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Evaluation of oesophageal pulse oximetry in patients undergoing cardiothoracic surgery*

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Summary
Pulse oximetry probes placed peripherally may fail to give accurate values of blood oxygen saturation when the peripheral circulation is poor. Because central blood flow may be preferentially preserved, we investigated the oesophagus as an alternative monitoring site. A reflectance blood oxygen saturation probe was developed and evaluated in 49 patients undergoing cardiothoracic surgery. The oesophageal pulse oximeter results were in good agreement with oxygen saturation measurements obtained by a blood gas analyser, a CO-oximeter and a commercial finger pulse oximeter. The median (IQR [range]) difference between the oesophageal oxygen saturation results and those from blood gas analysis were 0.00 (−0.30 to 0.30 [−4.47 to 2.60]), and between the oesophageal oxygen saturation results and those from CO-oximetry were 0.75 (0.30 to 1.20 [−1.80 to 1.80]). Bland–Altman analysis showed that the bias and the limits of agreement between the oesophageal and finger pulse oximeters were −0.3% and −3.3 to 2.7%, respectively. In five (10.2%) patients, the finger pulse oximeter failed for at least 10 min, whereas the oesophageal readings remained reliable. The results suggest that the oesophagus may be used as an alternative monitoring site for pulse oximetry even in patients with compromised peripheral perfusion.

Keywords *Blood gas analysis*; oximetry. *Monitoring*; intra-operative. *Surgery*; cardiac, thoracic.

Use of the pulse oximeter is standard in anaesthesia, intensive care, surgery, emergency medicine and general ward care. However, the reliability of pulse oximetry when probes are applied to peripheral parts of the body may be compromised in certain patients [1, 2], such as those who become hypothermic or hypovolaemic, or have decreased cardiac output [3–5]. Such clinical situations occur, for example, after prolonged operations, in particular hypothermic cardiopulmonary bypass surgery. Thus, S_pO_2 readings are often unobtainable in situations where they would be most valuable.

Prielipp *et al.* [6] presented results of haemoglobin–oxygen saturation measurements obtained at the cricopharyngeous muscle in the upper oesophagus using a 'transesophageal' probe. They compared this probe with the probes of two conventional finger pulse oximeters, and concluded that the 'transesophageal' probe did not perform as well as the standard oximeters. To overcome the limitations of measurements at the cricopharyngeous muscle, measurement of S_pO_2 from greater depths in the oesophagus has been suggested [7]. The use of a more central monitoring site could increase the likelihood of obtaining reliable readings of oxygen saturation from vulnerable patients, and in the study presented here such a location is investigated. Earlier studies on ASA I anaesthetised patients using a novel oesophageal probe have shown that measurable photoplethysmographic signals could be detected from the entire length of the oesophagus [7–9]. Good quality photoplethysmographic signals are essential for reliable measurements of

S_pO_2. A new oesophageal pulse oximetry processing system, which allows the online estimation of oesophageal S_pO_2, has been developed. The purpose of this study was to compare values of S_pO_2 measured using oesophageal pulse oximetry with those of S_pO_2 measured using conventional finger pulse oximeters and with those of arterial blood oxygen saturation (S_aO_2) obtained from laboratory blood analysis, in patients undergoing high-risk operations.

Methods

Local research ethics committee approval was obtained to study ASA 2–4 anaesthetised patients undergoing elective cardiothoracic surgery, after informed consent. Patients with oesophageal pathology or previous surgery to the oesophagus or stomach, and those who had undergone trans-oesophageal echocardiography, were not studied. An intravenous 14G cannula was placed in a forearm, and a 20G radial arterial cannula was placed to allow continuous monitoring of blood pressure during induction of anaesthesia. Anaesthesia was induced with midazolam and etomidate followed by a dose of rocuronium or pancuronium. Fentanyl was used for analgesia. The trachea was intubated and the lungs were mechanically ventilated. Anaesthesia was maintained using isofluorane (inspired concentration $\approx 1.2\%$) in a 1:2 mixture of oxygen and nitrous oxide. Heart rate and systolic and diastolic blood pressures were monitored continuously. Central temperature was measured from the nasopharynx and peripheral temperature from the left shoulder tip. The right internal jugular vein was cannulated using a triple lumen cannula to allow monitoring of central venous pressure.

A reflectance oesophageal pulse oximeter probe was developed using two infrared emitters with peak emission wavelength at 880 nm and two red emitters with peak emission wavelength at 655 nm [7]. A single photo-diode was used to detect light intensity backscattered by the tissue from the emitters. The oesophageal pulse oximeter probe was designed to fit into a conventional (20-FG) disposable transparent stomach tube (Pennine Healthcare, Derby, UK). A processing system, isolated for patients' safety, was developed to detect, process and display the oesophageal photoplethysmographic signals on a laptop computer. This computer was programmed to make continual estimations of oesophageal S_pO_2. The oesophageal pulse oximeter probe was inserted into a sealed 20-FG stomach tube, and a 30-cm marker was positioned on the plastic wall of the tube. The stomach tube, lubricated with aqueous gel, was placed via the mouth into the oesophagus under direct vision. Having previously found that photoplethysmographic signals in the mid-oesophagus (20–25 cm from the upper lip) are of large amplitude [9], the stomach tube was advanced into the oesophagus until the end of the probe itself was 30 cm from the lips, as indicated by the marker. Photoplethysmographic signals were observed at various depths in the oesophagus as the probe was withdrawn in increments of 1–2 cm, until the site that provided the highest amplitude photoplethysmographic signals and small ventilator artefact (synchronous modulation of the oesophageal photoplethysmographic traces at the frequency of the ventilator) was determined. The depth of the probe was calculated by measuring the distance from the 30-cm marker to the lip. Photoplethysmographic traces and values of S_pO_2 from the oesophagus were recorded simultaneously. During the oesophageal measurements, values of S_pO_2 from a commercial transmission-type finger pulse oximeter (Marquette, Tram 200 A; Marquette Electronics, Milwaukee, WI, USA) were also recorded.

Monitoring with the oesophageal pulse oximeter was temporarily stopped while moving the patient from the induction room to the operating theatre. Oesophageal monitoring and data collection in the operating theatre were performed intermittently during the following six periods.

1 For 10–15 min before skin incision. During this time the depth of the oesophageal probe was reconfirmed, as there was a possibility that it might have moved during transfer. Photoplethysmographic signals were recorded at this depth and any adjustments of probe depth were made if needed.

2 For 15 min after sternotomy.

3 For at least 10 min before cardiopulmonary bypass. Photoplethysmographic signals were recorded until cessation of cardiac activity on bypass, and when no pulsatile signals were seen on the laptop's screen.

4 For ≈ 10 min before coming off bypass until 30 min after the patient was completely off bypass and with stable cardiac activity (but before closure of the chest).

5 For 5–20 min after closure of the chest.

6 For 30–60 min in the intensive care unit while rewarming.

During these recording periods, 1-ml samples of arterial blood were drawn into heparinised 2-ml syringes and analysed immediately using an Instrumentation Laboratories IL 482 CO-oximeter or an Instrumentation Laboratories IL BG-1400 Blood Gas Analyser (Instrumentation Laboratories, Lexington, MA, USA). The arterial cannula was flushed with heparinised 0.9% saline solution (2 unit.ml^{-1}) after sampling. Care was taken to ensure that the arterial line and the blood-sampling syringes were free of air bubbles. Patients' results were accepted for statistical analysis with respect to S_aO_2 if at least one

blood sample was analysed by blood gas analysis or CO-oximetry and concurrent oesophageal and commercial finger S_pO_2 values existed.

Linear regression analysis was used to compare blood oxygen saturation from the oesophageal pulse oximeter with those from CO-oximetry and blood gas analysis. It has been suggested that linear regression analysis is appropriate when calibrating an approximate or simple method (such as the oesophageal pulse oximeter) with a precise method (such as CO-oximetry) [10]. The levels of agreement between the oesophageal and commercial finger probes were calculated using the between-method differences analysis outlined by Bland & Altman [10].

Results

Forty-nine patients (40 male and 9 female) aged 26–81 years were recruited to the study. Table 1 summarises the type of operation. Measurable oesophageal photoplethysmographic traces, of good quality and large amplitude, were obtained in all patients (before and after bypass). The mean (SD [range]) optimal oesophageal depth was 17.8 (3.3 [14–28]) cm, measured from the upper lip.

Comparisons of blood oxygen saturation measurements from the oesophageal and commercial finger pulse oximeters with those from blood gas analysis

A total of 155 sets of data points were used for the regression analysis, which gave the estimated slope and intercept of the regression line. Two to five arterial blood samples were collected from each patient (one before and one after bypass in all patients), with further samples in procedures of longer duration or in the event of the commercial pulse oximeter indicating hypoxaemia. A plot of S_pO_2 readings obtained from the oesophageal pulse oximeter against those of S_aO_2 from the blood gas analyser is shown in Fig. 1. The median (IQR [range]) of the differences between values obtained with the two methods was 0.00 (−0.30 to 0.3 [−4.47 to 2.60]).

Table 1 Type of surgery in patients monitored with oesophageal pulse oximetry. Values are number (proportion).

CABG* (continuous flow)	35 (71)
Heart valve replacement	7 (14)
CABG (pulsatile flow)	2 (4)
Heart valve replacement + CABG	2 (4)
Excision of cervical rib	1 (2)
Thoracoscopy	1 (2)
Thoracotomy	1 (2)

*CABG = coronary artery bypass graft.

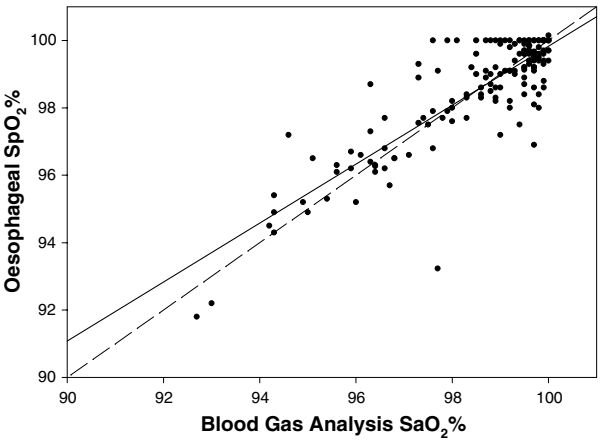

Figure 1 Plot of S_pO_2 measurements obtained from the oesophageal pulse oximeter against S_aO_2 from blood gas analysis for 49 patients undergoing cardiothoracic surgery ($n = 155$ readings). The dashed line represents the line of identity and the solid line represents the best fit linear regression line: (oesophageal S_pO_2) = 12.3 + 0.88 (blood gas analyser S_aO_2); $r^2 = 0.74$ (standard error of estimate 0.86; $p < 0.001$).

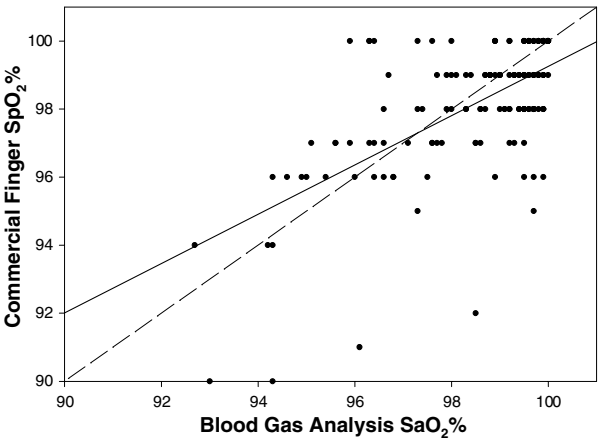

Figure 2 Plot of S_pO_2 measurements obtained from a commercial finger pulse oximeter against S_aO_2 from blood gas analysis for 49 patients undergoing cardiothoracic surgery ($n = 155$ readings). The dashed line represents the line of identity and the solid line represents the best fit linear regression line: (commercial finger pulse oximeter S_pO_2) = 26.8 + 0.73 (blood gas analyser S_aO_2); $r^2 = 0.39$; (standard error of estimate 1.48; $p < 0.001$).

Figure 2 shows a plot of S_pO_2 readings obtained from the commercial finger pulse oximeter against S_aO_2 values from the blood gas analyser. The median (IQR [range]) difference (commercial finger pulse oximetry–blood gas analysis) between values obtained with the two methods was 0.10 (−0.40 to 1.07 [−6.50 to 4.10]).

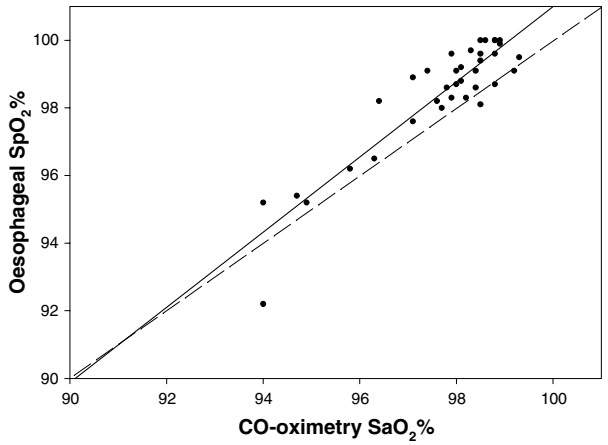

Figure 3 Plot of S_pO_2 measurements obtained from the oesophageal pulse oximeter against S_aO_2 from CO-oximetry for 17 patients undergoing cardiothoracic surgery ($n = 36$ readings). The dashed line represents the line of identity and the solid line represents the best fit linear regression line: (oesophageal S_pO_2) = 10.1 + 1.1 (CO-oximetry S_aO_2); $r^2 = 0.83$ (standard error of estimate 0.71; $p < 0.001$).

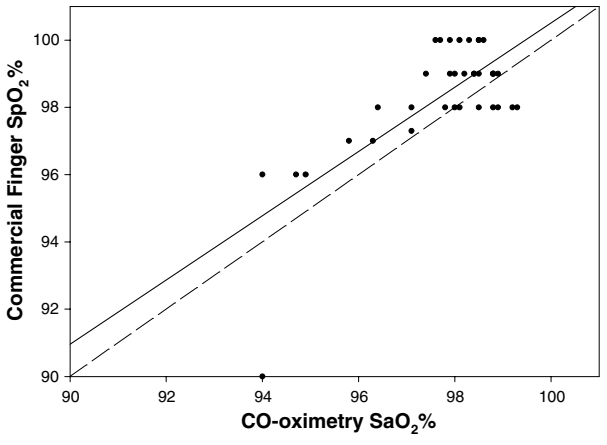

Figure 4 Plot of S_pO_2 measurements obtained from the commercial finger pulse oximeter against S_aO_2 from the CO-oximetry for 17 patients undergoing cardiothoracic surgery ($n = 36$ readings). The dashed line represents the line of identity and the solid line represents the best fit linear regression line: (commercial finger pulse oximeter S_pO_2) = 4.9 + 0.9 (CO-oximetry S_aO_2); $r^2 = 0.55$; (standard error of estimate = 1.26; $p < 0.001$).

Comparisons of blood oxygen saturation measurements from the oesophageal and commercial finger pulse oximeters with those from CO-oximetry

In a subset of 17 patients, arterial blood was also analysed using CO-oximetry, providing 36 sets of data for regression analysis, which gave the estimated slope and intercept of the regression line. A plot of oesophageal S_pO_2 readings against the S_aO_2 values from the CO-oximeter is shown in Fig. 3. The median (IQR [range]) difference between values obtained with the two methods was 0.75 (0.30 to 1.20 [−1.80 to 1.80]).

Figure 4 shows a plot of commercial finger S_pO_2 readings against the S_aO_2 values from the CO-oximeter. The median (IQR [range]) difference between values obtained with the two methods was 0.75 (0.15 to 1.50 [−4.0 to 2.40]).

Comparisons of blood oxygen saturation measurements from the oesophageal and commercial finger pulse oximeters

The 155 sets of measurements from all 49 patients were used to compare the S_pO_2 values from the oesophageal and commercial finger pulse oximeters. Figure 5 shows a Bland–Altman plot of the difference between the S_pO_2 values against their mean. Bias (mean difference) and limits of agreement (mean difference ± 2 SD) for the two methods were −0.3% and −3.3 to 2.7%, respectively.

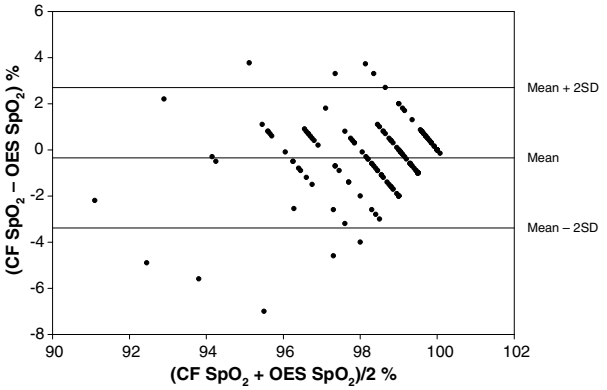

Figure 5 Bland–Altman plot [10] for the difference between S_pO_2 values obtained from the commercial finger pulse oximeter and the oesophageal pulse oximeter (CF S_pO_2–OES S_pO_2) plotted against their mean (CF S_pO_2 + OES $S_pO_2/2$) for 49 patients ($n = 155$ readings).

Failure of commercial pulse oximeter

Of the 49 patients included in the study, five (10.2%) had one or more periods of at least 10 consecutive minutes, during which the commercial finger pulse oximeter failed to record pulsatile photoplethysmographic signals and display S_pO_2 values, despite being correctly positioned on the finger. The oesophageal pulse oximeter operated successfully throughout these periods of failure. In four of these patients, the finger pulse oximeter failed postoperatively in the intensive care unit (within the first 30 min after surgery), and in the fifth patient, failure occurred in

Table 2 Blood oxygen saturation measured with the oesophageal pulse oximeter and by blood gas analysis in patients in whom peripheral pulse oximetry failed.

Patient no.	Oesophageal (%)	Blood gas analysis (%)
1	97.1	97.0
2	97.0	97.7
3*	98.5, 99.0	98.7, 99.0
4	97.9	97.9
5*	98.8, 98.9	98.9, 98.0

*Failure lasted long enough to allow two blood gas analyses.

the operating theatre before bypass. Results from arterial blood gas analysis performed during these periods of failed finger pulse oximetry are shown in Table 2, and demonstrate good agreement between the oxygen saturation values obtained from the oesophageal pulse oximeter and the blood gas analyser.

Discussion

We obtained good quality oesophageal photoplethysmographic signals with large amplitudes at various depths within the oesophagus (from the upper to the lower oesophagus) in all our patients, with 16–19 cm (measured from the lips) the most appropriate for S_pO_2. At these depths the magnitude of the ventilator artefact (synchronous modulation in the form of a sinusoidal baseline shift in time with the $\approx$5-s period of the ventilatory cycle) was $<30\%$ of the oesophageal photoplethysmographic peak-to-peak amplitude. In these circumstances, the algorithm for the continual estimation of oesophageal S_pO_2 was able to detect the AC component of the photoplethysmographic signal reliably.

Oesophageal S_pO_2 results were in good agreement with those from the blood gas analyser and CO-oximeter; in both cases the oesophageal S_pO_2 readings were higher on average than the laboratory S_aO_2 measurements, by $<1\%$. When the commercial finger pulse oximeter was compared with the laboratory blood gas analysers, the results were similar although the scatter was greater. The larger scatter may be due to the fact that the commercial finger pulse oximeter was constrained to give whole integer outputs. Bland–Altman analysis suggests that S_pO_2 obtained from the commercial finger pulse oximeter and the oesophageal pulse oximeter were in good agreement. The limits of agreement we found (−3.3 to 2.7%) would be considered acceptable in clinical practice [11]. Thus, it could reasonably be argued that the oesophageal pulse oximeter could be used interchangeably with this commercial finger pulse oximeter.

The oesophageal pulse oximeter was found to be reliable and accurate in cases of poor peripheral perfusion when the commercial finger pulse oximeter failed for at least 10 min. These results suggest that in patients undergoing cardiothoracic surgery, the arterial circulation to the oesophagus is less subject to vasoconstriction and decreased photoplethysmographic amplitudes than the finger. Although the pulse oximeter failed in only 10% of the patients, this represents a significant clinical problem. A more reliable means of monitoring would be of real clinical value.

In this preliminary investigation, none of the measured S_pO_2 values was $<90\%$. There is, therefore, a need to evaluate the oesophageal pulse oximeter in patients with lower S_pO_2. Nevertheless, this study shows that the oesophagus can be used as an alternative site for monitoring arterial oxygen saturation by pulse oximetry in patients undergoing cardiothoracic surgery. In addition, it provides evidence suggesting that the oesophagus may be a more reliable site for measuring saturation at times of poor peripheral circulation than a peripheral site such as the finger, although the number of failures was small and further work is needed to confirm these findings. This novel oesophageal pulse oximeter may also find application in patients who have burns or other serious injuries where the oesophagus may be the only available site for a pulse oximetry probe.

Acknowledgement

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