REFLECTION AND TRANSMISSION PULSE OXIMETRY DURING COMPROMISED PERIPHERAL PERFUSION

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ABSTRACT. The performance of a reflection pulse oximeter and a transmission pulse oximeter was assessed during open-heart surgery when cardiac output, peripheral temperature, pulse pressure, and systolic pressure were low and vascular resistance was high. Before and after extracorporeal circulation (ECC) there was no difference in ability of the sensors to obtain readings and no difference in the accuracy of those readings. During partial ECC, especially after coronary artery bypass grafting, the reflection sensor gave readings earlier and at a lower pulse pressure. In addition, the transmission sensor failed to give any readings for 2 patients on partial ECC, for whom the reflection sensor did give readings. The accuracy of heart rate (HR) data was comparable for both sensors before ECC; however, during partial ECC, the reflection sensor tended to give values closer to the electrocardiographic HR. The accuracy of saturation data given by the reflection oximeter was comparable to that of the transmission oximeter. It is concluded that the accuracy of the saturation and HR data provided by the two methods of pulse oximetry are comparable, but that the reflection sensor is more likely to obtain readings under conditions of poorer peripheral circulation.

KEY WORDS. Measurement techniques: pulse oximetry, reflection and transmission. Oxygen: measurement. Hemodynamics.

During the last decade, the pulse oximeter has become a popular device for measuring oxygenation. It monitors noninvasively and continuously, it is portable and easy to use, and it has proven reliable in most instances [1–4]. There is, however, still some question concerning the accuracy of the pulse oximeter in cases of low peripheral perfusion due to hypothermia, hypovolemia, or the use of vasoactive agents. Some studies indicate that the oximeter's reliability [5–9] and reaction time [2,10] are adversely affected in these situations, while others indicate that its accuracy remains good [11,12]. The present author and A. Vuori have recently demonstrated the reliability of 3 pulse oximeters at low cardiac index and with low peripheral temperature [13].

One probable source of problems is that transmission sensors work on peripheral areas, such as the fingers and ears, where pulsatile flow is most easily compromised. Transmission sensors have been placed on more central parts of the body (e.g., the nose and tongue) in an attempt to overcome problems arising from the centralization of the circulation, but these alternative sites are not promising. The nose sensor has been found to be less accurate than the finger and ear sensors [11,14], and the two studies concerning the tongue sensor included only four patients [15,16]. Moreover, the tongue is a suitable monitoring site only in anesthetized patients with a dry mouth.

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Compared with transmission probes, the reflection pulse oximeter probe, which has been introduced recently, can be placed on more central parts of the body with respect to circulation, such as the upper arm, the chest, and the forehead [17–20]. In some pulse oximeters, transmission probes can also double as reflection sensors. Reflection sensors are expected to provide reliable monitoring in situations of lower cardiac output (CO), cooler peripheral temperature, and higher vascular resistance than typically monitored by transmission probes; however, no studies evaluating their performance in patients with poor perfusion have been reported.

The purpose of this study was to compare the accuracy and reliability of pulse oximeter data obtained with a reflection probe to those obtained with a transmission probe in situations in which cardiac index, peripheral temperature, pulse pressure, and systolic pressure are low, and systemic vascular resistance index (SVRI) is high.

MATERIALS AND METHODS

Informed consent was obtained from 23 patients (19 men and 4 women; mean age, 56.8 years; range, 26 to 65 years) presenting for open heart surgery (20 patients, coronary artery bypass grafting [CABG]; 1 patient, CABG and mitral valve prosthesis; 1 patient, CABG and aortic valve prosthesis; and 1 patient, aortic valve prosthesis). The study protocol was approved by the ethical committee of Turku University and Turku University Central Hospital.

Morphine, 0.2 mg/kg, and scopolamine, 6 μg/kg, were given 1 hour before induction of anesthesia with 100% oxygen, 0.08 mg/kg lorazepam, 50 μg/kg fentanyl, and 0.1 mg/kg pancuronium. Additional fentanyl was given up to the time of sternotomy, and pancuronium was added as needed. End-tidal CO_2 was monitored (Normocap, Datex-Instrumentarium, Espoo, Finland) to achieve normoventilation.

The two pulse oximeters used in the study were identical Criticare 504 US monitors (version 1.1, Criticare Systems, Milwaukee, WI). The sensors were two identical multisite probes. For the reflection sensor, a standard forehead applicator was used to keep the distance between both the red and infrared light-emitting diodes and the light detector constant at 11 mm. The two oximeters and sensors were used, in random order, as reflection or transmission monitors and probes. The reflection sensor was placed on the forehead and the transmission sensor on the earlobe.

The reliability of the pulse oximeters was tested before, during, and after extracorporeal circulation (ECC) as the bias between oxygen saturation measured by pulse oximetry (SpO_2) and radial artery blood oxygen saturation (SaO_2), assessed simultaneously with a hemoximeter (OSM-3, Radiometer AS, Copenhagen, Denmark). Cardiac index was measured as a mean of 5 thermodilution runs, the highest and lowest values of which were omitted. The SVRI was calculated according to a standard formula. Peripheral temperature was measured continuously with thermistor probes on the forehead (T_f) and the earlobe (T_e) beside the oximeter sensors, and central temperature (T_c) was measured from the esophagus with a thermistor probe.

During partial ECC, before beginning surgery of the heart, the time from the start of ECC to the moment at which each sensor failed to give readings was measured in seconds. The time from the DC shock to the moment at which each sensor was again able to give readings, after surgery of the heart, was also measured with a stopwatch. Systolic and pulse pressures were recorded at the moment the sensors failed before surgery of the heart and the moment they resumed working after surgery of the heart. The standard 3-lead electrocardiogram (ECG) and radial arterial pressure were assessed with a Kone 565 A monitor (Kone Corp, Espoo, Finland).

BMDP statistical software (Statistical Software, Inc, Los Angeles, CA) was used for the statistical analyses. Normality of distributions was tested with Shapiro and Wilk's W statistical and nonparametric methods were used if the distributions were skewed. The differences between the mean values were evaluated by Student's paired *t*-test and Wilcoxon signed-rank test; 95% confidence intervals were calculated for the significant differences. A value of $p < 0.05$ was considered significant.

RESULTS

Measurements Before and After ECC

The mean T_f was 2 to 3°C higher than the mean T_e (Table 1). Vascular resistance was increased and CO reduced before ECC, but there were no differences in the two monitors' ability to give reliable saturation and pulse data either before or after ECC (Table 1).

Measurements During ECC

There were no statistically significant differences in the ability of the two oximeters to work during partial perfusion before surgery of the heart. After surgery of the heart, during partial ECC, the reflection sensor reported data earlier and at a significantly lower mean pulse pressure than the transmission sensor (Table 2).

Table 1. Metabolic and Cardiac Measurements Before and After ECC in 23 Patients Undergoing Open Heart Surgery

	Before ECC	After ECC
T_f(°C)	30.9 ± 1.0	31.8 ± 1.2
T_e(°C)	28.8 ± 1.1[a]	28.8 ± 1.8[a]
T_c(°C)	35.0 ± 0.9	36.5 ± 0.9[b]
CI(L/min/m^2)	2.1 ± 0.5	2.5 ± 0.5
SVRI(dyne·sec·cm^{-5}·m^{-2})	2,900 ± 940	2,060 ± 680

[a] $p < 0.001$ compared with T_f at the same time.
[b] $p < 0.001$ compared with before ECC.
[c] $p < 0.01$ compared with before ECC.
Note: Values are given as mean ± SD.
T^f = forehead temperature; T_e = earlobe temperature; T_c = esophagus temperature; CI = mean cardiac index; SVRI = systemic vascular resistance index.

Saturation and Heart Rate Display Accuracy

The bias and its standard deviation were −0.4 ± 1.5% units (U) for transmission oximetry and +0.7 ± 2.0% U for reflection oximetry (N = 34), the difference being insignificant. These data were obtained in normoxic patients; the hemoximeter saturation data varied from 95.0 to 98.1%, and the saturation display of the reflection and transmission oximeters varied from 91 to 99% and 92 to 99%, respectively.

Before ECC, the heart rate (HR) data given by reflection and transmission oximetry differed from HR data obtained by ECG by 2.4% (SD 2.8). During partial perfusion, the HR data given by both oximeters became less accurate, with reflection oximetry showing a difference of 3.8% (SD 8.4) and transmission oximetry a difference of 6.8% (SD 12.1) from HR data obtained by ECG. Some individual values were up to 39% incorrect. In addition, the ECG had occasional difficulties reading HR correctly during partial ECC. In one of the patients, a 59-year-old man undergoing coronary bypass and aortic valve replacement due to valvular insufficiency and stenosis, we had difficulties gathering data at the beginning of anesthesia, and both methods of pulse oximetry failed to give data during partial ECC. In addition, the transmission oximeter did not resume working during partial ECC after surgery in 2 of the CABG patients. These patients were omitted from the study.

DISCUSSION

In cases of poor peripheral perfusion, pulse oximeter probes on the extremities give inaccurate readings. However, the blood supply to the forehead, via the supraorbital artery, is better maintained during peripheral vasoconstriction than is blood flow to the ear lobe and finger [21]. We theorized, therefore, that a forehead sensor would give more reliable readings than a peripheral sensor in cases of peripheral vasoconstriction.

In this study, the skin temperature differed markedly between the areas of monitoring (earlobe, forehead), both statistically and clinically. However, this fact did not seem to affect the ability of the sensors to give accurate data. Before open heart surgery, both oximeters were equally reliable. Indeed, studies have shown that in patients undergoing open heart surgery, skin temperature does not directly reflect blood flow conditions in the area [22].

Low central temperature, together with low skin temperature, poor cardiac index, and high SVRI, did not affect the reliability of either sensor immediately before ECC. After surgery, the patients were centrally warmed and both the CO and SVRI improved. Therefore, there were no difficulties in getting reliable readings after ECC.

There were significant differences between the transmission and reflection oximeters' ability to give display during poor pulsatile perfusion after open-heart surgery. These differences may be attributed to the better blood flow in the area of internal carotid artery when compared with the earlobe.

The algorithm that pulse oximeters use to process signals is derived from the Lambert-Beer law, which assumes that the substance for light transmission is homogeneous and the length of the light path constant. In

Table 2. Pulse Oximeter Data From Reflection and Transmission Pulse Oximeters

	Before ECC			After ECC		
	SBP (mm Hg)	PP (mm Hg)	t (s)	SBP (mm Hg)	PP (mm Hg)	t (s)
Reflection sensor	57 ± 14	10 ± 10	163 ± 173	66 ± 14	17 ± 7	699 ± 453
Transmission sensor	58 ± 15	12 ± 11	131 ± 146	73 ± 18	24 ± 13[a]	938 ± 548[a]

[a] $p < 0.05$ compared with the same variable with the reflection sensor.
Note: Values are given as mean ± SD.
ECC = extracorporeal circulation; SBP, systolic blood pressure; PP, pulse pressure; t, time from the start of partial ECC to the moment the monitor failed to give a reading (before ECC) and time from the DC shock to the moment the monitor began to give readings again (after ECC).

biologic tissues, neither of these suppositions is true. Moreover, the reflection sensor deals with back-scattered light that may have passed through various paths. Hanning warns that this involvement with back-scattered light may affect the reliability of reflection monitors (Hanning CD, personal communication, 1990).

Light scattering is a function of wavelength, causing different light paths in the skin for the 2 colors of the pulse oximeter light-emitting diodes. Studies have shown that increasing the distance between the light source and detector from 4.8 to 10.1 mm changes the red to infrared ratio and may cause a change of 2.2% U in saturation values [23].

Mendelson et al [19] modified their reflection pulse oximeter by adjusting the intensities of the red and infrared light-emitting diodes to achieve a better plethysmogram. Otherwise, the infrared plethysmogram tended to be too weak for a reliable display. Possible differences in accuracy might thus be due to changing light source and detector distances together with poor plethysmograms due to weak back-scatter. In this study with well-oxygenated patients whose peripheral pulsatile perfusion was severely compromised, the accuracy was excellent. The light source and detector distance remained constant and the back-scatter from the frontal bone was good as judged by the plethysmograms. Additionally, the patients were anesthetized and therefore no motion artifacts occurred. In their study with deliberate hypoxia, Severinghaus and colleagues [1] also found practically no differences in accuracy of forehead and ear sensors.

It is concluded that the reflection sensor on the forehead is a suitable alternative site for monitoring oxygen saturation in patients with poor peripheral pulsatile perfusion.

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