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In-Vivo Evaluation of a Fiber-Optic Splanchnic Photoplethysmographic Sensor during Open Laparotomy

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Abstract— **There is a need for a reliable and continuous monitoring of abdominal organ oxygen saturation (SpO_2). Splanchnic ischemia may ultimately lead to cellular hypoxia and necrosis and may well contribute to the development of multiple organ failures and increased mortality. A new prototype reflectance fiber optic photoplethysmographic sensor and signal processing system was evaluated on six anaesthetized patients undergoing elective laparotomy. PPG signals were obtained from various organs, including large and small bowel, liver, and stomach. The normalized amplitudes of the splanchnic PPG signals were in good agreement with those obtained from the periphery using an identical fiber optic sensor. Furthermore, average SpO_2 values were in good agreement and showed correlation with those obtained from a commercial system. These preliminary results suggest that a miniaturized 'indwelling' fiber optic sensor may be a suitable method for pre-operative and post-operative evaluation of splanchnic organ SpO_2 and their health.**

I. INTRODUCTION

It is essential that the organs and tissues of the splanchnic region are sufficiently perfused with oxygenated blood in order to survive [1,2]. When an organ suffers severe hypoperfusion or extreme hypoxia, organ dysfunction can follow, which can in turn lead to the onset of multiple organ failure [3]. Previous studies have indicated that the gastrointestinal tract may be the canary of the body, making early detection of malperfusion feasible [4].

Currently there is no widely accepted technique for assessing splanchnic perfusion. Techniques such as laser Doppler, Doppler ultrasound [5,6], and intravenous fluorescein [3] do not measure oxygenation directly, and are not suitable for routine use. Gastric tonometry, one of the few techniques currently used in clinical practice for estimating intestinal hypoxia, has been shown to be useful as a prognostic tool in detecting hypovolaemia. However, due to the intermittent, heavily operator dependent and time consuming nature of the device it has not been widely accepted [7,8].

Pulse oximetry has also been investigated as a technique for monitoring splanchnic organ saturation [9]. It was found to be a rapid, reproducible, as well as a highly sensitive and specific technique for detecting small bowel ischemia in animals [10]. However, current pulse oximeter probes are not suitable for prolonged continuous monitoring in the human abdomen [11].

In an attempt to overcome the limitations of the current techniques for measuring splanchnic perfusion, a new fiber-optic sensor utilizing the principle of reflectance pulse oximetry was developed [11]. This prototype hand-held sensor was designed with the intention to be used in a pilot clinical study for measuring blood oxygen saturation (SpO_2) of splanchnic organs during open laparotomy. An electrically isolated processing system and a virtual instrument were also developed for driving the optical components of the sensor, and pre-processing and displaying the acquired PPG signals on the screen of a laptop computer.

This paper briefly describes the construction of the fiber optic sensor and its processing system. Preliminary results from the clinical trials are also presented.

II. METHODS

A. Fiber Optic PPG Sensor

After discussions with the clinical partners it was decided that preliminary investigations of splanchnic photoplethysmographic obtained using s fiber-optic sensor would take place on patients during open laparotomy, Therefore, it was decided that a handheld fiber optic sensor was required. Such a sensor would also be suitable for the intra-operative assessment of organ viability by the surgeon, as well as providing an indication of the feasibility of fiber-optics for splanchnic monitoring prior to sensor miniaturization.

The reflectance PPG sensor was designed using 600 µm.

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core silica glass step index fibers, infrared (850nm) and red (650nm) emitters, a 1mm^2 active area photodiode, and a custom-made Y-Piece (Ocean Optics Netherlands). For the construction of the sensor, a custom-made Perspex rod was precision drilled to accommodate the fibers, and to protect the 10mm of bare fiber exposed at the end

According to results obtained from a previous investigation into the optimal spacing between emitting and receiving fibers [11], the Perspex rod was designed to ensure a separation distance of 3mm between the both fibers. The fibers were then secured within the Perspex rod using medical UV curing adhesive (epoxy). The footprint of the sensor was covered with a 1mm layer of the epoxy, and polished so as to give a plane surface. Fig.1(a) shows the finished splanchnic sensor.

Fig.1. (a) Outline of Perspex rod and (b) the developed splanchnic fiber optic sensor

An identical fiber optic sensor was also developed to enable the monitoring of PPG signals from a periphery site, and so allow for comparison between splanchnic and periphery values (Fig.1(b)).

A. Isolated PPG Processing System and Virtual Instrument

An electrically isolated processing system was constructed to drive the optical components and to pre-process the PPG signals from both the splanchnic and peripheral sites. A Lead III ECG channel was also included to facilitate the acquisition of ECG signals for timing information. (Fig. 2)

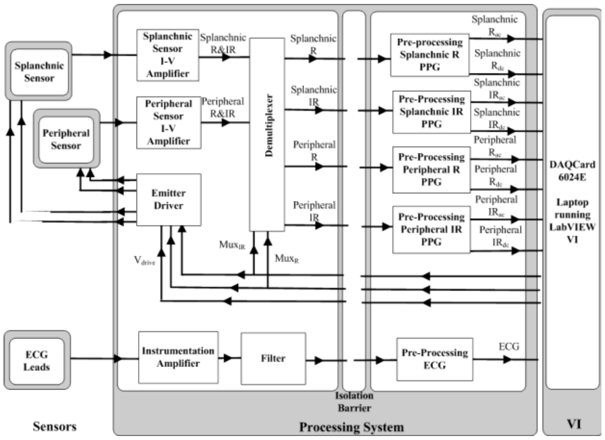

Fig.2. Isolated PPG Processing System, illustrating input side and output side circuitry

The emitters of both the splanchnic and peripheral sensors were driven by a software controlled constant current source, which used three signals supplied from the output ports of a 14-bit data acquisition card (DAQCard 6024E). Two multiplexing signals (Mux_R and Mux_{IR}) were generated from the DAQCard to switch the red (R) and infrared (IR) emitters on and off at a frequency of 500Hz, ensuring that they are never on at the same time. A voltage signal (V_{drive}) was also generated to control the intensities of the emitters.

Photodetectors detect the light backscattered by the tissue of the splanchnic organ and peripheral site. Two differential transimpedance amplifiers (I-V Amplifier) were utilized to convert each photodetector current into a mixed signal voltage containing red and infrared PPGs (Splanchnic R&IR and Peripheral R&IR). These mixed PPG signals were then demultiplexed (MC14052) to separate the PPG signals into their red and infrared components. The demultiplexer was synchronized to the two multiplexing signals from the DAQ card. The red (Splanchnic R and Peripheral R) and infrared (Splanchnic IR and Peripheral IR) PPG signals were then passed through the isolation barrier, included for increased patient safety. The R and IR signals were then filtered in order to extract the corresponding ac and dc components at both wavelengths.

For the ECG channel, an instrumentation amplifier with high CMRR and a gain of 100 was used. The ECG signal was then filtered to remove noise before passing through the isolation barrier. Finally, the ECG was amplified.

All eight PPG signals and the ECG signal at the output of the processing system were digitized by the data acquisition card at a sampling frequency of 200Hz. The signals were then further filtered by the Virtual Instrument (VI) to remove any noise, such as quantization noise, added to the signal during acquisition. All signals were then continuously displayed on the front panel of the VI to allow the user to easily see the amplitude and morphology of the signals acquired. All acquired PPGs signals were also simultaneously saved in spreadsheet format to a text file therefore enabling further offline signal processing and analysis. Algorithms were also included for calculating PPG amplitude, and estimating SpO_2 values.

B. Preliminary Investigation of Fiber-Optic Sensor during Open Laparotomy

Ethics Committee approval was obtained to study patients undergoing elective laparotomy. To enable the use of the fiber-optic PPG sensor in the sterile surgical site, the 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 splanchnic PPG sensor on the surface of each accessible abdominal organ (Fig 3). For comparison purposes the identical fiber optic PPG peripheral sensor was also placed on the finger or toe, and ECG leads were attached. Overhead lights were turned off, and signals were monitored and acquired for approximately two minutes on each site. Blood oxygen saturation from a commercial pulse oximeter (GE Healthcare) was also simultaneously monitored and recorded.

Fig.3. Fiber-optic splanchnic PPG sensor being held on small bowel by surgeon during open laparotomy

III. RESULTS

Good quality photoplethysmographic signals were obtained from all splanchnic sites available during each open laparotomy procedure. Figures 4 - 7 show typical ac red and infrared PPG signals obtained for the large bowel, small bowel, liver and stomach respectively.

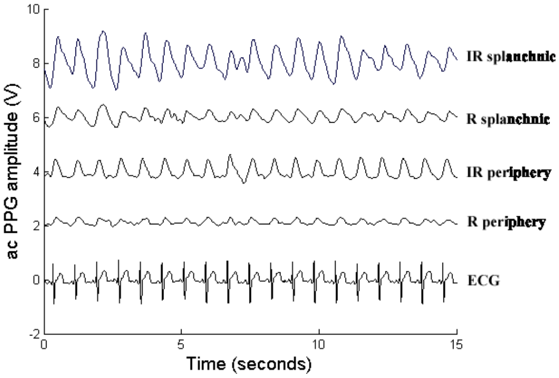

Fig.4. ac PPG signals from the large bowel and periphery with simultaneous ECG

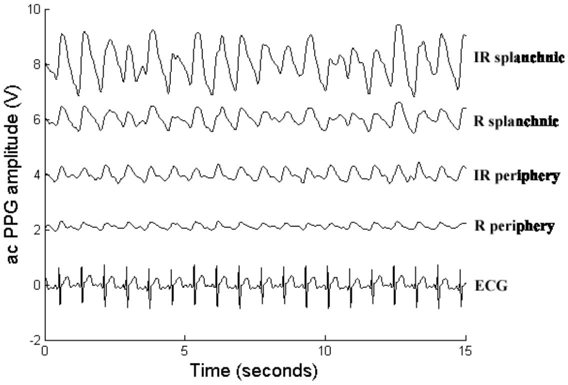

Fig.5. ac PPG signals from the small bowel and periphery with simultaneous ECG

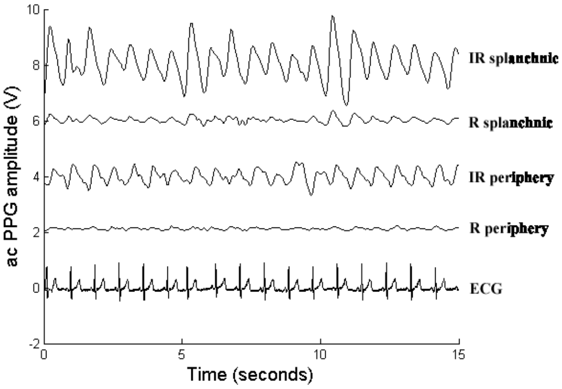

Fig.6. ac PPG signals from the liver and periphery with simultaneous ECG

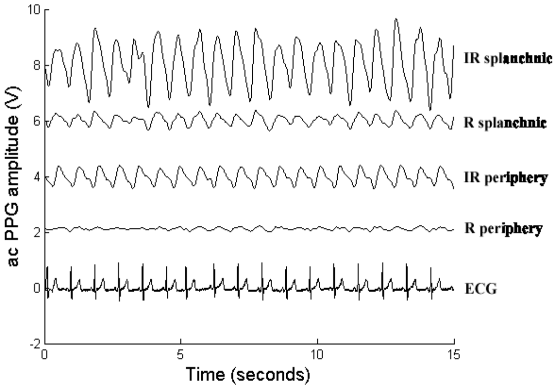

Fig.7. ac PPG signals from the stomach and periphery with simultaneous ECG

The low frequency artifact present on the splanchnic PPG traces was due to the mechanical ventilator and movement of the handheld sensor.

The amplitudes of the normalized ac splanchnic PPG signals were analyzed with those obtained from the peripheral site (Fig. 8).

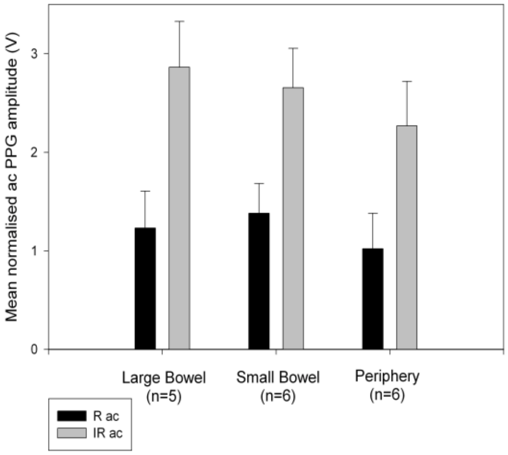

Fig.8. Normalized mean ac PPG amplitudes for the large bowel, small bowel and periphery

The normalized amplitudes of the splanchnic PPG signals are in reasonable agreement with those obtained from the periphery using an identical fiber optic sensor.

Although this is an uncalibrated system, preliminary SpO_2 values were estimated to evaluate if the fiber optic sensor and processing system may be capable of providing a reliable means of estimating blood oxygen saturation. SpO_2 values were estimated using the equation [12]:

$$SpO_2\% = 110 - 25R$$

where

$$R = \frac{R_{ac}/R_{dc}}{IR_{ac}/IR_{dc}}$$

Figure 9 shows the mean SpO_2 values estimated from the splanchnic fiber-optic and peripheral fiber-optic sensors, as well as the SpO_2 values from a commercial device (GE Healthcare). These preliminary estimates of splanchnic SpO_2 from the uncalibrated system show good agreement with commercial SpO_2 values from the finger.

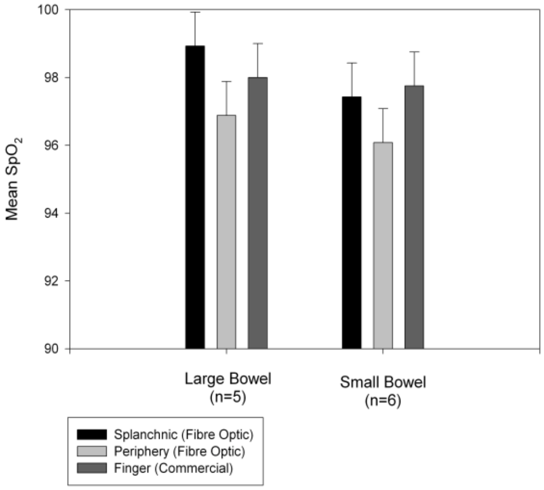

Fig.9. Mean SpO_2 values for the large bowel and small bowel compared with simultaneous peripheral and commercial SpO_2 values

IV. CONCLUSION

A prototype fiber optic PPG sensor comprising a fiber optic sensor, a processing system and a virtual instrument were successfully developed and evaluated.

Photoplethysmographic signals were acquired from all accessible splanchnic organs. As is to be expected, the splanchnic PPG signals showed greater sensitivity to the mechanical ventilator than those from the periphery. The amplitude of the ac splanchnic signals were approximately twice those from the corresponding peripheral site (Fig. 4-7). However, a more complete comparison is achieved in analyzing the normalized amplitudes (ac/dc). This comparison indicates that there is reasonable agreement between the normalized amplitudes of the splanchnic PPG signals and those obtained from the periphery (Fig. 8).

Using a typical linear approximation used in pulse oximetry, preliminary SpO_2 values were calculated for each splanchnic site (Fig. 9). Again, there was good agreement between the values from the splanchnic site, the peripheral site, and the commercial device. The maximum variation of 2% is perhaps due to the fact that the developed system is uncalibrated. However, these results are encouraging as they indicate that the fiber-optic splanchnic PPG sensor does not produce overtly erroneous estimations of blood oxygen saturation value.

Collectively, from the PPG signals and estimated SpO_2 values, there is a degree of confidence that a fiber-optic sensor is a feasible method for monitoring splanchnic organ health pre-operatively, operatively and post-operatively. Clinical trials are being extended on a larger group of patients to provide a complete evaluation of the system and to verify its use and ability prior to further miniaturization.

REFERENCES

[1] 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.

[2] D. Rittoo, P. Gosling, C. Bonnici et al, “Splanchnic oxygenation in patients undergoing abdominal aortic aneurysm repair and volume expansion with eloHAES”, *Cardiovascular Surgery*, vol. 10, pp. 128-133, 2002.

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

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

[5] D. Lynn Dyess, B.W. Bruner, C.A. Donnell, J.J. Ferrara, and R.W. Powell, “Intraoperative Evaluation of Intestinal Ischemia: A Comparison of Methods”, *Southern Medical Journal*, vol. 84(8), pp. 966-970, 1991.

[6] Helle D Zacho and Jan Abrahamsen, “Chronic intestinal ischaemia: diagnosis”, *Clin Physiol Funct Imaging*, vol:28(2), pp. 71–75, 2008.

[7] P.J. Kinnala, K.T. Kuttila, J.M. Gronroos, T.V. Havia, T.J. Nevalainen, and J.H.A. Niinikoski ,“Splanchnic and Pancreatic Tissue Perfusion in Experimental Acute Pancreatitis”, *Scandinavian of Gastroenterology*, vol. 7, pp. 845-849, 2002.

[8] H. P. Povoas, M. H. Weil, W. Tang, B. Moran, T. Kamohara, and J. Bisera, “Comparisons between sublingual and gastric tonometry during hemorrhagic shock”, *Chest*, vol: 118(4), pp.1127– 1132, 2000.

[9] P. H. MacDonald, P.K. Dinda, I.T. Beck, and C.D. Mercer, “The use of oximetry in determining intestinal blood flow”, *Surg. Gynecol. Obstet.*, vol. 176, pp. 451-458, 1993.

[10] J. DeNobile, P. Guzzetta, and K. Patterson, “Pulse Oximetry as a means of assessing bowel viability”, *Journal of Surgical Research*, vol. 48, pp. 21-3, 1990.

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

[12] J.G. Webster, *Design of Pulse Oximeters*, 1st ed. Bristol: Institute of Physics Publishing, 1996.