An oesophageal pulse oximetry system utilising a fibre-optic probe

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Abstract. A dual-wavelength fibre-optic pulse oximetry system is described for the purposes of estimating oxygen saturation (SpO_2) from the oesophagus. A probe containing miniature right-angled glass prisms was used to record photoplethysmographic (PPG) signals from the oesophageal wall. Signals were recorded successfully in 19 of 20 patients, demonstrating that PPG signals could be reliably obtained from an internal vascularised tissue site such as the oesophageal epithelium. The value of the mean oxygen saturation recorded from the oesophagus was 94.0 ± 4.0%. These results demonstrate that SpO_2 may be estimated in the oesophagus using a fibre-optic probe.

1. Introduction

An optical fibre-based oximetry system was developed for estimating the oxygen saturation (SpO_2) in internal tissue from photoplethysmographic signals obtained using red and infrared light sources. The oesophagus was chosen as a suitable internal measurement site since it is easily accessible in anaesthetised patients. To overcome the problems associated with the measurement of SpO_2 in states of poor peripheral perfusion, Kyriacou et al. described a reflectance oesophageal pulse oximetry system [1]. The oesophageal probe comprised two infrared and two red LEDs (of peak emission 880 nm and 655 nm respectively) arranged adjacent to a photodetector and was designed to fit into a size 20 French gauge plastic transparent disposable stomach tube before insertion into the oesophagus.

In a clinical trial of the system [2, 3], the oesophageal and finger PPGs and SpO_2 in 49 patients undergoing hypothermic cardiothoracic bypass surgery were compared. Photoplethysmographic signals were observed at various depths in the oesophagus and oesophageal SpO_2 values, estimated from the backscattered intensities measured using the probe, were compared with those measured using a commercial finger pulse oximeter. Measurable PPG traces at red and infrared wavelengths were obtained in the oesophagus in all 49 patients [2]. It was found that five of the 49 patients in the study had one or more periods of at least ten consecutive minutes, during which the commercial finger pulse oximeter failed to display PPG signals and SpO_2 values, despite being correctly positioned on the finger. Conversely, the oesophageal pulse oximeter operated successfully throughout these periods. Use of the oesophageal pulse oximeter has also been successfully demonstrated in patients suffering from major burns [4]. Another study using a smaller version of the oesophageal pulse

oximetry probe showed that reliable signals could be obtained from neonatal and paediatric patients [5].

In the present study, a fibre-optic probe for use in the oesophagus was designed and evaluated in 20 patients undergoing surgery requiring tracheal intubation and mechanical ventilation. Optical fibres are of interest since their use confers the benefit of electrical isolation of the patient from the optoelectronic components. The use of optical fibres to transmit photoplethysmographic signals from tissue has been demonstrated in other applications [6, 7]. The oesophageal probe utilises a pair of prisms to change the path of the light through an angle of 90˚, so the light is transmitted perpendicular to the axis of the transmitting fibre (unlike a bare fibre which transmits light in a cone, whose axis is aligned with the cylindrical axis of the fibre) and similarly, the probe is sensitive to light back-scattered from the oesophageal wall.

2. Materials and methods

2.1. Probe and instrumentation

The oesophageal probe was constructed from a pair of glass optical fibres with a core diameter of 600 µm terminated at the proximal end with SMA connectors. The distal end was polished flat using Grade 5 followed by Grade 3 sandpaper. A right-angled glass prism (Edmund Optics, York, UK) of dimensions 2 mm x 2 mm x 2 mm was affixed to the ends of each optical fibre using 144-M glass adhesive (Dymax Inc., Torrington, CT, USA). The fibres ends and prisms were then encased in an cylindrical epoxy resin (ER1100/CT1100, Dymax Inc.) moulding as shown in figure 1. The reflecting surfaces of the prism were remained free of epoxy to ensure full total internal reflection.

The probe was designed to be inserted into an 18 French gauge naso-gastric tube (N-G tube). The N-G tube keeps the probe isolated from body fluids, so the probe may be re-used with a new N-G tube without the risk of cross-contamination between patients. The probe was connected at the proximal end to a processing system consisting of a box containing LED light sources and a photodetector. The box also contained current sources for the LEDs, and a signal processing system. This was interfaced to a 16-bit data acquisition card (National Instruments Inc. Austin, TX, USA) installed into a notebook computer, which recorded the signals acquired from the tissue.

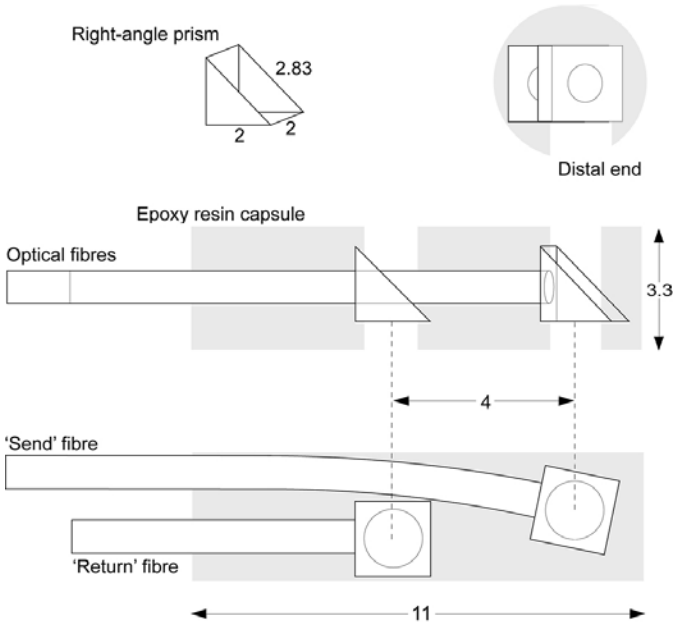

Figure 1. Diagram of the fibre-optic oesophageal oximetry probe. All dimensions are in millimetres.

2.2. **Patient measurements**

The study was approved by the local Research Ethics Committee, and permission was given to conduct the study in 20 patients. Patients undergoing minor general surgical procedures requiring tracheal intubation and ventilation were deemed suitable for this study. Adult patients aged (18-70) and deemed 'low risk' by the American Society of Anesthesiologists (score of 1-3) were identified from the elective operating lists at Barts and The London NHS trust. Any patients in whom difficulty or increased risk of probe placement was anticipated, were excluded.

After induction of anaesthesia and immediately after tracheal intubation, the probe contained within a sterile N-G tube was inserted into the oesophagus by the anaesthetist, via the patient's mouth, under direct vision with a laryngoscope. The tip of the probe was placed at a depth of 35 cm in the oesophagus as measured from the front incisors. Once the probe was in position, the light sources were switched on and signals recorded for 100 seconds. The probe was then withdrawn 5 cm at a time and signals recorded for a further 100 seconds at each position until the probe was at a depth of 15 cm. The arterial oxygen saturation was measured using a commercial finger pulse oximeter (Datex-Ohmeda, Helsinki, Finland). The probe was removed at the end of the measurement period, before the patient was moved from the anaesthetic room to the operating theatre, and surgery commenced. Each patient was reviewed post-operatively, to check for any adverse events.

2.3 Estimation of oxygen saturation values

The PPG (AC signal) was separated from the total intensity (AC+DC) signal using filters incorporated into the measurement circuitry. The PPG signal was normalized by dividing the signal by the simultaneously recorded AC+DC signal. The peak-to-peak amplitudes of the normalized PPG signals were calculated for each heart-beat using a peak and valley detection algorithm incorporated into a LabVIEW virtual instrument. The mean value of R_R for each data stream was calculated mean peak to peak amplitudes of the two PPG signals thus

$$R_R = \sum_{i=1}^{n} A_{i,R} \Big/ \sum_{i=1}^{n} A_{i,IR} \qquad (1)$$

where the $A_{i,R}$ and $A_{i,IR}$ are the peak-to-peak amplitudes of the *i*th red and infrared PPG cycle in the data stream respectively and n is the total number of PPG cycles (heartbeats) in the data stream. The ratio-of-ratios R_R was thus averaged over a finite time period. The mean value of R_R was used to estimate the arterial oxygen saturation (SpO_2) by substituting in the equation

$$SpO_2 = 110 - 25R_R \qquad (2)$$

which is a linear approximation to an empirically determined calibration curve, obtained from measurements in healthy volunteers [8]. It should be noted that this equation was derived using a measurement system utilising a 940 nm infrared light source. As the present system uses an 850 nm LED, significant error in estimation should be expected. However as no other equation is available, Equation 2 may be used to produce a rough estimation of oxygen saturation.

3. Results

Signals were successfully obtained from 19 patients, with one failure attributable to a technical fault. Examples of the signals recorded at all five measurement depths for one patient are shown in Figure 2. the peak-to-peak amplitude of the photoplethysmographic waveform varies considerably with different

measurement depths. The waveform has been compressed horizontally as 500 seconds of recorded data are shown so very little detail can be discerned.

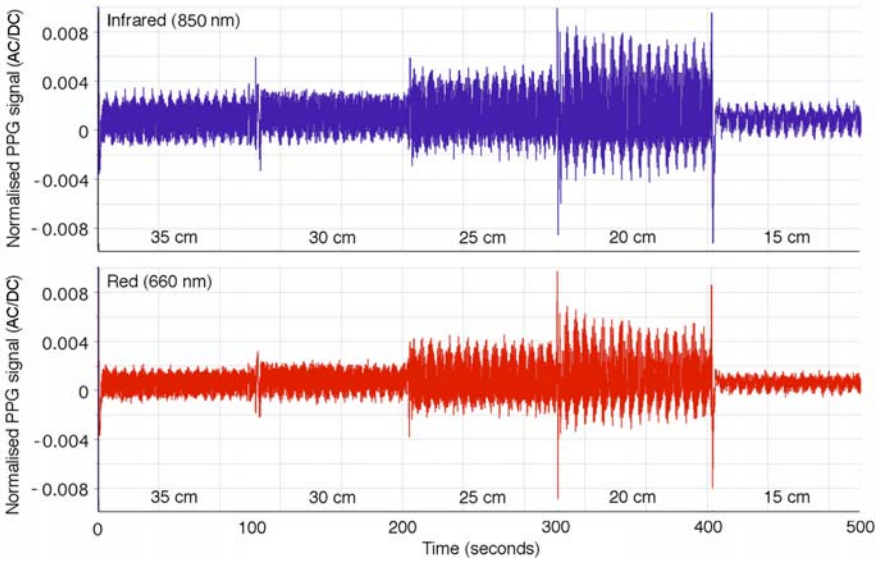

Figure 2. An example of a 100 s recording of the normalised infrared and red PPG signals at all five measurement depths for one patient (Patient number = 17).

Figure 3 shows a 60-second sample of the normalized infrared and red PPG waveforms (the same waveforms shown in Figure 2) obtained at a measurement depth of 20 cm The dominant periodic feature occurs at a frequency consistent with the cardiac frequency, but the waveform also contains a low frequency modulation at about 0.18 Hz, equal to the frequency of artificial ventilation. It can be seen that the morphology of the PPG waveform varies with varying depth of measurement. As well as the change in amplitude with depth, the ventilator modulation varies in amplitude, relative to the periodic cardiac variation. Between 35 and 25 cm there is significant baseline modulation but at depths of 20 cm or less there also appears to be modulation of the peak-to-peak amplitude.

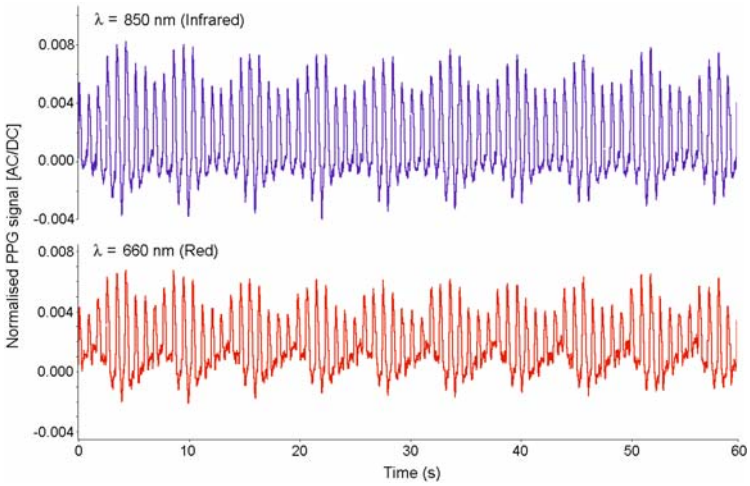

Figure 3. 60-second sample of the normalized infrared and red PPG waveforms obtained at a measurement depth of 20 cm.

Figure 4 shows a graph of the mean (±SD) of the AC PPG amplitudes at red and infrared wavelengths at the five monitoring depths for all patients. The AC signals in the mid to lower oesophagus (depths

of 20 cm or greater) have significantly larger mean amplitudes at both wavelengths than those in the upper oesophagus (15 cm). The maximum mean oesophageal amplitude for each wavelength occurs at the depth of 20 cm.

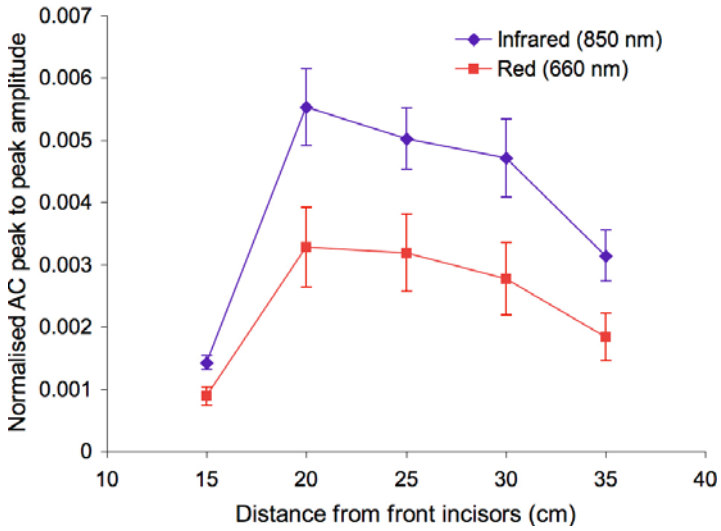

Figure 4. Graph showing normalised mean (± SEM) peak-to-peak amplitude of AC red and infrared signals measured from the oesophagus in 19 patients.

The amplitudes of the red and infrared normalized PPG signals obtained at 15 cm were significantly smaller (P<0.001) than those obtained at all other depths, as evaluated by a paired Student's t-test. There was no significant difference between amplitudes at other adjacent depths (i.e. 20–25 cm, 25–30 cm and 30–35 cm). To compare the signals between patients, a 'best' depth was chosen for each patient, i.e. the depth at which the infrared PPG amplitude was greatest, found by manual measurement the amplitude from printouts of the PPG waveforms. The mean ratio-of-ratios for each patient (at the best depth) was also calculated from the PPG amplitudes, using Equation (1) and the estimated oxygen saturation calculated using Equation (2). The mean value (±SD) of oxygen saturation is 94.0% (± 4.0%). The arterial oxygen saturation recorded from the finger with the commercial pulse oximeter was in the range 98-100% for all 19 patients.

4. Discussion

These results show that reliable photoplethysmographic signals may be obtained from the oesophageal wall. The acquired signals showed different morphology and amplitudes, depending on the depth of the monitoring site. The measurements suggest that the greatest amplitude signals, and therefore probably the most suitable measuring site, is 20-30 cm from the teeth. Kyriacou et al compared PPG signals at the same depths as these studies, but using a non-fibreoptic probe. Their findings were similar; statistically significant differences between the PPG amplitudes in the upper oesophagus (15 cm) and the amplitudes at all other depths at the infrared wavelength were found. This was also true for the red wavelength except that there is no significant difference between the amplitudes at the depths of 15 cm and 35 cm [9].

The value of the mean oxygen saturation of 94 ± 4.0% was lower than that recorded from the finger using the commercial pulse oximeter. The slight negative bias may be attributable to the use of an algorithm (Equation 2) for calculation the SpO_2 which was developed from experimental measurements using transmittance mode probes on a different measurement site (the finger rather than the oesophagus), and for a different infrared wavelength. Kyriacou et al found their oesophageal measurements to be on average 6.5% lower than those measured from a commercial finger pulse oximeter [1].

Another possible source of inaccuracy is possible mechanical artifact induced by the patients' heartbeat and ventilation due to the proximity of the probe to the heart and lungs. It has been observed that the PPG signals are sensitive to movement of the fibre tips relative to the tissue surface as well as movement of the fibres themselves. It may be supposed that a periodic (AC) modulation would be induced in the detected signals with cardiac and respiratory frequency. It may also be supposed that this induced movement modulation would be similar in magnitude for both wavelengths so the calculated ratio-of-ratio (normally < 1 for arterial blood) would be higher than in the case with no movement, most likely producing an underestimation of the reported oxygen saturation. There are many potential advantages of using optical fibres for this type of application, such as electrical and thermal isolation of the optoelectronic components from the patient. These advantages may be offset however by problems of movement artefact, and further study is needed to ascertain whether movement artefact would limit the application of this type of sensor.

The oesophageal measurements were made with the aim of investigating whether PPG signals could be obtained from internal vascularized tissue using a fibre-optic probe. Other than by pulse oximetry (which is not considered a 'gold-standard' method), accurate measurements of the arterial and venous oxygen saturations were not recorded, so further analysis of oxygen saturation in these patients was not deemed appropriate at this stage. The oesophageal measurements however, demonstrate that PPG signals may be reliably obtained from internal tissue using a reflectance mode fibre-optic probe.

References

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