A new fibre optic pulse oximeter probe for monitoring splanchnic organ arterial blood oxygen saturation

M. Hickey[a,*], *N. Samuels*[b], *N. Randive*[b], *R. Langford*[b], *P.A. Kyriacou*[a]

[a] *School of Engineering and Mathematical Sciences, City University London, London, UK*
[b] *Anaesthetic Laboratory and Department, St Bartholomew's Hospital, London, UK*

A B S T R A C T

A new, continuous method of monitoring splanchnic organ oxygen saturation (SpO_2) would make the early detection of inadequate tissue oxygenation feasible, reducing the risk of hypoperfusion, severe ischaemia, and, ultimately, death. In an attempt to provide such a device, a new fibre optic based reflectance pulse oximeter probe and processing system were developed followed by an *in vivo* evaluation of the technology on seventeen patients undergoing elective laparotomy. Photoplethysmographic (PPG) signals of good quality and high signal-to-noise ratio were obtained from the small bowel, large bowel, liver and stomach. Simultaneous peripheral PPG signals from the finger were also obtained for comparison purposes. Analysis of the amplitudes of all acquired PPG signals indicated much larger amplitudes for those signals obtained from splanchnic organs than those obtained from the finger. Estimated SpO_2 values for splanchnic organs showed good agreement with those obtained from the finger fibre optic probe and those obtained from a commercial device. These preliminary results suggest that a miniaturized 'indwelling' fibre optic sensor may be a suitable method for pre-operative and post-operative evaluation of splanchnic organ SpO_2 and their health.

Keywords:
Fibre optics
Pulse oximetry
Photoplethysmography
Perfusion
Splanchnic organs

1. Introduction

If an organ or tissue is not sufficiently perfused with oxygenated blood, cell death and tissue necrosis can ensue. Failure of one organ due to malperfusion may lead indirectly to the dysfunction of distant organs through the release of various toxins into the portal blood stream [1]. This could result in the onset of multiple organ failure, which is a common cause of morbidity following major surgery [2]. Previous studies have indicated that the gastrointestinal tract may be the canary of the body, making early detection of malperfusion feasible [3]. This suggests that a continuous method for monitoring perfusion of the splanchnic area would be invaluable in the early detection of inadequate oxygenation [4].

Currently, there is no widely accepted method for assessing splanchnic perfusion in the clinical care environment. Techniques such as polarographic oxygen electrodes and positron emission tomography remain research tools [2], while laser Doppler, Doppler ultrasound [5], and intravenous fluorescein [2] methods are complex, expensive, do not measure oxygenation directly, and are not suitable for routine monitoring. Gastric tonometry, although one of the few techniques currently used in clinical practice for estimating intestinal hypoxia, has not been widely accepted due to the intermittent, heavily operator dependent and time consuming nature of the device [6].

Pulse oximetry has also been used experimentally in both animals and humans [7–10] where it was found to be a

* *Corresponding author at*: School of Engineering and Mathematical Sciences, City University London, Northampton Square, London, UK EC1 V 0HB. Tel.: +44 02070403878.
E-mail address: Michelle.Hickey.1@city.ac.uk (M. Hickey).

rapid, reproducible, as well as a highly sensitive and specific technique for detecting small bowel ischaemia. The use of commercial pulse oximeters for estimating splanchnic perfusion in humans has been found to be impractical (bulky probes, cannot be sterilized, etc.) [4]. More recently a custom made reflectance pulse oximeter has shown for the first time that good quality photoplethysmographic (PPG) signals can be detected from various human abdominal organs (bowel, kidney, liver) during open laparotomy [4]. However, this probe is not suitable for prolonged continuous monitoring in the abdomen.

In an attempt to overcome the limitations of the current techniques for measuring splanchnic blood oxygen saturation, a new prototype fibre-optic probe was developed for investigating PPG signals from various splanchnic organs and also estimating arterial blood oxygen saturation (SpO_2) of splanchnic organs during open laparotomy. An electrically isolated instrumentation system and a signal acquisition system were also developed for driving the optical components of the sensor, pre-processing and displaying the acquired PPG signals on the screen of a laptop computer. The developed system was evaluated *in vivo* on seventeen patients undergoing surgery.

2. Methods

2.1. *Fibre optic pulse oximeter probes*

A reflectance fibre optic splanchnic pulse oximeter probe was designed using 600 μm core silica glass step index fibres, infrared (850 nm) and red (650 nm) emitters, and a 1 mm^2 active area photodiode [9]. In order to facilitate the evaluation of the fibre optic probe during open laparotomy, it was decided to configure the probe as a handheld device. Fig. 1(a) shows the finished splanchnic probe. For comparison purposes an identical (electrically and optically) reflectance fibre optic probe was also developed to enable the monitoring of PPG signals from a peripheral site (finger or toe) (Fig. 1(b)).

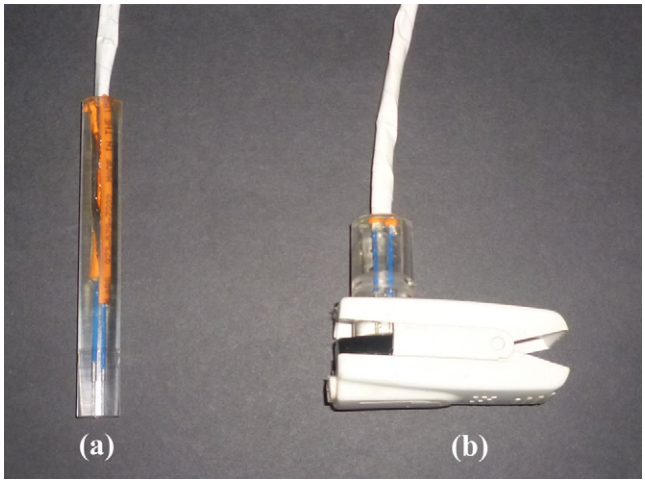

Fig. 1 – (a) The developed splanchnic fibre optic probe and (b) the identical finger probe.

2.2. *Isolated instrumentation system and virtual instrument*

An electrically isolated instrumentation system was designed and developed to drive the optical components of the fibre optic probes and also to detect and pre-process the red and infrared ac and dc PPG signals (Fig. 2). For each probe, the light detected by the photodiode is split into its red (R) and infrared (IR) PPG components, before passing through an isolation barrier, which was included for increased patient safety. The R and IR PPG signals from each probe where then further processed to divide each signal into its ac and dc PPG parts.

A virtual instrument (VI) implemented in *LabVIEW* (National Instruments, USA) was also developed. The VI is used for driving various hardware sections of the instrumentation system and for the acquisition, displaying, analysis and storing of all acquired PPG signals. It also provides an algorithm for the estimation of SpO_2. Detailed technical details of the processing system are described by Hickey and Kyriacou [11].

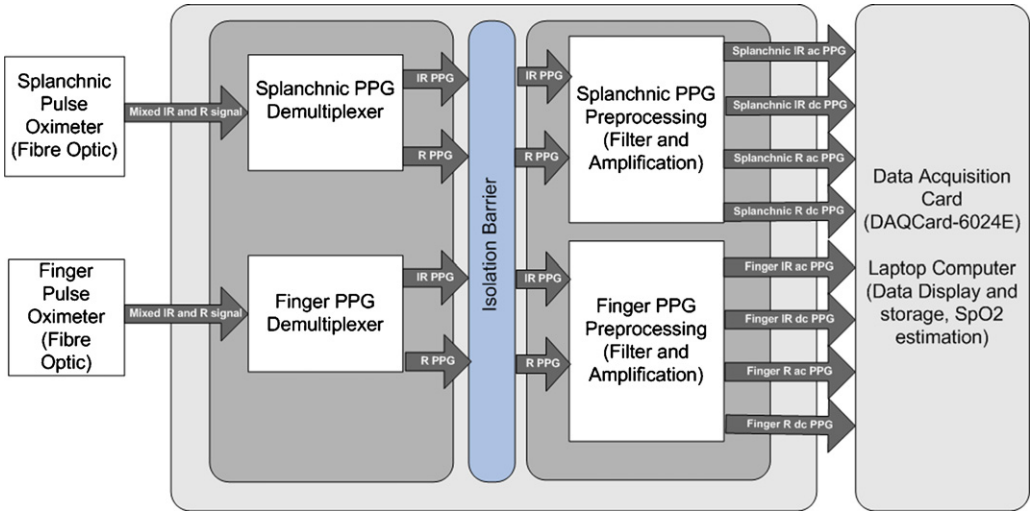

Fig. 2 – Block diagram illustration the functional aspects of the instrumentation system (IR: infrared and R: red).

2.3. *Preliminary investigation of fibre-optic probe during open laparotomy*

Local Research Ethics Committee approval was obtained to investigate ASA 1 and 2 (American Standard of Anaesthesiology; scale 1–5, with 5 the most critically ill patient) patients undergoing elective laparotomy following informed written consent. Photoplethysmographic measurements were made in seventeen patients (three male and fourteen female, mean age (±SD): 54 ± 9.7). Table 1 presents more details on the patients included in the investigation. As the study was observational, patients' surgical, anaesthetic and monitoring management were as per routine. All patients were induced with propofol (2 mg/kg IV) and anaesthesia 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 anaesthetic was varied to maintain hemodynamic stability. All patients were intubated and ventilated using volume controlled intermittent positive pressure ventilation set at 12 breaths per minute (Datex-Ohmeda Aestiva/5, GE Healthcare, UK). Patient temperature was measured using temperature probes (Temprecise, Arizant, UK) sited in the oesophagus. Blood pressure was measured non-invasively from the arm every 5 min. The blood pressure cuff was placed on the opposite arm to the finger pulse oximetry sensor.

Before introducing the splanchnic fibre optic pulse oximeter into the surgical site, the probe was placed into a sterile medical ultrasound cover which was transparent to the light being emitted. At an appropriate time during the surgery, the surgeon placed the splanchnic pulse oximeter probe on the surface of each accessible abdominal organ (Fig. 3). For comparison purposes the identical fibre optic finger pulse oximeter probe was also placed on the index finger of the right hand. Signals were monitored and acquired for approximately 2 min at each site. Blood oxygen saturation from a commercial finger pulse oximeter (GE Healthcare, UK) was also simultaneously monitored and recorded. The commercial finger probe was placed on the middle finger of the right hand as well.

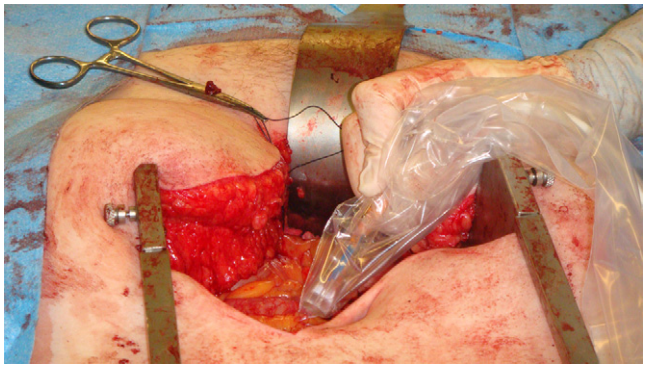

Fig. 3 – *In vivo* measurement of red and infrared splanchnic PPG signals during open laparotomy.

3. Results

Good quality PPG signals with large amplitudes were recorded in all attempts from the small bowel ($n = 17$), large bowel ($n = 14$), liver ($n = 5$) and stomach ($n = 5$). Fig. 4 depicts ac red (R) and infrared (IR) PPG traces from the large bowel, stomach and the finger. The low frequency artifact present on the splanchnic PPG traces was due to the mechanical ventilator and movement of the handheld sensor.

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 in Matlab [12]. The SNR values of all signals were approximately 80 dB.

Table 1 – Details of patients included in the preliminary investigation. All parameters were taken prior to the investigation.

	Sex	Procedure	Pulse rate (bpm)	Temp (°C)	Blood pressure (mm Hg)
1	M	Whipples	90	36.2	108/62
2	F	Laparotomy	85	36.4	100/76
3	F	Laprascopy assisted Anteriorresectum ± open	92	36	90/63
4	M	Laparotomy + subtotal colectomy	89	36.9	90/56
5	F	Laparotomy + debulking anterior resection	61	36.7	112/65
6	M	Laparotomy	71	36.2	98/64
7	F	TAH[a] radical	74	36.7	122/71
8	F	Hepatectomy	104	36.5	114/60
9	F	Laparotomy for invitional hernia repair	64	36.4	118/71
10	F	Laparotomy	69	36.7	117/67
11	F	Laparotomy	67	36.7	98/60
12	F	TAHBSO[b]	87	35.9	129/85
13	F	TAHBSO[b]	70	36.2	100/50
14	F	TAHBSO[b] + removal of ovarian mass	61	36.4	144/64
15	F	Laparotomy + pelvic exentoration	74	36.1	110/54
16	F	Laparotomy for pelvic mass	60	36.2	96/67
17	F	TAHBSO[b]	73	36.2	100/60

[a] Total abdominal hysterectomy.
[b] Total abdominal hysterectomy bilateral salpingo-oophorectomy.

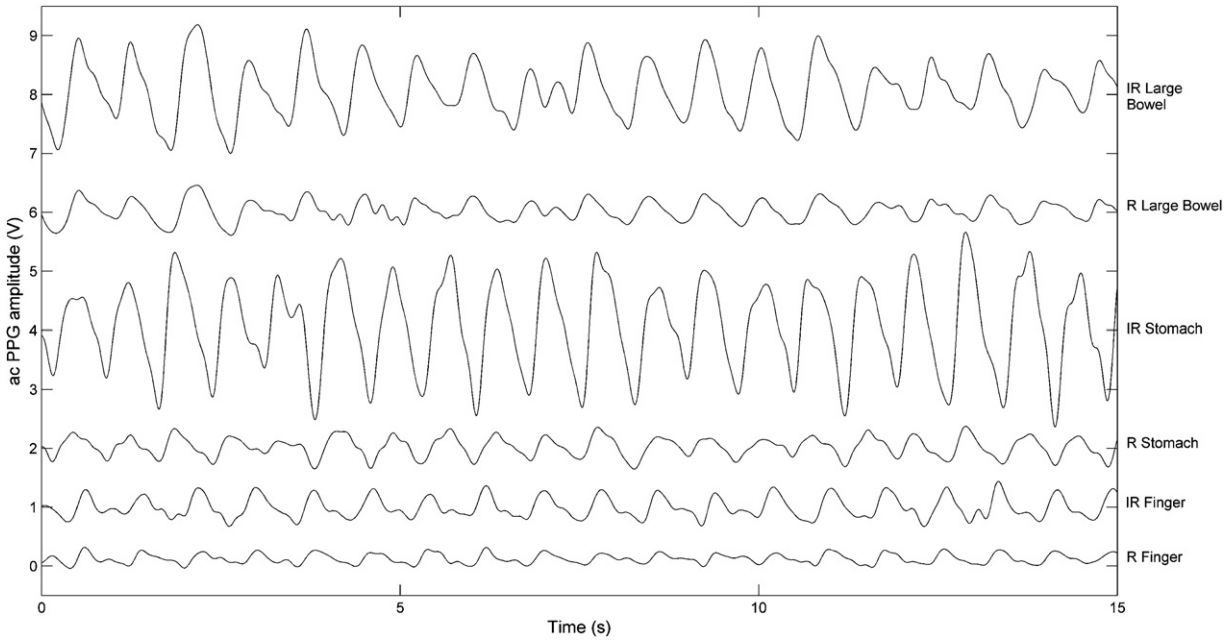

Fig. 4 – Ac red (R) and infrared (IR) PPG signals from the large bowel, stomach and periphery.

Table 2 – Mean (±SD) infrared (IR) and red (R) ac and dc amplitudes for all sites.

Site	Mean IR ac (V)	Mean R ac (V)	Mean IR dc (V)	Mean R dc (V)
Small bowel ($n = 17$)	2.37 ± 1.26	0.76 ± 0.41	1.23 ± 0.07	0.84 ± 0.04
Large bowel ($n = 14$)	2.29 ± 1.11	0.76 ± 0.35	1.20 ± 0.06	0.83 ± 0.03
Liver ($n = 5$)	3.32 ± 2.47	0.91 ± 0.82	1.16 ± 0.03	0.79 ± 0.03
Stomach ($n = 5$)	1.71 ± 0.84	0.62 ± 0.23	1.20 ± .07	0.84 ± 0.02
Finger ($n = 17$)	0.85 ± 0.26	0.23 ± 0.07	0.09 ± 0.03	0.05 ± 0.01

In order to provide an indication of how PPG amplitudes differ between sites, the mean splanchnic ac and dc PPG amplitudes for each site were calculated. The mean finger ac and dc amplitudes were also calculated (Table 2).

Although this is an uncalibrated pulse oximetry system, preliminary mean SpO_2 values were calculated for the small bowel, large bowel, liver, stomach and finger (Table 3). The-mean SpO_2 values from the commercial pulse oximeter are also included for comparison purposes.

Table 3 – Mean (±SD) SpO_2 values for each patient and each measurement site. The mean of the mean (±SD) SpO_2 for each measurement site is included at the end of the table.

Patient	Small bowel	Large bowel	Liver	Stomach	Finger	Commercial
1	96.99 ± 3.77	98.31 ± 3.11	103.7 ± 1.02	100.99 ± 2.13	97.46 ± 2.74	98 ± 0
2	97.29 ± 3.25	98.15 ± 2.27	101.18 ± 3.71	90.46 ± 1.58	97.14 ± 2.99	97 ± 0
3	95.49 ± 3.61	95.39 ± 2.94	–	–	95.40 ± 2.86	97 ± 0
4	92.01 ± 5.29	91.30 ± 4.36	96.92 ± 4.31	–	95.79 ± 3.03	97 ± 0
5	94.88 ± 3.62	94.47 ± 3.5	–	–	97.28 ± 2.51	98 ± 0
6	94.86 ± 2.71	96.61 ± 2.95	–	–	96.01 ± 2.89	97 ± 0
7	99.93 ± 3.31	102.34 ± 2.51	–	–	101.52 ± 2.54	99 ± 0
8	92.50 ± 3.24	94.78 ± 3.5	–	–	95.86 ± 2.89	98 ± 0
9	100.46 ± 1.91	100.83 ± 2.75	–	–	97.75 ± 2.96	97 ± 0
10	101.12 ± 2.33	–	–	–	100.42 ± 3.17	99 ± 0
11	101.38 ± 3.78	–	–	98.81 ± 3.88	97.64 ± 2.92	98 ± 0
12	100.79 ± 2.15	100.51 ± 2.4	–	–	98.96 ± 2.5	99 ± 0
13	95.38 ± 2.13	94.64 ± 3.27	–	94.73 ± 2.95	95.77 ± 2.52	97 ± 0
14	97.22 ± 4.88	–	–	–	100.25 ± 2.4	99 ± 0
15	94.58 ± 2.12	95.51 ± 1.5	99.46 ± 2.4	93.95 ± 3.08	97.88 ± 2.83	98 ± 0
16	100.29 ± 4.4	100.39 ± 3.8	–	–	101.18 ± ±2.92	99 ± 0
17	101.86 ± 2.17	96.7 ± 4.29	101.8 ± 3.25	–	98.11 ± 3.17	97 ± 0
Mean	97.41 ± 3.14	97.14 ± 3.11	100.60 ± 2.70	95.80 ± 4.32	97.94 ± 1.87	97.88 ± 0.86

Table 4 – Results of paired *t*-test comparisons on estimated SpO_2 values from all sites.

	Small bowel	Large bowel	Liver	Stomach	Finger	Commercial
Small bowel	–	NS	$p = 0.023$	NS	NS	NS
Large bowel	NS	–	$p \leq 0.001$	NS	NS	NS
Liver	$p = 0.023$	$p \leq 0.001$	–	NS	NS	$p = 0.038$
Stomach	NS	NS	NS	–	NS	NS
Finger	NS	NS	NS	NS	–	NS
Commercial	NS	NS	$p = 0.038$	NS	NS	–

A paired *t*-test was used to determine if there was any significant difference between the estimated SpO_2 values obtained between sites (Table 4).

4. Conclusion

A new fibre optic pulse oximeter probe, an instrumentation system and a virtual instrument were successfully developed and evaluated on seventeen patients during surgery. Good quality PPG signals with high signal-to-noise ratios were recorded on all attempts from various splanchnic organs. By observing Fig. 4 and Table 2, it can be seen that there is a significant difference between the mean ac and dc PPG amplitudes obtained from the splanchnic sites when compared with those obtained from the finger. These differences might be due to differences in tissue type and vasculature amongst the sites investigated. It is possible that in the tissue of splanchnic organs, the arteries and, therefore the blood supply, are closer to the surface than in a peripheral site such as the finger. In this case, the light travelling through the splanchnic tissue will possibly encounter more pulsatile arterial blood along its path, than light travelling in the finger. This may explain the larger red and infrared ac PPG signals obtained from the various splanchnic organs in comparison with those obtained from the finger. Peripheral tissue, such as that on the finger, has a thick epidermis layer and as a result light travelling in the finger may undergo more absorption due to non-pulsatile tissue than light travelling in the splanchnic region. Again, this may explain the smaller red and infrared dc PPG amplitudes obtained from the finger. During the described clinical study, amore detailed and thorough investigation into the morphology of the splanchnic PPGs in comparison to the peripheral PPGs was not possible. However, it is proposed that a more controlled study (perhaps animal studies) where every organ can be looked at in more detail may provide answers to the suggested hypothesis.

Despite the differences in the amplitude of the splanchnic PPGs, the mean SpO_2 values from all splanchnic sites together with the finger SpO_2 values estimated from the finger fibre optic pulse oximeter and the SpO_2 values obtained from the commercial pulse oximeter showed a broad agreement (Table 3). There was larger variation in the obtained finger SpO_2 values obtained using the fibre optic sensor than those obtained from the commercial sensor (Table 3). This may be due to the different signal processing methods applied to the acquired PPG signals within the commercial device. Therefore, the commercial SpO_2 values were only included for comparison purposes. Furthermore, the SpO_2 values obtained from both fibre optic probes sometimes give estimations over 100%. This is not alarming in an uncalibrated device.

The results of a paired *t*-test on the SpO_2 data (Table 4) showed that there was no significant difference in the estimation of blood oxygen saturation from the small bowel, large bowel, stomach, and finger. Furthermore, no statistically significant difference was found when the signals from these sites were compared with the recorded commercial pulse oximeter SpO_2 values. The SpO_2 values from the liver showed statistically significant differences between the values from the commercial device, as well as those obtained at the small and large bowel. However, this may be due to the small sample size ($n = 5$) of the liver data.

This preliminary evaluation has provided sufficient confidence that the PPG signals acquired from the small and large bowel using a new fibre optic pulse oximeter probe are of sufficient quality to be used in the determination of splanchnic arterial blood oxygen saturation. Good quality PPG signals from the liver and stomach were obtained, however, the sample sizes for both sites ($n = 5$) were too small to allow for more robust conclusions.

REFERENCES

[1] D. Rittoo, P. Gosling, C. Bonnici, S. Burnley, P. Millns, M.H. Simms, S.R.G. Smith, R.K. Vohra, Splanchnic oxygenation in patients undergoing abdominal aortic aneurysm repair and volume expansion with eloHAES, Cardiovascular Surgery 10 (2002) 128–133.

[2] Jury of the Consensus, Tissue hypoxia: how to detect, how to correct, how to prevent? Intensive Care Med 22 (1996) 1250–1257.

[3] D.R. Dantzker, The gastrointestinal tract. The canary of the body? JAMA 270 (1993) 1247–1248.

[4] A.J. Crerar-Gilbert, P.A. Kyriacou, D.P. Jones, R.M. Langford, Assessment of photoplethysmographic signals for the determination of splanchnic oxygen saturation in humans, Anaesthesia 57 (2002) 442–445.

[5] D. Lynn Dyess, B.W. Bruner, C.A. Donnell, J.J. Ferrara, R.W. Powell, Intraoperative evaluation of intestinal ischemia: a comparison of methods, Southern Medical Journal 84 (1991) 966–970.

[6] P.J. Kinnala, K.T. Kuttila, J.M. Gronroos, T.V. Havia, T.J. Nevalainen, J.H.A. Niinikoski, Splanchnic and pancreatic tissue perfusion in experimental acute pancreatitis, Scandinavian of Gastroenterology 7 (2002) 845–849.

[7] J. DeNobile, P. Guzzetta, K. Patterson, Pulse oximetry as a means of assessing bowel viability, Journal of Surgical Research 48 (1990) 21–23.

[8] P.H. MacDonald, P.K. Dinda, I.T. Beck, C.D. Mercer, The use of oximetry in determining intestinal blood flow, Surgery, Gynecology & Obstetrics 176 (1993) 451–458.

[9] K. Ouriel, W.M. Fiore, J.E. Geary, Detection of occult colonic ischemia during aortic procedures: use of an intraoperative photoplethysmographic technique, Journal of Vascular Surgery 7 (1988) 5–9.
[10] E.R.L. Hei, A. Shun, Intra-operative pulse oximetry can help determine intestinal viability, Pediatric Surgery International 17 (2001) 2–3.
[11] M. Hickey, P.A. Kyriacou, Development of a new splanchnic perfusion sensor, in: Conf. Proc. IEEE. Eng Med. Biol. Soc., 2007, pp. 2952–2955.
[12] J.G. Proakis, D.G. Manolakis, Digital Signal Processing: Principles, Algorithms and Applications, Prentice Hall, New Jersey, USA, 1996, pp. 911–913.