Pulse oximetry of body cavities and organs

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***Abstract*— The focus of this paper will be in the development and in vivo applications of new custom made photoplethysmographic (PPG) and pulse oximetry optical and fiber optic sensors and instrumentation in an effort to investigate their suitability in the estimation of blood oxygen saturation and their contribution in the assessment of organ/tissue perfusion and viability. The paper describes the development of optical and fiber optic PPG and blood oxygen saturation (SpO_2) sensors and covers examples of application areas including real-time PPG monitoring from body cavities (esophagus) and solid or hollow organs (bowel, liver, stomach, brain, etc). The clinical studies presented successfully demonstrated the feasibility in acquiring PPGs and estimating blood oxygen saturation values from a variety of organs and tissues. The technological developments and the measurements presented in this work pave the way in a new era of pulse oximetry where direct and continuous monitoring of blood oxygen saturation of internal organs and tissues could be made possible.**

I. Introduction

Current advancements in semiconductor and optoelectronic technologies including new advancements in biosignal processing techniques enable the development of intelligent sensors. Such sensors are challenging the current status quo in medical monitoring as more sensors are now applied invasive or non-invasively in various anatomical parts which was not possible only a few years ago. These sensors reveal for the first time information to clinical experts which will aid in the more optimized treatment of patients and in the further understanding of various pathophysiological phenomena.

A most popular optical sensor that has revolutionized medical monitoring is the pulse oximeter. It is well accepted that pulse oximetry provides a global indication of perfusion or more specific arterial oxygen saturation. This can be made possible via the peripheral pulse oximetry probes mainly attached to the finger, toe or earlobe. For many years researchers have critically evaluated and compared pulse oximeters under deferent environments, conditions and clinical cases. Many pulse oximetry manufacturers have been actively developing and optimizing their designs both in sensors and processing systems in order to overcome some of the well-known pulse oximetry limitations (failures due to low peripheral perfusion and motion artifact, etc.), plus expand the pulse oximetry technology capabilities beyond the traditional arterial oxygen saturation by providing quantifying information on other blood chromophores such as Methemoglobin (MetHb), carboxyhemoglobin (COHb), etc.

Although pulse oximetry seems to be at the peak of its development, there is always room for further improvement, optimization and innovation. Many of these innovations could relate to specific applications and this will be the focus of this article. Perhaps this is the time to make a step forward and investigate regional pulse oximetry in body cavities and organs. The direct application of pulse oximetry to an organ such as the esophagus, liver, kidney, or the bowel might be a very useful application in determining organ specific SpO_2, regardless if the patients SpO_2 as measured from an extremity (finger) is normal. Also, the placement of a pulse oximetry probe at a more central site such as the esophagus might be proved more reliable at a time where conventional peripheral oximetry fails.

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II. Methods

A. Esophageal optical sensor

A reflectance adult esophageal pulse oximeter probe was developed [1]. The esophageal pulse oximeter probe was fabricated utilizing two infrared and two red surface mount emitters and a surface mount photodetector (Fig. 1). The probe was designed to fit into a 20 French gauge plastic transparent disposable stomach/esophageal tube.

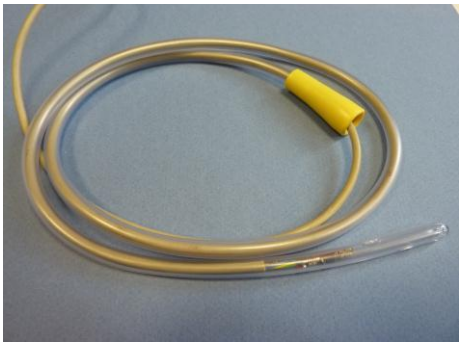

Fig.1. Adult oesophageal pulse oximetry probe

B. Splanchnic fiber optic sensor

A fiber optic photoplethysmographic/pulse oximetry sensor was developed as a means of assessing splanchnic organ perfusion during surgery in humans (Fig. 2) [2]. Fiber optic cables were chosen as a means of transmitting and receiving the light as they are electrically safe and their dimension (cross sectional area) can be quite small so as to ultimately facilitate insertion of the sensor into a small cavity. Glass silica step index multimode fibers with a Numerical Aperture (NA) of 0.37 and a core diameter of 600 μm were used, with each fiber cable SMA terminated at one end. Two

optical fibers were coupled to red and infrared SMA mounted emitters and the third fiber was coupled to an SMA mounted photodiode.

Fig.2. Splanchnic pulse oximetry fibre optic probe

C. Brain fiber optic pulse oximetry probe

A fiber optic pulse oximeter has been developed for assessing blood oxygen saturation in the brain tissue of patients recovering from neurosurgery or head injury [3]. The probe consisted of two silica optical fibers (a transmitting fiber and a receiving fiber) each with a core diameter of 400 μm, and a numerical aperture (NA) of 0.39. The light sources used were red and infrared light emitting diodes (LEDs), with peak emission wavelengths at 660 nm and 850 nm, respectively, mounted in SMA packages. Both LEDs were connected to the single transmitting optical fiber using a Y-coupler, i.e. a bifurcated optical fiber assembly. The photodetector was an SMA packaged PIN photodiode of active surface area 0.8 mm^2. The photodetector was coupled directly to the receiving optical fiber (see Fig. 3).

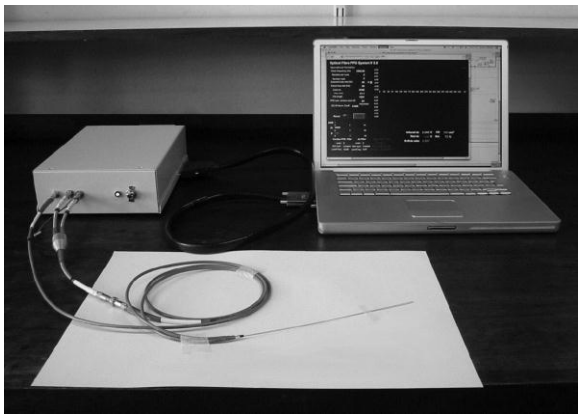

Fig.3. Brain fiber optic pulse oximetry system

D. Processing and data acquisition system

All sensors developed were interfaced with a generic PPG processing system. The PPG signals at the output of the PPG system were digitized by a 16-bit data acquisition card on a laptop personal computer. The digitized PPG signals are analyzed by a Virtual Instrument (VI) implemented in LabVIEW (National Instruments Corporation, Austin, Texas). This VI reads all acquired PPG data, converts them into a spread sheet format and saves them into a file specified by the user and displays the signals in real time on the screen of the laptop computer. Algorithms were also developed in the VI for the online estimation of SpO_2.

III. Clinical studies

This section will describe the various in vivo investigations performed using the above described pulse oximeter probes to investigate, sometimes for the first time, PPG signals and SpO_2 values from various organs, tissues and cavities.

A. Clinical investigation 1: esophageal PPG signals and blood oxygen saturation measurements in cardiothoracic surgery adult patients

This study investigated and compared esophageal and finger PPGs and SpO_2s in patients undergoing high-risk operations, such as hypothermic cardiothoracic bypass surgery, in who conventional pulse oximetry might fail due to poor peripheral circulation [1]. Following ethics approval and written consent fifty adult patients were recruited for this study. The esophageal pulse oximeter probe was advanced into the esophagus at 30 cm from the lips following induction of anesthesia. During the esophageal measurements, values of blood oxygen saturation from a commercial transmission type finger pulse oximeter (Marquette, Tram 200A; Marquette Electronics, Milwaukee, Wisconsin) were also recorded.

B. Clinical investigation 2: Investigation of PPG signals and blood oxygen saturation from various abdominal organs

Local Research Ethics Committee approval was obtained to investigate ASA 1 and 2 patients undergoing elective laparotomy following informed written consent [4]. Photoplethysmographic measurements were made in seventeen patients, (three male and fourteen female, mean age (±SD): 54 ± (9.7)), undergoing open laparotomy. When the abdominal cavity was open the surgeon placed the splanchnic pulse oximeter probe on the surface of each accessible abdominal organ (bowel, liver, kidney, etc.). Blood oxygen saturation from a commercial finger pulse oximeter (GE Healthcare, UK), placed on the middle finger of the right hand was also recorded.

C. Clinical investigation 3: Preliminary investigation of PPG signals and blood oxygen saturation from brain tissue

This study was approved by the local Research Ethics sought prior to the study [3]. These measurements utilize the IM-3 Cranial Access System (Integra Neurosciences Inc., Plainsboro, NJ, USA), which incorporates a triple lumen cranial bolt. Six patients have been recruited, mean (±SD) age 45.5 (±19) years. Following induction of anesthesia and insertion of the cranial bolt by the neurosurgeon the fibers were then inserted via the bolt, approximately 5 mm into the brain and the luer caps tightened to form a seal around the fiber. PPG signals were recorded for several minutes. The patient's arterial oxygen saturation was monitored using a commercial finger pulse oximeter.

IV. RESULTS

A. *Results from the investigation of esophageal PPGs and SpO_2s in cardiothoracic surgery adult patients*

The esophageal PPG signals recorded from all patients (before and after bypass) were of good quality with large amplitudes. Fig. 4 depicts typical PPG traces (postoperatively) from one patient undergoing cardiopulmonary bypass surgery.

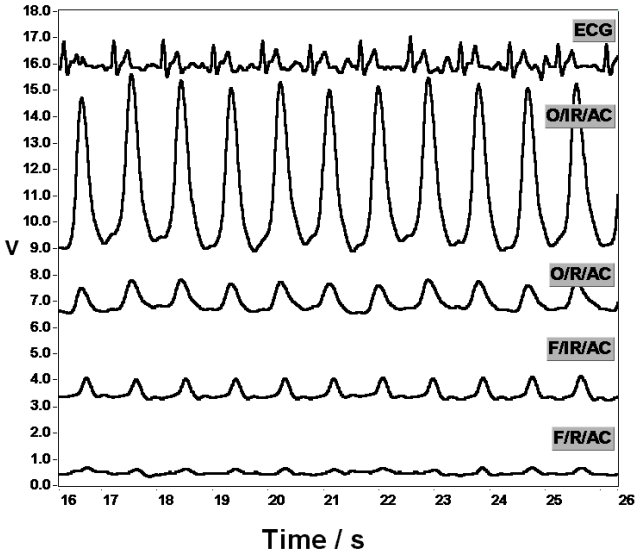

Fig. 4. Esophageal (O), Finger (F) PPG traces at both wavelengths red (R) and infrared (IR) and ECG traces obtained in intensive care from an anaesthetized patient undergoing cardiopulmonary bypass surgery

A set of 155 values of blood oxygen saturation data points from 49 patients were used for the comparison of the two different pulse oximeters used in the study (the esophageal and the commercial finger pulse oximeter. The between-method differences analysis as suggested by Bland and Altman [5] was used to compare the two pulse oximeters. For the SpO_2 data the mean difference (d) (commercial pulse oximeter minus esophageal pulse oximeter) was –0.3% and the standard deviation (s) was 1.5%. Since the differences were normally distributed (Gaussian), 95% of them were expected to lie between d-2s and d+2s. These are referred as the "limits of agreement". For the SpO_2 data (commercial finger and esophageal) the limits of agreement were:

$$d - 2s = -0.3 - (2*1.5) = -3.3\ \% \quad (1)$$

$$d + 2s = -0.3 + (2*1.5) = 2.7\ \% \quad (2)$$

Thus, the esophageal pulse oximeter may be 3.3% below or 2.7% above the commercial pulse oximeter. The limits of agreement were approximately within the ± 3% accuracy of commercial pulse oximeters as given by the manufacturers. It can reasonably be argued that these levels of difference are clinically irrelevant, thereby making either device a satisfactory method for monitoring the patient's blood oxygenation.

B. *Results from the investigation of PPG signals and SpO_2s from various abdominal organs*

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. 5 depicts red (R) and infrared (IR) PPG traces from the large bowel. The low frequency artifact present on the splanchnic PPG traces was due to the mechanical ventilator and movement of the handheld sensor.

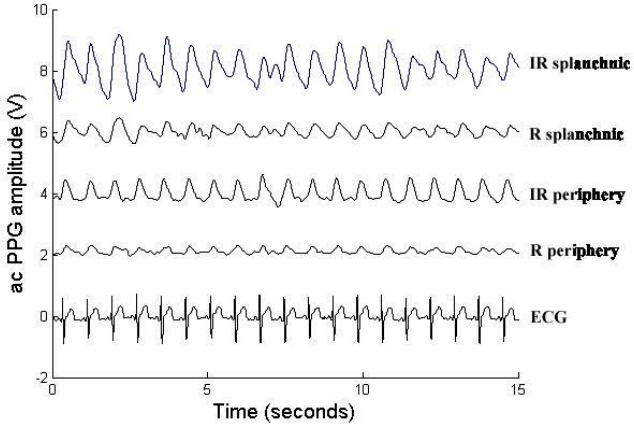

Fig. 5. AC red (R) and infrared (IR) PPG signals from the large bowel. All splanchnic PPGs are accompanied by a finger PPG

Table 1 shows the mean AC PPG amplitudes for each investigated organ including the finger using a custom made fiber optic finger probe (identical to the splanchnic probe).

TABLE I. MEAN (±SD) INFRARED (IR) AND RED (R) AC PPG AMPLITUDES FOR ALL SITES

Site	Mean IR AC (V) ± SD	Mean R AC (V) ± SD
Small Bowel (n=17)	2.37±1.26	0.76±0.41
Large Bowel (n=14)	2.29±1.11	0.76±0.35
Liver (n=14)	3.32±2.47	0.91±0.82
Stomach (n=5)	1.71±0.84	0.62±0.23
Finger (n=17)	0.85±0.26	0.23±0.07

Preliminary SpO_2 values were calculated for the small bowel, large bowel, liver, stomach and finger (Table 2). The mean SpO_2 values from the commercial pulse oximeter are also included for comparison purposes.

TABLE II. MEAN (±SD) BLOOD OXYGEN SATURATION VALUES FOR ALL SITES

Small Bowel SpO_2 (%) n=17	**Large Bowel SpO_2 (%) n=14**	**Liver SpO_2 (%) n=5**	**Stomach SpO_2 (%) n=5**	**Commercial Finger SpO_2 (%) n=17**
97.41±3.14	97.14±3.11	100.60±2.70	95.80± 4.32	97.88±0.86

C. Results from the preliminary investigation of PPG signals and SpO_2s from brain tissue

Table 3 shows the mean cerebral arterial oxygen saturations ($ScaO_2$) from all six patients. During these measurements the SpO_2 values acquired from commercial finger probe were between 98-100%.

TABLE III. MEAN CEREBRAL ARTERIAL OXYGEN SATURATIONS ($SCAO_2$) (N=6)

Patient #	**$ScaO_2$ (%)**
1	98.2
2	100.5
3	94.8
4	90.4
5	52.0
6	92.6
Mean ± SD	**88.1 ± 18.1**

V. CONCLUSION

Currently pulse oximetry utilizes peripheral probes which are mainly attached to the finger, toe or earlobe. Despite its success as an indicator of global perfusion there is a need to explore pulse oximetry as a technique for monitoring regional perfusion. This could be made possible with the design of new pulse oximetry probes with the capability of placement or attachment to specific organs or tissues. Such new applications will perhaps enhance our knowledge of organ perfusion and will also aid in the direct monitoring of perfusion of transplanted tissues and organs. This paper presented new custom made pulse oximetry probes which were designed and fabricated for placement on various organs and tissues. The clinical studies successfully demonstrated the feasibility in acquiring PPGs and estimating blood oxygen saturation values from a variety of organs and tissues. The technological developments and the measurements presented in this work pave the way in a new era of pulse oximetry where direct and continuous monitoring of blood oxygen saturation of internal organs and tissues could be made possible.

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