small bowel, large bowel, liver, stomach, and finger. The mean SpO_2 (±SD) value from the commercial pulse oximeter is also included

In order to facilitate a more thorough analysis of the SpO_2 data sets, the Bland and Altman between-method-differences analysis was utilized to investigate the level of agreement between the fiber optic finger PPG sensor and the commercial finger pulse oximeter, as well as the level of agreement between the small bowel, large bowel and finger SpO_2 values (fiber optic PPG sensors) [12]. 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±2s (the limits of agreement) would not be clinically important then the two measurement methods or instruments could be used interchangeably [12].

Figures 7 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 are included in Figure 7.

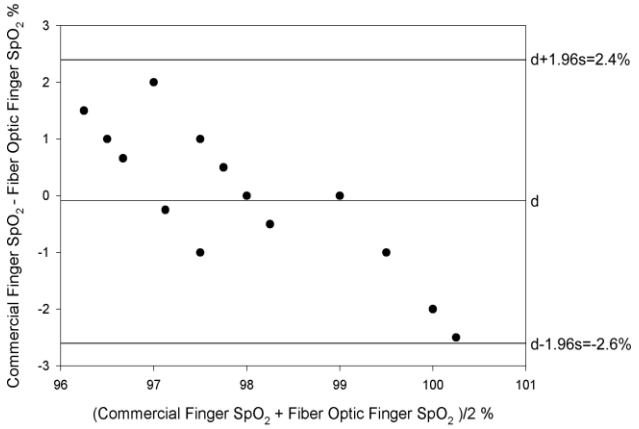

Fig.7. Difference against the mean for SpO_2 data obtained from the finger when using the commercial and the fiber optic pulse oximeters (d:mean; s: standard deviation).

Figures 8 and 9 show the plots of the difference between finger and abdominal SpO_2 values against the mean for the small bowel and large bowel respectively. Again no obvious relation is observed between the difference and the mean in each case. Therefore, the limits of agreement were calculated and are included in Figures 8 and 9.

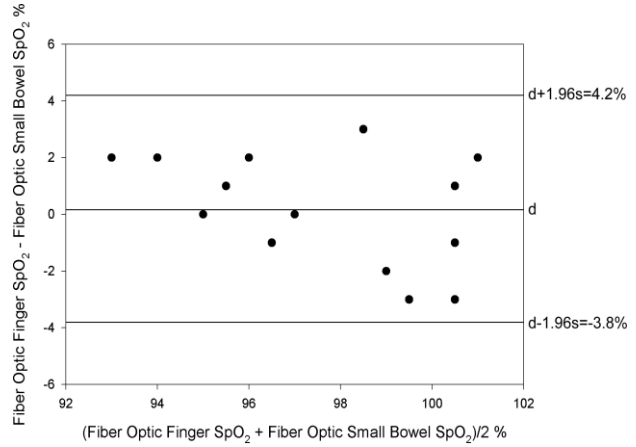

Fig.8. Difference against the mean for SpO_2 data obtained from the small bowel using the abdominal fiber optic PPG sensor and the corresponding finger SpO_2 values obtained using the finger fiber optic PPG sensor (d:mean; s: standard deviation).

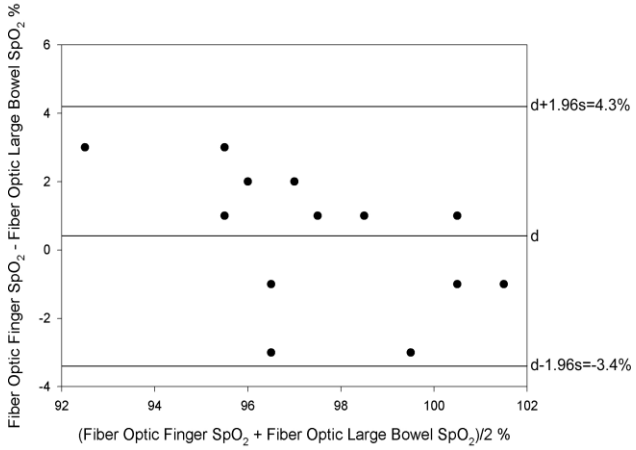

Fig.9. Difference against the mean for SpO_2 data obtained from the small bowel using the abdominal fiber optic PPG sensor and the corresponding finger SpO_2 values obtained using the finger fiber optic PPG sensor (d:mean; s: standard deviation).

IV. Conclusion

A prototype fiber optic PPG sensor and processing system were successfully developed and evaluated during open laparotomy. Good quality PPG signals with large amplitudes were obtained from each investigated abdominal organ.

The difference in the mean ac and dc PPG amplitudes as shown in Figures 4 and 5 could be due to differences in tissue type and vasculature amongst the various sites investigated. It is also possible that the arteries are closer to the surface of the tissue in abdominal organs when compared to a peripheral site such as the finger. In such occasions the light travelling through the abdominal tissue will possibly encounter more pulsatile arterial blood along its path, than light travelling in the finger, which may explain the larger red and infrared ac PPG signals obtained from the various abdominal organs in comparison with those obtained from the finger. 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 abdominal organ tissue. This may explain the smaller red and infrared dc PPG amplitudes obtained from the finger.

There was good agreement between blood oxygen saturation values obtained from the abdominal organs and the finger when using the custom made fiber optic sensors and the commercial pulse oximeter. A pared t-test statistical analysis of the estimated SpO_2 values from the small and large bowel and the finger showed no significant difference. Also, there was no statistically significant difference between the abdominal SpO_2 values and the commercial pulse oximeter SpO_2 values. The result of the Bland and Altman test showed broad agreement between both the fiber optic PPG sensors and the commercial finger pulse oximeter.

These preliminary clinical results are positive and suggest that the abdominal fiber optic PPG sensor may prove a useful tool for the intraoperative assessment of abdominal perfusion.

References

[1] Jury of the Consensus, "Tissue Hypoxia: How to detect, how to correct, how to prevent?", *Intensive Care Med*, vol. 22, pp. 1250-1257, 1996.

[2] D.R. Dantzker, "The gastrointestinal tract. The canary of the body?", J*AMA*, vol. 270(10), pp. 1247-1248, 1993.

[3] G.B. Bulkley, G.D. Zuidema , S.R. Hamilton, O'Mara CS, Klacsmann PG, Horn SD. Intraoperative determination of small intestinal viability following ischemic injury: a prospective, controlled trial of two adjuvant methods (doppler and fluorescein) compared with standard clinical judgment. Ann Surg 1981;193:628–637

[4] C. V. Soong, P. H. Blair, M. I. Halliday, M. D. McCaigue, G. R. Campbell, J. M. Hood, B. J. Rowlands, and A. A. B. D'Sa, "Endotoxaemia, the generation of the cytokines and their relationship to intramucosal acidosis of the sigmoid colon in elective abdominal aortic aneurysm repair." Eur J Vasc Surg, vol. 7, no. 5, pp. 534–539, Sep 1993.

[5] M. Hatherill, S. M. Tibby, R. Evans, and I. A. Murdoch, "Gastric tonometry in septic shock." Arch Dis Child, vol. 78, no. 2, pp. 155–158, Feb 1998.

[6] A.J. Crerar-Gilbert, P.A. Kyriacou, D.P. Jones and R.M. Langford, "Assessment of photoplethysmographic signals for the determination of splanchnic oxygen saturation in humans", *Anaesthesia*, vol. 57, pp. 442-445, 2002.

[7] J. DeNobile, P. Guzzetta, and K. Patterson, "Pulse oximetry as a means of assessing bowel viability", *J Surg Res*, vol. 48, pp. 21-23, 1990.

[8] K. Ouriel, W.M. Fiore, and J.E. Geary, "Detection of occult colonic ischemia during aortic procedures: use of an intraoperative photoplethysmographic technique", J Vasc Surg, vol. 7, pp. 5-9, 1988.

[9] E.R.L Hei, and A. Shun, "Intra-operative pulse oximetry can help determine intestinal viability", *Pediatr Surg Int*, vol. 17, pp. 2-3, 2001.

[10] M. Hickey, and P. A. Kyriacou, "Development of a New Splanchnic Perfusion Sensor", *Conf. Proc. IEEE. Eng Med. Bil. Soc,* pp. 2952-5, 2007.

[11] M. Hickey,N. Samules, N. Randive, R. Langford and P. A. Kyriacou, "In-vivo evaluation of a fiber-optic splanchnic photoplethysmographic sensor during open laparotomy", *Conf. Proc. IEEE. Eng Med. Bil. Soc,* pp. 1505-8, 2009.

[12] J.M. Bland, and D.G. Altman, "Statistical methods for assessing agreement between two methods of clinical measurement", *Lancet*, vol. 1, pp. 307-310, 1986.