Development of an intraluminal intestinal photoplethysmography sensor

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Abstract— **Intestinal ischemia is a serious medical condition and can lead to life threatening sepsis. Currently, there are no reliable techniques available for directly monitoring intestinal viability for prolonged periods of time, and intraoperatively, the majority of the surgeons still rely on subjective methods, such as visual inspection to assess viability of the intestine. The development of an intraluminal optical sensor for monitoring intestinal viability is being proposed. The sensor will continuously monitor changes in blood volume and oxygen saturation. The developed reflectance photoplethysmography/pulse oximetry sensor comprises of two emitters (red and infrared) and a photodiode. A photoplethysmography processing and data acquisition system was also utilized. The prototype sensor was evaluated in a pilot study in the buccal mucosa of 12 healthy volunteers, given the locations similarity to the intestinal mucosa and its easy accessibility. Good quality photoplethysmography signals with high signal-to-noise ratio were acquired from the buccal mucosa in all the volunteers. Preliminary blood oxygen saturation values from the intraluminal sensor were in broad agreement with the standard finger pulse oximeter probes.**

I. INTRODUCTION

At rest, approximately 25% of the cardiac output is directed to the splanchnic region. The vascularity of the intestinal tract supplied by splanchnic circulation is often compromised to a variable extent in systemic illnesses and is susceptible to ischemia[1]. Intestinal viability can also be reduced as a consequence of treatment of other conditions; e.g. colonic ischemia following aortic aneurysm repair[2]. In patients with colorectal cancer, the second most common cause of cancer deaths in the UK[3], surgical excision of the tumor bearing area with lymph nodal clearance is the only curative treatment.

The gold standard surgical treatment requires primary restoration of intestinal continuity by anastomosing the two cut ends of the intestine after removing the tumor-bearing segment of the intestine. Anastomotic failure is a major risk occurring in 2 – 10% of patients undergoing such restorative surgery, primarily due to inadequate vascularity surrounding the anastomosis and this requires close monitoring for predicting the outcome of the anastomosis[4].

Intestinal ischemia results in disruption of intestinal mucosal barrier, which allows bacterial translocation and endotoxin absorption into the portal circulation, resulting in amplification of systemic inflammatory response[5]. Biochemical inflammatory markers such as C-reactive protein (CRP) assay and white blood cell (WBC) count are routinely used to monitor the condition along with physiological measurements including heart rate, respiratory rate, blood pressure and peripheral oxygen saturation (S_pO_2).

During surgery, the surgeon assesses the color, arterial pulsation and presence of peristalsis and relies on this visual inspection to determine the adequacy of intestinal viability[1], [6], [7]. There are several other techniques described for assessing intestinal viability including measurements of oxygen tension[2], Doppler ultrasound, fluorescence and laser Doppler flowmetry[8], [9]. All such techniques are mainly used as research tools rather than routine clinical monitoring techniques. Furthermore, none of these techniques can provide continuous bowel perfusion measurements, either intraoperatively and/or postoperatively. In addition, most of these technologies are operator dependent, hence prone to inter-observer variability and are inconsistent in their performance[1].

To overcome these limitations, the development of an intraluminal optical sensor system is being proposed, with the aim of providing dynamic monitoring of intestinal viability. Photoplethysmography (PPG) and pulse oximetry technology, known for many clinical and research applications[10], [11], would be used to monitor changes in blood volume and blood oxygen saturation by shining light from within the lumen of the intestine. Such a sensor will enable continuous, quantitative measurements of intestinal tissue viability, intraoperatively and postoperatively. This paper describes the development of such a system for the measurement of the amplitudes of photoplethysmography (PPG) signals and blood oxygen saturation values from the human buccal mucosa as a first step prior to its evaluation in the human intestine.

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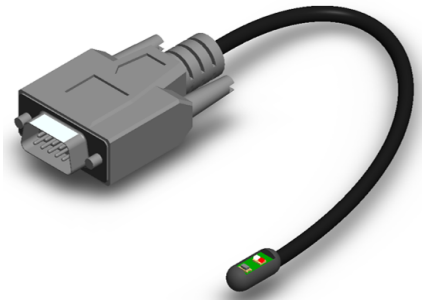


Fig. 1: 3D visualization of the proposed intraluminal PPG sensor. The distal end of the sensor is the optical reflectance sensor, encapsulated within a sensor casing.

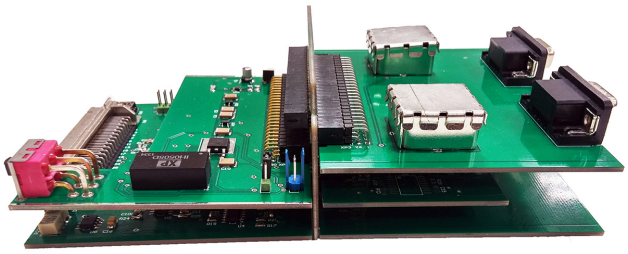


Fig. 2: Customized modular photoplethysmography processing and data acquisition system, ZenPPG. Developed by the Research Centre of Biomedical Engineering (RCBE) at City, University of London[13].

II. MATERIALS AND METHODS

A. Development of intraluminal PPG sensor

A reflectance PPG sensor suited for the site of measurement (large and small intestine) was developed. The sensor consists of two modules: (i) reflectance PPG sensor and (ii) sensor casing. The large intestine (colon and rectum) is a tubular shaped structure with an approximate lumen dimension and wall thickness of 50 mm and 3 mm, respectively[12]. These features were taken into consideration when developing the intraluminal PPG sensor.

1) Reflectance PPG sensor: A printed circuit board (PCB) with the dimensions of 10.4×5.2 mm ($l \times w$) was fabricated using an electronic computer aided design software. The PPG sensor consists of two light emitting diodes (LEDs), with peak wavelength emissions of 660 nm (*KP-2012SRC, Kingbright, Taiwan*) and 880 nm (*KP-2012SF4C, Kingbright, Taiwan*). A flat top photodiode with an active area of 0.65 mm^2 and peak wavelength sensitivity of 900 nm (*SR10BP, Excelitas technologies, Massachusetts*) was placed next to the LEDs. The separation distance from the center of the photodiode to the center of each LED was set to be 5 mm, as such a separation distance will provide good quality PPGs with a high signal-to-noise-ratio (SNR)[10].

2) Sensor casing: A capsular design for the casing was developed using SolidWorks 2013 (*Dassault Systems SolidWorks Corp.*) and 3D printing technology, Object24 3D printer (*Stratasys Ltd*). The casing provides a smooth and even surface with rounded edges to minimize any intestinal damage during placement of the sensor. The diameter and length of the casing is 5.5×20 mm, respectively, with a rectangular extruded cut, allowing placement of the optical components within the capsular casing.

The reflectance PPG sensor was firmly fixed within the sensor casing with optically clear medical epoxy (*DYMAX 141-M, Dymax Corporation, Torrington, CT*) to provide electrical isolation, should the sensor come into contact with biological tissue and fluids. In order to connect the PPG sensor to the processing and data acquisition system, a D-Sub 9 connector was used (Fig 1).

B. Processing and data acquisition system

A battery operated, customized PPG processing system (ZenPPG), developed by the Research Centre of Biomedical Engineering (RCBE) at City, University of London[11] was used. ZenPPG is a modular system which is interconnected by a double sided system bus, as shown in Fig 2, comprising of emitter driver circuits, amplifiers and filters, to condition the acquired signals prior to analogue-to-digital conversion[11], [13].

All output signals were digitized by a 16-bit data acquisition card (*NI DAQ-6211, National Instruments Inc. Austin, Texas*). All acquired signals will be displayed and recorded by a Virtual Instrument (VI), implemented in LabVIEW (*National Instruments Inc. Austin, Texas*). The AC and DC components of the raw PPG signals were separated in order to calculate the ratio of ratios (R_r) values for both red (R) and infrared (IR), using equation (1). Furthermore, arterial oxygen saturation was determined using the empirically derived calibration equation (2)[14].

$$R_r = \frac{(\frac{AC}{DC})_R}{(\frac{AC}{DC})_{IR}} \tag{1}$$

$$S_pO_2 = 110 - 25(R_r) \tag{2}$$

C. Evaluation of the developed technology

This section describes the sensor *in-vitro* thermal evaluation and *in-vivo* study of the prototype intraluminal PPG sensor.

1) In-vitro thermal evaluation: Thermal contribution of the intraluminal sensor was tested in a simulated environment. The intraluminal sensor was placed in a plastic sheath, which was then placed intraluminally in contact with a section of a pig's intestine. Both the section of the bowel and the intraluminal sensor were immersed in a static water bath at $36^{\circ}C$, as water is known to have similar thermal properties to those of soft tissue[10]. The rise in temperature was recorded on: (i) the outside of the intraluminal sensor, immediately adjacent to both LEDs and (ii) the outer surface of the pig's intestine, where temperatures were recorded before and after the LEDs were switched on and steady state conditions had been achieved. During these experiments, the intensity of the LEDs was maintained at 20 mA.

2) In-vivo study in human buccal mucosa: The study involved 12 healthy volunteers participating in the investigations of PPGs from the buccal mucosa and the left index finger. For the finger PPG measurements, a custom made reflectance PPG probe was used. This probe was optically and electrically identical with the intraluminal sensor, in order to allow comparative measurements. The buccal mucosa was chosen, as it is easily accessible and is similar to the intestinal mucosa. With the prototype PPG sensor covered in a plastic sheath, volunteers were asked to place the sensor against the buccal mucosa. Monitoring lasted for 10 minutes, and during the measurements, volunteers were asked to sit comfortably in order to avoid any movement artifacts on the PPG signal. During the buccal PPG measurements, a PPG signal was also obtained concurrently from the left index finger, using a separate but identical reflectance PPG sensor.

The mean peak-to-peak AC PPG amplitudes for each volunteer were calculated. To quantify the quality of the PPG signals obtained for each wavelength, the signal-to-noise ratio (SNR) was calculated using the signal power against the background noise within the frequency domain. The mean arterial oxygen saturation (S_pO_2) for each volunteer was also calculated from the acquired signals from the buccal mucosa and the finger. Comparisons between the two sites were made using Pearson's correlation coefficient (r^2)[15].

III. RESULTS

Fig 3 shows the results of the thermal evaluation. These results showed that the rise in temperature at the outside of the intraluminal sensor was no more than $0.32^{\circ}C$. Also, the temperature rise from the outer surface of the pig's intestine was no more than $0.23^{\circ}C$. Therefore, it was concluded that that the risk of thermal injury to the intestine would be negligible when using the intraluminal sensor.

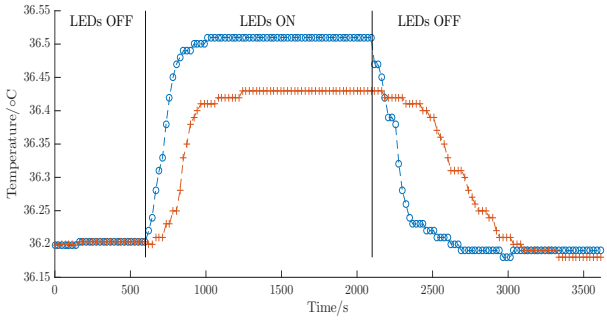


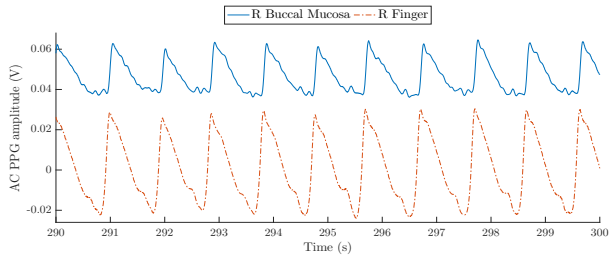
Fig. 3: *In-vitro* thermal evaluation of the intraluminal sensor. Rise of temperatures were recorded on the intraluminal sensor, adjacent to the LEDs (blue -o-) and, the outer surface of the pig's bowel (orange -+-). Whilst in a static water bath of $36^{\circ}C$, temperatures were recorded before and after LEDs were switched on, illustrated with a solid vertical line.

Fig 4 shows PPG signals acquired from a typical healthy volunteer from the buccal mucosa and the finger at both wavelengths. The buccal PPGs are of good quality and large amplitudes, with a signal-to-noise ratio of 23.4 dB for red PPGs and 35.6 dB for the infrared PPGs. Table I shows the mean of the mean finger and buccal AC PPG amplitudes at both wavelengths for all volunteers.

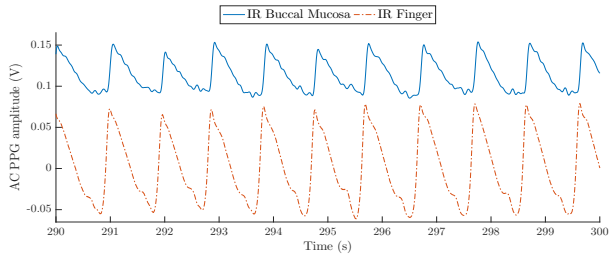
TABLE I: Mean of the mean peak-to-peak amplitude and standard deviation ($\pm$SD) of the AC components of the red (R_{AC}) and infrared (IR_{AC}) photoplethysmography signals acquired from the buccal mucosa and the left index finger.

	IR_{AC} $\pm$ SD (mV)	R_{AC} $\pm$ SD (mV)
Buccal	826 $\pm$ 141	544 $\pm$ 61
Finger	860 $\pm$ 367	460 $\pm$ 149

Preliminary estimation of blood oxygen saturation for each volunteer (Table II) was acquired from the buccal mucosa and the index finger, using the prototype PPG sensor and the identical reflectance sensor respectively. Blood oxygen saturation (S_pO_2) results were found to be within the expected range (97 - 100%) for healthy volunteers and in close agreement, with the correlation coefficient (r^2) of 0.80 ($p < 0.05$).



(a) Red (R) AC PPG signals



(b) Infrared (IR) AC PPG signals

Fig. 4: AC PPGs from the buccal mucosa (blue) and left index finger (orange) from a healthy volunteer. (a) Red AC PPGs from the finger and buccal mucosa; (b) Infrared AC PPGs from the finger and buccal mucosa.

IV. Conclusion

The design and development of an intraluminal intestinal PPG sensor is presented. The long-term aim is to evaluate this technology as a clinical tool for dynamic monitoring of intestinal viability. Alongside the intraluminal PPG sensor, a PPG processing and data acquisition was utilized and evaluated successfully. A rise in temperature of $0.32^{\circ}C$ at the outside of the intraluminal sensor, as demonstrated in the *in-vivo* thermal evaluation, shows that the risk of thermal tissue damage would only be negligible. The PPG signals acquired from the *in-vivo* study were of good quality, as indicated with the high signal-to-noise ratio. Preliminary estimations of S_pO_2 from the buccal mucosa and the left index finger were found to be within the expected range and in close agreement. The results presented in this paper indicate that the newly developed intraluminal intestinal PPG sensor is capable of measuring intestinal mucosal S_pO_2. Currrently, further clinical studies are being designed to validate the intraluminal intestinal PPG sensor in human large intestine.

TABLE II: Comparison of blood oxygen saturation (S_pO_2) calculated from the acquired PPG signals from the prototype sensor and an identical reflectance pulse oximetry sensor, measuring at the site of the buccal mucosa and the left index finger respectively.

Subject #	Buccal Mucosa (S_pO_2 %)	Index Finger (S_pO_2 %)
1	98	99
2	98	98
3	99	99
4	100	100
5	100	99
6	98	99
7	98	99
8	98	98
9	100	100
10	98	99
11	97	98
12	100	100
Mean $\pm$ SD	**98.67 $\pm$ 1.07**	**99 $\pm$ 0.74**

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