A System for Investigating Oesophageal Photoplethysmographic Signals in Anaesthetised Patients

by

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ABSTRACT

The monitoring of arterial blood oxygen saturation in patients with compromised peripheral perfusion is often difficult, since conventional non-invasive techniques such as pulse oximetry (SpO_2) can fail. Poor peripheral circulation commonly occurs after major surgery including cardiopulmonary bypass. The difficulties in these clinical situations might be overcome if the sensor were to monitor a better perfused central part of the body such as the oesophagus. A new oesophageal photoplethysmographic (PPG) probe and an isolated processing system have been developed to investigate the pulsatile signals in the lower oesophagus of anaesthetised adult patients undergoing routine surgery. The AC PPG signals are sampled by a data acquisition system connected to a laptop computer. The signals recorded correspond to infrared and red AC PPGs from the lower oesophagus and the finger. Preliminary results from 20 patients show that good quality AC PPG signals can be measured in the human oesophagus. The ratio of the oesophageal to finger AC PPG amplitudes was calculated for the infrared and red wavelengths for each patient. The mean (± standard deviation) of this ratio was 2.9 ± 2.1 ($n = 19$) for the infrared wavelength and 3.1 ± 2.4 ($n = 16$) for the red wavelength. The red and infrared wavelengths used are appropriate for pulse oximetry and this investigation indicates that the lower oesophagus may be a suitable site for the reliable monitoring of SpO_2 in patients with poor peripheral perfusion.

Keywords – Photoplethysmography (PPG), pulse oximetry, oesophagus, non-invasive monitoring, physiological measurements

1. Introduction

Pulse oximetry has been one of the most significant technological advances in clinical monitoring in the last decade (BOWES et al., 1989) and is widely used in anaesthesia and intensive care units. The oximeter provides non-invasive continuous monitoring of arterial blood oxygen saturation (SpO_2) using sensors attached to peripheral sites such as the finger, the ear and the toe.

Pulse oximeters estimate arterial oxygen saturation by shining light at two different wavelengths, red and infrared, through vascular tissue. In this method the pulsatile photoplethysmographic (AC 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 reduced haemoglobin. From the ratios of these amplitudes and the corresponding DC photoplethysmographic components SpO_2 is estimated. Hence, the presence of a measurable AC PPG signal is essential for the successful operation of a pulse oximeter.

Although pulse oximeters give reliable readings of blood oxygen saturation for many clinical purposes, there are significant limitations on the accuracy and the availability of pulse oximetry data in some circumstances (FREUND et al., 1991; MOLLER et al., 1993; REICH et al., 1996). Pulse oximetry is a pulse dependent technique, and any significant reduction in the amplitude of the pulsatile component of the photoplethysmographic signal can lead to dubious values for blood oxygen saturation (SpO_2) or complete failure. Hence, pulse oximeters require adequate peripheral perfusion to operate accurately. When peripheral perfusion is

poor, as in states of hypovolaemia, hypothermia and vasoconstriction, oxygenation readings become unreliable or cease. Such clinical situations occur, for example, after prolonged operations, especially hypothermic cardiopulmonary bypass surgery, and in patients with extensive burns. The problem arises because conventional sensors must be attached to the most peripheral parts of the body where pulsatile flow is most easily compromised. Measurements at sites other than the finger or ear, such as the forehead and nose, give no improvement in poorly perfused patients (CLAYTON et al., 1991; ROSENBERG and PEDERSEN, 1990). Thus, SpO_2 readings are often unobtainable at just the time when they would be most valuable.

In an attempt to avoid the difficulties associated with conventional measurements of arterial blood oxygen saturation during conditions of poor peripheral perfusion and pulsation, it has been proposed to use the oesophagus as a measurement site on the hypothesis that, being more central, it should be better perfused. A transoesophageal pulse oximetry probe has been described by ATLEE and BRATANOW (1995) and used to estimate oxygen saturation in the upper oesophagus at the cricopharyngeus muscle. The results showed that the transoesophageal probe underestimated or overestimated SpO_2 values depending on the orientation of the sensor. It was also found that electrocautery interference resulted in more frequent signal dropouts than from a peripheral pulse oximetry probe. Moreover, the positioning of the probe at the cricopharyngeus muscle proved to be difficult (PRIELIPP et al., 1996; BORUM, 1997). No investigations of PPG signals from the oesophagus were made in these studies. It may be possible to overcome the limitations of the above device, which can operate only in the upper oesophagus, by obtaining signals from the mid or lower oesophagus, where the pulsatile signals necessary for SpO_2 estimation may be larger and more consistent. As a preliminary to developing a suitable pulse oximeter, a new system to investigate the

morphology and quality of AC PPG signals from the oesophagus has been designed and is described.

2. Materials and Methods

2.1 OESOPHAGEAL PPG SENSOR DESIGN

A reflectance oesophageal PPG probe has been constructed utilising miniature surface mount infrared and red emitters and a photodetector, see Figure 1. The probe uses two infrared emitters (CR10IRG, Cerled) with peak emission wavelengths at 880 nm and two red emitters (CR10HR, Cerled) with peak emission wavelengths at 655 nm. The dimensions of the emitter chips are 3.2 mm x 1.27 mm and their maximum rated continuous forward current is 75 mA. A single silicon photo-diode detector (CFD10, Cerled) with dimensions 4.57 mm x 3.81 mm was used to detect radiation backscattered by the tissue from the emitters. The emitters and the photodetector were mounted on a 1 mm thick Veroboard (20 mm x 3.5 mm). The distance between each pair of emitters and the photodetector was 5 mm, see Figure 1. The PPG probe was connected to a multicore screened cable (external diameter 4.0 mm) and was designed to just slide along a plane containing the axis and diameter of a conventional disposable transparent stomach tube (20 French gauge) of internal diameter of 4.6 mm (Pennine Healthcare, Derby, UK). There is little clearance between the wall of the stomach tube and the probe thereby minimising relative movement. In its final position the end of the PPG probe was approximately 60 mm from the end of the stomach tube, see Figure 1.

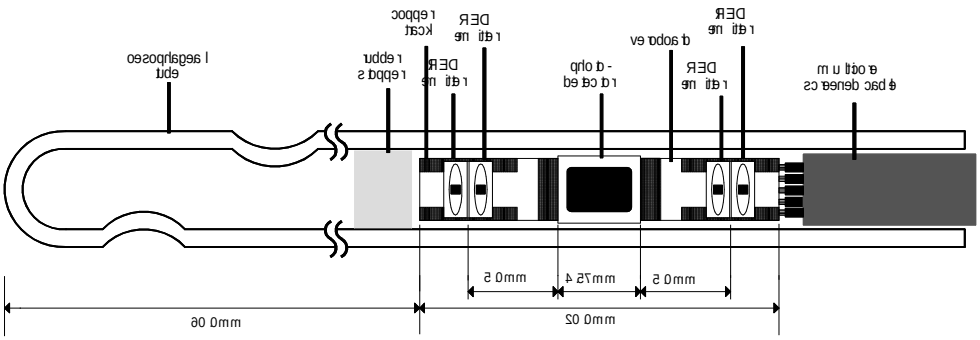

Fig. 1 **Diagram of the Reflectance Oesophageal PPG Probe**

2.2 PPG SIGNAL ACQUISITION AND PROCESSING SYSTEM

An electrically isolated data acquisition and processing system has been developed to detect, pre-process, sample, record and display the red and infrared AC PPG output signals on a laptop personal computer. A block diagram of the system is shown in Figure 2. It consists of two identical PPG processing channels, which allow the monitoring of oesophageal and finger PPG signals simultaneously. Red and infrared PPG measurements are made consecutively. At a given time, the same wavelength is used in the finger and oesophageal channels; mechanical switches effect the changeover between red and infrared wavelengths. The emitters in each channel are driven by a constant current source comprising an operational amplifier and a series transistor. The red (R) and infrared (IR) emitter output intensities depend on the forward current which is maintained at 45 mA in each case. This operating current is well below the maximum rated value of 75 mA for the emitters. The power dissipation of the red and infrared emitters is 62.3 mW and 42.7 mW, respectively. The photodetector detects the energy backscattered by the tissue and gives an output current proportional to the detected light intensity. The photodetector I-V (current-to-voltage) amplifier is an operational amplifier connected in a transresistance configuration that converts the photodiode current into a signal voltage. The output of the transresistance amplifier is connected to a band-pass filter that

consists of a first order high-pass active filter and a Butterworth 2-pole low-pass active filter. The frequency response is 0.5 Hz to 20 Hz (at -3dB) with a gain of 1.58 in the pass band.

An analogue isolation amplifier is used to electrically isolate the input side (patient side) from the output side in each channel. The input sides of the two channels are physically isolated from each other (see Figure 2). The isolation amplifier in each channel is a Hewlett Packard type HCPL7820. This is an inexpensive 8-pin dual-in-line, opto-electronic device. The output of the band-pass filter is transmitted across the isolation barrier with a gain of approximately eight. The differential output of the isolation amplifier is converted to a single ended signal by a differential amplifier with a gain of one. The signal is then passed to a variable amplification stage with a gain in the range of 1 to 50. The final stage comprises a DC level shifting circuit which gives an output signal compatible with the unipolar input range (0 to 2.5 V) of the analogue-to-digital converter (ADC).

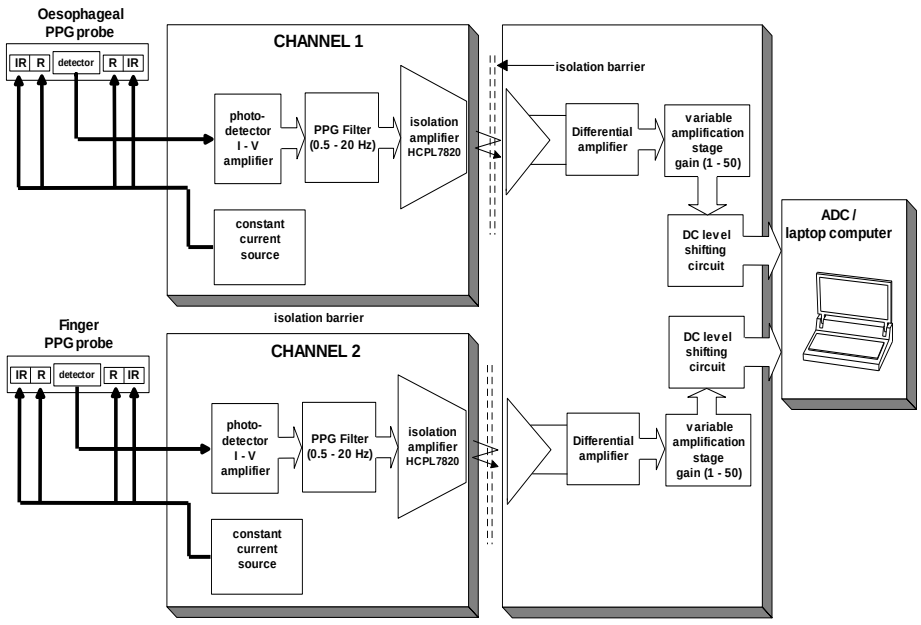

Fig. 2 Block Diagram of the Isolated PPG Signal Acquisition and Processing System

2.3 DATA ACQUISITION & RECORDING SYSTEM

The PPG signals at the output of the level shifting circuit are sampled using a 10-bit data acquisition system (ADC11, Pico Technology Ltd., Cambridge, UK) connected to the parallel port of a laptop personal computer. The signals recorded and displayed by the laptop computer correspond to infrared and red AC PPGs from the oesophagus and the finger. The finger probe used is identical to the oesophageal reflectance probe and was also constructed in the laboratory.

2.4 CLINICAL METHODS

Adult patients were studied who were to undergo tracheal intubation as a routine part of general anaesthesia for elective urological, gynaecological and general surgery. Twenty patients were studied, 2 male and 18 female. The oesophageal PPG probe was inserted into a disposable transparent stomach tube (external diameter 6.6 mm), as described in section 2.1. A new stomach tube was used for each patient. The exterior surface of the tube was lubricated with aqueous gel prior to insertion through the mouth into the oesophagus. General anaesthesia was induced with intravenous propofol; a muscle relaxant (atracurium or vecuronium) was given, and the trachea was intubated with an endotracheal tube. The stomach tube was advanced into the oesophagus under direct vision until the end of the probe, distal to the multicore cable, was between 25 cm and 30 cm from the upper incisors. The lungs were mechanically ventilated and anaesthesia was maintained using nitrous oxide (70%, in oxygen) and isoflurane (approximately 1.5% inspired concentration). The reflectance finger probe was placed on the finger of the patient. Simultaneous AC PPG traces from the oesophagus and the finger were recorded for approximately 15 minutes.

3. Performance Evaluation

3.1 TEMPERATURE TESTS

The operating current of the emitters is relatively low (45 mA) and they are thermally insulated from the tissue by the 1 mm thick plastic wall of the oesophageal tube. However, it was still necessary to confirm that the red and infrared sources would not cause any direct thermal damage to the oesophagus. Temperature tests both *in vitro* and *in vivo* were conducted to investigate the possibility of excessive temperature rises in the oesophagus during PPG measurements.

3.1.1 *In vitro* Measurements

Measurements were made of the changes in temperature at the outside of the oesophageal tube. In order to simulate conditions in the oesophagus, the oesophageal tube with the PPG probe inside was immersed in a static water bath at 37°C, as water has thermal properties similar to those of soft tissue. Two type K thermocouples were used as temperature sensors. The first thermocouple was attached to the outside of the oesophageal tube adjacent to one of the infrared emitters. The second thermocouple was used to monitor the temperature of the water bath. Two thermocouple amplifiers (AD595, Analog Devices) were used to produce linear voltage outputs with sensitivity 10 mV/°C. The two signals from the thermocouple amplifiers were subtracted using operational amplifier circuits and the temperature difference displayed on a chart recorder (Servogor, Model 464). After a constant baseline reading was achieved, the infrared light emitters were switched on and the temperature difference was monitored. Steady state conditions were achieved after approximately 15 minutes and monitoring was continued for a further 15 minutes. The measurement was repeated for a red

emitter. The rise in temperature at the outside surface of the oesophageal tube in this test was no more than 0.2°C for both the red and infrared emitters.

3.1.2 *In vivo* Measurements

In vivo simulations were also made in three normal healthy volunteers. The oesophageal tube with the PPG probe inside was placed in contact with the mucosa of the cheek inside the mouth. A type K thermocouple was attached to the outside of the oesophageal tube immediately adjacent to one of the infrared emitters. The temperature at the outside surface of the tube was recorded until a constant baseline was attained. The infrared light emitters were switched on and the temperature was monitored. Steady state conditions were achieved after approximately 10 minutes and monitoring was continued for a further 10 minutes. The measurement was repeated for a red emitter.

In these *in vivo* tests the rise in temperature at the outside surface of the oesophageal tube, when in contact with the cheek mucosa, was less than 0.7°C for the red emitter and 0.6°C for the infrared emitter in all cases. The higher temperature rise in the *in vivo* measurements compared with the *in vitro* measurements may be due to the cheek mucosa making poorer thermal contact with the wall of the stomach tube than the water. None of these temperature rises would be expected to result in tissue damage.

3.2 PPG ACQUISITION AND PROCESSING SYSTEM SAFETY TEST

To minimise the risk to the patient, the PPG acquisition and processing system and the laptop computer were all battery operated. Furthermore, the oesophageal PPG probe was isolated from the tissue by the plastic wall of the stomach tube and the finger probe was insulated from the finger by a transparent plastic sheath. As an added precaution, the input and output circuits

of the system were isolated using two HCPL 7820 Analogue Isolation Amplifiers (see Fig. 2). The PPG acquisition and processing system was tested for electrical safety using a Rigel Safety Tester Model 233. The insulation resistance between the patient applied parts (probes) and the output circuitry was measured for the oesophageal and finger channels. The current flowing across the isolation barrier with mains voltage on the applied parts, and with mains voltage at the output terminals was measured for both channels. The insulation between the input circuits of the finger and oesophageal channels was also similarly investigated.

In these tests the insulation resistance between the input and output circuits of the PPG processing system was too large to register on the tester meter, but was well in excess of 100 MΩ for each channel. The test with mains on the patient applied parts and on the output gave leakage currents across the isolation barrier of less than 9 μA in all cases. This is well below the 50 μA current limit for Class 1 and 2 type CF instruments.

4. Results

Figures 3 shows red and infrared AC PPG traces obtained from the lower oesophagus and the finger of an anaesthetised patient with the mechanical ventilator temporarily switched off for approximately twenty seconds. The oesophageal PPGs appear to be of good quality with relatively large amplitudes at both red and infrared wavelengths. The electrical characteristics and gain of the oesophageal and finger channels were identical for all measurements. The large deviations at the centre of each trace are due to the switching artefact when changing between red and infrared. When the mechanical ventilator is switched on, the oesophageal PPG traces are modulated by an artefact synchronous with the approximately 5 second period of the ventilator, as shown in Figure 4.

Table 1 shows the means and standard deviations of the peak-to-peak amplitudes of the red and infrared AC PPGs for the oesophagus and the finger at the output of the differential amplifier (see Figure 2). In a few cases, at the beginning of the study, no measurements were possible at the red or infrared wavelengths due to technical problems.

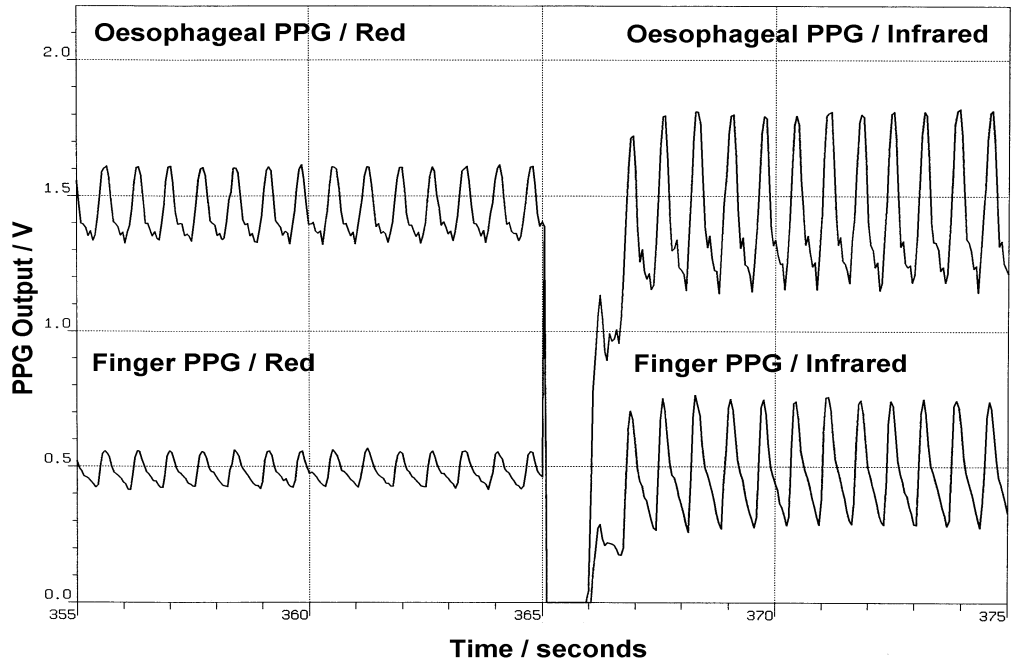

Fig. 3 AC PPG traces for the red and infrared wavelengths from the lower oesophagus and the finger of an anaesthetised patient with the mechanical ventilator temporarily switched off

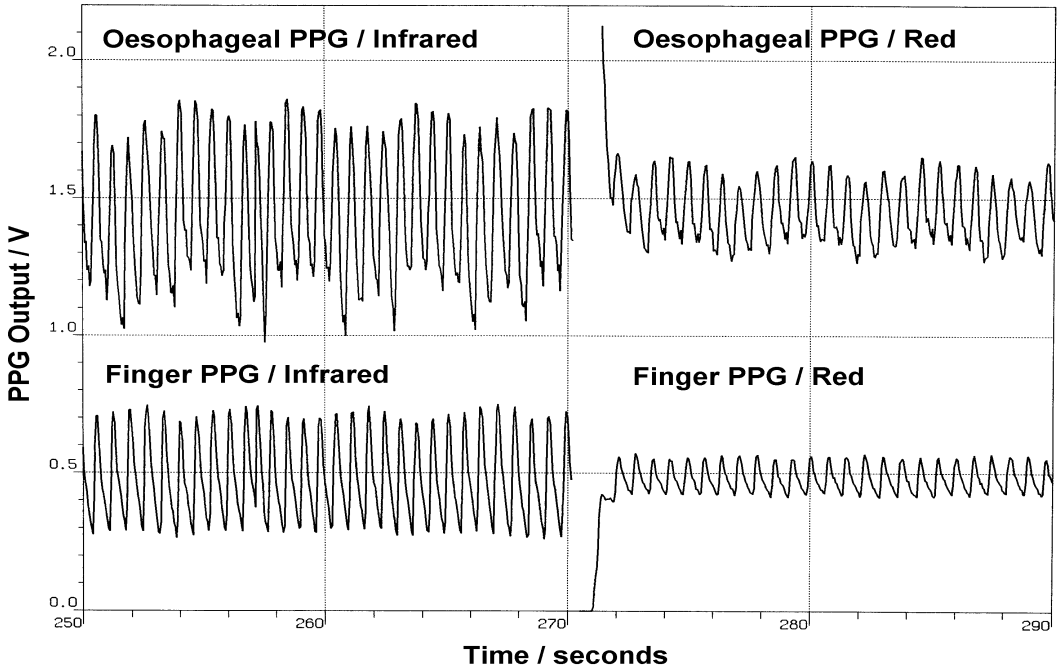

Fig. 4 AC PPG traces for the red and infrared wavelengths from the lower oesophagus and the finger of an anaesthetised patient with the mechanical ventilator switched on

Table 1. Means and standard deviations of the peak-to-peak amplitudes of the infrared and red AC PPGs for the oesophagus and the finger

	Oesophageal amplitude / mV INFRARED	**Oesophageal amplitude / mV RED**	**Finger amplitude / mV INFRARED**	**Finger amplitude / mV RED**
Mean	**29.2**	**13.2**	**16.5**	**6.5**
Std. Dev.	**13.2**	**9.8**	**12.4**	**4.8**
Number of Patients (n)	**20**	**17**	**19**	**16**

The ratio of the oesophageal to finger AC PPG amplitudes was calculated for the infrared and red wavelengths for each patient. The mean (± standard deviation) of this ratio was 2.9 ± 2.1 (n = 19) for the infrared wavelength and 3.1 ± 2.4 (n = 16) for the red wavelength.

6. Discussion and Conclusions

A new oesophageal PPG probe and an isolated processing system have been developed which allow measurements to be made within the lower oesophagus. It is concluded from the temperature measurements on the probe that there is negligible risk of thermal injury to the oesophagus when using this system. Oesophageal PPG signals have been obtained with high signal-to-noise ratio and large amplitudes at two wavelengths. This appears to be the first report of PPG signals from the oesophagus. The amplitudes of the oesophageal PPGs are on average approximately three times larger than those obtained simultaneously from a finger for both wavelengths, although there is considerable variability. The red and infrared wavelengths used are suitable for pulse oximetry, therefore, in principle, it should be possible to estimate arterial blood oxygen saturation in the lower oesophagus. Since the oesophagus is more central than other measurement sites, it may prove to be more reliable for monitoring SpO_2 in patients with poor peripheral circulation. Further work needs to be done to validate this hypothesis.

Acknowledgements

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