Case Report

LIMITATIONS OF FOREHEAD PULSE OXIMETRY

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ABSTRACT. During initial clinical tests to calibrate our reflectance pulse oximetry system, we observed serious physiologic limitations to the use of pulse oximetry in the forehead region. We present a case of simultaneous reflectance and transmission mode pulse oximetry monitoring in a child undergoing cardiac surgery for congenital cyanotic heart disease with a large intracardiac shunt. During general anesthesia, when the patient was endotracheally intubated and mechanically ventilated, the transmission mode saturation agreed well with arterial oxygen saturation measurements; but, our reflectance pulse oximeter, with the sensor applied to the forehead, displayed spuriously lower (−18%) oxygen saturations. Before and after anesthesia and surgery, there was fine agreement between reflectance and transmission mode saturation values. We suggest that the difference was caused by vasodilatation and pooling of venous blood due to compromised venous return to the heart, and a combination of arterial and venous pulsations in the forehead region. This means that the reflectance pulse oximeter measured a mixed arterial–venous oxygen saturation.

KEY WORDS. Monitoring: pulse oximetry. Measurement techniques: pulse oximetry.

INTRODUCTION

Pulse oximetry, a standard noninvasive technique used worldwide to monitor arterial hemoglobin oxygen saturation [1], combines the principles of optical plethysmography and spectrophotometry. The pulse oximeter emits red and infrared light into tissue and measures light intensity after absorption in the tissue and the vascular bed. Absorbance in bloodless tissue and blood in (normally) nonpulsating veins gives a signal constant in time (DC), while absorbance in blood in pulsating arteries and arterioles gives a periodically changing signal (AC). Arterial oxygen saturation is calculated on the assumption that arterial pulsation is the sole source of this periodic change [2]. Most modern commercial pulse oximeters work in the transmission mode, in which tissue is placed between emitting and receiving light diodes. This requires the sensor to be applied peripherally—e.g., on a finger. The theoretical advantages of a reflectance mode sensor, its instrumentation, and related technical problems have been discussed [3]. A notable advantage is that it can be applied centrally—e.g., on the head or chest—or even at the presenting part of the fetus during labor. Several attempts to design such reflectance sensors have been reported [4–6]. We have developed a clinically applicable reflectance mode system [7].

To assess the accuracy and calibration of our system, initial clinical testing of the system was planned where

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low saturation ranges were expected. This testing included monitoring children before, during, and after surgical correction of congenital cyanotic heart disease. A case is presented where we observed serious limitations to the use of pulse oximetry in the forehead region.

METHODS AND MATERIALS

Equipment

Our reflectance mode pulse oximeter was developed in-house for special research purposes, and is not commercially available. The reflectance sensor (Fig 1) is radially symmetric, with an outer diameter of 21 mm. Two light-emitting diodes (LEDs; red at 600 nm and infrared at 920 nm) are centrally placed. Six receiving photodiodes (Siemens BPX90) surround the LEDs. The sensors can be applied by different fixation methods, such as double-adhesive transparent tape, or by suction. In either case, the housing is of metal or silicon-rubber; but, the optical arrangement is unchanged. After electronic amplification, filtering and ambient light subtraction, the signals are directly transferred through an analog-to-digital converter into an IBM 386 (IBM Corporation, Armonk, NY) computer. The computer processes the input data using a Pascal program and displays the calculated saturation, the heart (pulse) rate, and a graphic presentation of the ratio of red/infrared AC signals to evaluate their intensity and quality (Fig 2).

CASE HISTORY

An 8-year-old girl underwent open-heart surgery (Fontan's operation) for cyanotic heart disease with a bidirectional intracardiac shunt (right ventricular hypoplasia, subvalvular pulmonary stenosis, atrial and ventricular septal defects). The tricuspid valve was found to be competent by cardiac catheterization. Oxygen saturation in the ascending aorta was 79%. The patient was premedicated with midazolam. Saturation was monitored with a commercial transmission pulse oximeter (Ohmeda, Boulder, CO) at the right index finger. Our reflectance sensor was applied with double-adhesive tape on the midline of the forehead 2 to 3 cm below the hairline. General anesthesia was induced with nitrous oxide and halothane, and maintained with flunitrazepam and fentanyl. Neuromuscular blockade was induced by pancuronium bromide.

Mechanical ventilation was performed using a volume-controlled ventilator (Servo Ventilator 900D, Siemens-Hema). During the oxyhemoglobin saturation measurements the patient was not in a head-down position and no positive end-expiratory pressure was applied. Arterial blood samples were taken from a left radial artery catheter, and analyzed directly in a CO-oximeter (OSM2 Hemoximeter, Radiometer Copenhagen).

Before induction of anesthesia, there was agreement between mean finger and forehead saturation readings (82% and 79%, respectively). The mean pulse rate was 110 beats/min at both fixation sites (Fig 3).

During induction of anesthesia, a constant increase in the transmission saturation was observed. During mechanical ventilation, the transmission mode and arterial values were in close agreement with saturations of 91% and 93%, respectively. Reflectance mode saturation from the forehead remained at 79% (see Fig 2). Calculated heart rates of the two systems and ECG heart rates were identical. During cardiopulmonary bypass, there

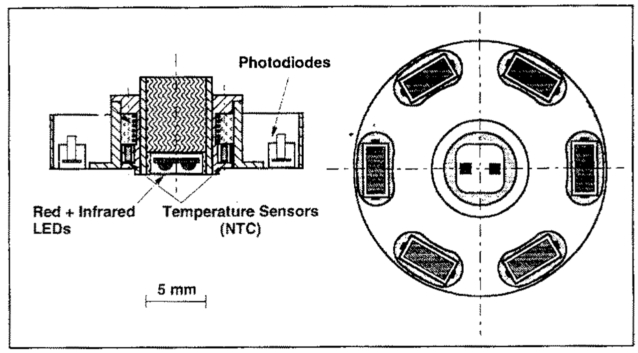

Fig 1. The reflectance sensor. Cross-section and a view of the optical components (skin surface).

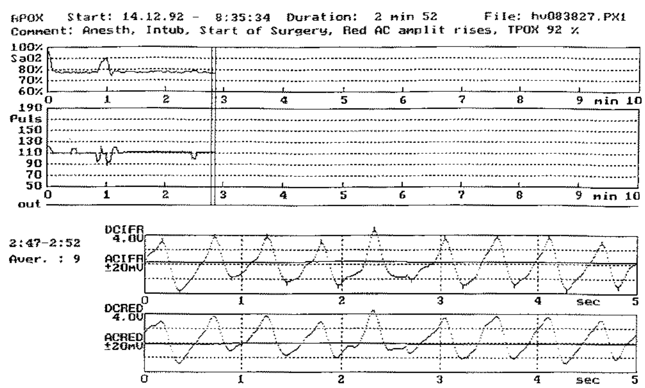

Fig 2. Reflectance mode pulse oximetry tracing of the monitoring period just after intubation. The computer displays the calculated saturation (SaO_2) and heart-rate (pulse) values in the upper part. The lower part shows the pulsatile plethysmographic red/infrared AC absorbance signals and the level of the DC signals. Note high amplitude of red AC signal.

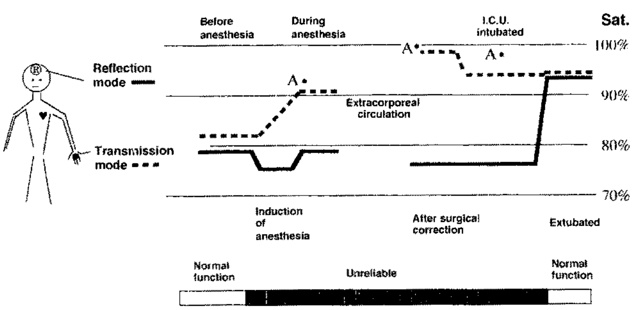

Fig 3. Oxygen saturation (Sat.) measured by the forehead sensor (bold line), the finger sensor (dashed line), and arterial blood samples (A●). Shaded period indicates unreliable function of the forehead sensor.

were no detectable AC signals and, therefore, no reasonable reflectance mode saturation or heart-rate values. The transmission mode pulse oximeter displayed "disturbed function," and neither saturation nor heart-rate values.

After a successful surgical repair and weaning from bypass, the forehead sensor continued to show low saturation values of 76% with correct heart-rate calculations. Transmission mode saturation and arterial values were high, around 99%. In the intensive care unit 6 hr later, the patient was still sedated and endotracheally intubated with stable vital signs. The same discrepancy between transmission mode and reflectance mode saturation was observed (94% vs 76%). Direct measured arterial oxygen saturation was 98%.

The next day, extubation was performed, and the patient was no longer sedated. Transmission mode saturation was now 94% and reflectance mode saturation was 95%.

To test whether the heart–lung machine or other theater and recovery room electronics were affecting the function of our equipment, one of the investigators was placed in the same rooms, with the same electronics working, and with the reflectance sensor applied to his forehead. The saturation was between 96% and 98%, and pulse oximeter heart rate corresponded to the radial pulse. Red and infrared AC signals were of normal pulsatile plethysmographic shape. No low- or high-frequency disturbances were observed.

DISCUSSION

In this case, our forehead reflectance mode pulse oximetry system failed to agree with both a finger transmission pulse oximetry system and oximeter saturation measurements during anesthesia with endotracheal intubation. The reflectance mode pulse oximetry readings were all approximately 18% lower. The pulsatile plethysmographic shape of the AC signals and the agreement between the heart rate as measured by our equipment and the electrocardiographic values indicated that our system was functioning normally. Before and after anesthesia and surgery, the two pulse oximetry systems were in fine agreement.

Identical observations under analogous circumstances were observed when monitoring a 2½-year-old boy who also underwent a Fontan operation for a large intracardiac shunt. Unfortunately all transmission pulse oximetry data were lost in the data sampling process, so that neither data analysis nor comparison between the two pulse oximetry methods and the two cases was possible.

Electronic devices have been reported to affect pulse oximeter function [8]. Exclusion of the possibility of technical interference indicates physiologic reasons for the observed phenomenon, although this was only in a single patient with a large intracardiac shunt. These observations prompted a systematic study in endotracheally intubated and ventilated adults during surgery and general anesthesia, and in healthy adult subjects placed in the head-down tilt (Trendelenburg) position. With the reflectance sensor applied to the forehead, a similar phenomenon was observed, which was most pronounced in the head-down tilt position. Even transmission pulse oximetry with the sensor applied on the nose showed spuriously low saturation measurements when the subjects were kept in a head-down tilt with an angle of −30° (Jørgensen et al, unpublished data). Other investigators may have observed the same phenomena using commercially available reflectance sensors. The information insert for RS-10 Reflection SpO_2 Sensor (Nellcor, Germany) states under "Directions for Use" that it should not be used on patients connected to a mechanical ventilator or when the patient is in a head-down tilt (Trendelenburg) position. However, no scientific publications concerning these situations have been found.

We propose the following explanation. Vasodilatation is common during anesthesia and is compounded by mechanical ventilation, which reduces venous return to the heart. Since veins in the head and facial region are valveless, these factors combine to cause local pooling of venous blood, which is favored in the head-down tilt position. Venous pulsation—i.e., retrotransmitted heart movements—occurs in central veins under normal physiologic conditions [9–10] and has been reported to affect pulse oximeter function during cardiac surgery with observed abnormal systolic central venous pressure [11, 12]. When venous return is compromised, venous pulsation is transmitted even further backwards, due to the local absence of valves, resulting in a pool of venous blood moving from a combination of arterial and venous pulsations [13].

This phenomenon was not seen using the finger transmission mode sensor, probably because the venous valves in the limbs, and the distance between the sensor and the heart, reduce the effect of the retrotransmitted venous pulsations. Thus, the oxygen saturation measured by the forehead sensor during anesthesia and surgery was not arterial, so much as arteriovenous, with average values of 75 to 80%. Others have reported spuriously low saturations measured in the tip and the base of a dependent finger with a transmission mode sensor and postulate that this is due to venous pulse volume generated by shunting of the arterial pulse via open arteriovenous anastomoses in the cutaneous circulation of the dependent finger [14]. This is a similar phenomenon, which we did not observe when our patient's finger with the sensor was kept horizontal. Central venous pressure (CVP) measurements cannot be used to support our hypothesis because the CVP line was inserted after induction of anesthesia and mechanical ventilation, and thus no baseline values for CVP were recorded. In the intensive care unit, only the mean CVP was measured. It was found to be slightly higher during mechanical ventilation than during spontaneous breathing following extubation (12–13 and 11–12 mm Hg, respectively). Mean CVP during mechanical ventilation, however, is influenced by the higher mean intrathoracic pressures during inspiration, and thus does not necessarily reflect effective transmural right atrial pressure.

We conclude that, in this case, forehead pulse oximetry was unreliable during anesthesia with endotracheal intubation and mechanical ventilation. Presumably, this conclusion applies generally. To clarify this, and to test our system in settings with expected low saturation, further studies are now underway in our respective departments.

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