FOREHEAD PULSE OXIMETRY COMPARED WITH FINGER PULSE OXIMETRY AND ARTERIAL BLOOD GAS MEASUREMENT

Eugene Y. Cheng, MD,
Margaret B. Hopwood, RN,
and Jonathan Kay, MD

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ABSTRACT. Usual monitoring sites for pulse oximetry involve the fingers, toes, ear lobe, and nasal septum. This study examined the performance of a forehead sensor compared with a finger sensor for the pulse oximeter and arterial blood gas (ABG) analysis. Ten healthy adult volunteers and 22 ventilator-dependent patients were studied. The arterial oxygen saturation detected by forehead pulse oximetry (SpO_2) correlated well with finger SpO_2 and arterial oxygen saturation (SaO_2) determined by arterial blood gas analysis in the healthy volunteers. Forehead SpO_2 in mechanically ventilated patients correlated well with finger SpO_2 and SaO_2 when heart rate detected by pulse oximeter differed less than 10% from apical heart rate. Factors that caused a difference in oximeter-detected heart rate and apical heart rate were extensive tissue edema, head movement, and difficulty securing good tape placement. This suggests that when signal strength is weak, causing poor pulse rate detection, there will also be problems associated with accurate SpO_2.

The forehead pulse oximeter sensor works well on healthy, well-oxygenated volunteers. Difficulty was experienced when applying and using the sensor on critically ill patients. The reliability of the forehead pulse oximeter sensor has not been established at low saturations.

KEY WORDS. Measurement techniques: oximetry. Blood: gas analysis.

Early detection of untoward events in the operating room, postanesthesia care unit, or intensive care unit (ICU) can contribute to the prevention of hypoxic insults. Within the past several years use of the pulse oximeter to monitor a patient's arterial oxygenation has become widespread, both in the operating room and the ICU. Major advantages of pulse oximetry over measurement of arterial blood gases (ABGs) include ease of use, nearly continuous measurement of arterial oxygenation, and noninvasiveness. Standard probes for pulse oximeters are available for the finger, nasal septum, and ear lobe. This study evaluates the accuracy and utility of a new forehead sensor probe for the pulse oximeter when compared with a standard pulse oximeter finger sensor and ABG analysis.

METHODS AND MATERIALS

Ten healthy adult volunteers and 22 consecutive mechanical ventilator–dependent patients in the medical/surgical ICU were studied. Equipment used for pulse oximetry evaluation were the Criticare 501+ pulse oximeter, a standard finger probe, and a new forehead sensor (Criticare Systems, Waukesha, WI). The two Criticare 501+ pulse oximeters, each used exclusively

From the Department of Anesthesiology, Medical College of Wisconsin, 9200 W Wisconsin Ave, Milwaukee, WI 53226.

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Address correspondence to Dr Cheng.

for either the finger or forehead probe, had similar electronic specifications from the factory. Healthy subjects were resting in a semirecumbent position and all ICU patients were supine. All healthy volunteers were breathing room air and all critically ill patients were receiving appropriate oxygen supplementation to keep arterial oxygen tension greater than 80 mm Hg. The finger sensor was placed on a forefinger on the hand opposite from which the ABG was sampled. The forehead sensor comprised two parts: the sensor portion and a part containing two light-emitting electrodes, each measuring 14 × 20 × 5 mm. These probes were placed side by side with no more than 2 to 3 mm between them. The sensor unit was taped to the head with 25-mm-wide microfoam tape. The tape was secured so as to apply only enough pressure to keep the probes flat on the forehead surface.

When stable pulse oximeter readings of oxygen saturation (SpO_2) were reached for 10 seconds, arterial blood was drawn for analysis of ABGs. In volunteers, the radial artery was punctured. In the ICU patients, finger and forehead pulse oximeter sensors were placed shortly before scheduled arterial sampling for ABGs. Blood was obtained via arterial catheters already in place as part of clinical management. ABGs were analyzed and arterial oxygen saturation (SaO_2) was calculated by an ABL-1 blood gas analyzer (Radiometer Emdrupvej 72, Copenhagen).

Simultaneous pulse rate and SaO_2 readings were obtained from each oximeter probe, as was apical pulse rate when arterial blood was drawn. Current ventilator settings and temperature were noted for each ICU patient. Ten individual data points were collected from the volunteers and 45 data points from the ICU patients, some patients contributing more than 1 data point.

Statistical analysis was by Student's paired *t* test. Values are expressed as mean ± standard error; $P < 0.05$ was considered significant.

RESULTS

The mean age of the volunteers was 30.2 ± 5.6 years (range, 26 to 43 years). The mean age of the critically ill patients was 42.9 ± 4.9 years (range, 16 to 73 years). The fraction of inspired oxygen was 0.44 ± 6.6 on the ventilated patients (range, 0.3 to 1.0). Their mean temperature was 37.5 ± 0.2°C (range, 35.6 to 38.3°C). In the 10 volunteers there was a small but statistically significant difference between finger and apical pulse rates. The pulse rate detected by the forehead probe and SpO_2 detected by both probes did not differ significantly from the apical pulse rate and ABGs, respectively (Table).

In the ICU patients, 45 data sets were collected. The pulse rates detected by the forehead sensor were significantly lower than those from the finger probe and apex. SpO_2 from the forehead was significantly lower than from the ABGs (see Table). In 2 ICU patients who were severely edematous we were unable to obtain any readings from the forehead probe. Data from these patients were not included in the analysis. In 4 other ICU patients yielding 7 data points the forehead probe showed an SpO_2 less than 90% at the same time ABGs showed SaO_2 greater than 90%. The difficulty in forehead pulse detection seemed to occur with agitated or perspiring patients in whom the probe could not be properly secured.

Comparison of Measurements in Volunteers and Critically Ill Patients

	Pulse (beats/min)			Oxygen Saturation (%)		
Group	Forehead	Finger	Apical	Forehead	Finger	Laboratory
Volunteers (n = 10)						
Mean ± SEM	73.9 ± 3.4	75.2 ± 2.9[a]	73.4 ± 3.1	96.6 ± 0.5	97.3 ± 0.3	97 ± 0.4
Range	54–90	61–90	56–88	93–98	96–98	95–99
Critically ill patients (n = 45)						
Mean ± SEM	96.3 ± 2.9[a]	102.8 ± 2.8	104.2 ± 3.2	94.3 ± 1.3[b]	96.1 ± 0.3	97.4 ± 0.3
Range	52–127	52–141	52–140	50–99	91–99	91–100
Critically ill patients (n = 38)[c]						
Mean ± SEM	98.9 ± 3.1	101.6 ± 3.1	101.6 ± 3.3	96.3 ± 0.4	96.2 ± 0.3[b]	97.4 ± 0.3
Range	52–129	52–120	52–133	89–99	92–99	92–100

[a] $P < 0.05$ when compared with apical pulse.
[b] $P < 0.05$ when compared with laboratory O_2 saturation.
[c] Seven data points were deleted because of a greater than 10% difference in pulse rate.

It was noted that the false desaturation points tended to occur when the forehead pulse rate differed by more than 10% from the apical pulse rate. When all points in which forehead pulse differed from apical pulse rate by ±10% were removed, we obtained a good correlation between forehead SpO_2 and SaO_2 (see Table). Looking at the difference of the means of this group we found that the maximum difference between pulses was 2.7 beats/min, while the maximum difference between SaO_2 values was 0.7%.

DISCUSSION

Pulse oximetry functions by positioning a pulsating arterial vascular bed between a light source emitting at two different wavelengths and a detector. The variation in amplitude of light transmitted or scattered across the tissue during arterial pulsation is measured, and saturation is estimated from empiric evidence of the effect of oxygen on the relative pulse amplitudes in the red and infrared light transmission.

The site used for noninvasive detection of SaO_2 should have a profuse blood supply and a minimal amount of vasoactivity in response to vasoconstrictive stimuli. The usual pulse oximeter sensor clips onto the toe or finger. In some circumstances, especially in the operating room or when the patient's extremities are bandaged or covered, access to these sites becomes difficult. Alternative sites such as the nasal septum and ear lobe have been used.

Brinkman et al [1] were the first to develop a forehead pulse oximeter. However, their forehead reflexometer, "Cyclops," never was easy to use.

Theoretically the forehead should be a good site for pulse oximetry. In 1938, Hertzman [2] estimated blood supply of various skin areas by photoelectric plethysmography. He found that next to digits the ear lobe and forehead had the richest arterial supply when compared with the dorsum of finger, hand, foot, forearm, knee, and tibia. In addition Hertzman noted an absence of vascular reactivity of the forehead and ear lobe to the cold pressor test in contrast to lability of the arterial supply to the finger tip.

Even though the forehead should have a good arterial blood supply we experienced several episodes of poor forehead pulse detection that affected the monitor accuracy.

Small differences of 1 to 2% between pulse oximeter and apical pulse rate, even though different statistically, as seen with our healthy volunteers, did not affect the accuracy of SpO_2 when compared with SaO_2. These small differences between the pulse rate detected by the pulse oximeter and the apical pulse rate should be expected because of variabilities in normal sinus rhythm and the different times at which the pulse rate is determined by pulse oximeter, electrocardiographic monitor, or auscultation.

Larger differences between forehead pulse oximeter and apical pulse rates did produce a significant difference between SpO_2 and SaO_2 in our critically ill subjects. When we removed the data points in which there was a greater than 10% difference between forehead pulse oximeter and apical heart rate there was good correlation between SpO_2 and SaO_2.

One of the common causes of large differences between actual and pulse oximetry–determined pulse rates is poor tissue perfusion. Poor peripheral perfusion is commonly associated with hypotension or the effect of therapy with vasopressive drugs. In our study neither of these two specific causes was noted; however, severe forehead edema could decrease tissue perfusion.

Another factor that contributed to poor pulse correlation was the inability to securely place the forehead sensor because of forehead wetness or excessive head movement.

In 1972 several investigators demonstrated that the forehead could be used as a location to monitor arterial oxygen saturation [1,3], but they did not quantitate the oxygen saturation changes or test the accuracy in relation to ABGs. In 1981 Mendelson et al [4] demonstrated in a group of volunteers a good quantitative correlation between an ear pulse oximeter and their "skin reflectance oximeter system" that was placed on the forehead. They believed that the function of their instrument was based on optical reflectance rather than on detection and analysis of transmitted light. At that time, Mendelson et al surmised that the reflectance photoplethysmograph would be applicable to other centrally located body surface areas. In actuality the light used for analyzing SaO_2 was the scatter through the tissue rather than the light reflected by the skin [5].

We encountered two patients in whom forehead SpO_2 was undetectable and who also had extensive head edema. Edema increases the distance from surface to bone and may have decreased the scatter back to the pulse oximeter sensor. In addition, in several patients we placed the forehead sensor on the neck over the carotid artery, and on the abdomen, thigh, and upper arm; none of these areas proved useful for the detection of SaO_2. Thus, we surmise that noninvasive assessment of SaO_2 by using the sensor probe depends on analysis of light scatter returning from the cranial bone through the tissue rather than reflected from the skin.

A potential source of error in this study was the use of the ABL-1 blood gas analyzer rather than a bench oximeter for determining SaO_2. The ABL-1 calculates

rather than directly measures the SaO_2. This may create a 1 to 2% overestimation of SaO_2 readings because hemoglobin species other than oxyhemoglobin and deoxyhemoglobin are not considered (i.e., methemoglobin and carboxyhemoglobin). In our study methemoglobin or carboxyhemoglobin should not be an important variable since all the volunteers were nonsmokers and the mechanically ventilated patients were not exposed to any known sources of carbon monoxide or drugs that could potentiate the development of methemoglobin.

During the testing period the performance of the forehead probe at low saturation values could not be assessed because the clinical staff diligently tried to prevent significant desaturation and administered supplemental oxygen. However, information obtained from Severinghaus and Naifeh (personal communication, December 1987) shows that forehead pulse oximetry, like finger pulse oximetry, is not always accurate at very low SaO_2 values. Severinghaus and Naifeh also tested the Criticare 501+ pulse oximeter and forehead sensor on two different sets of healthy volunteers subjected to hypoxic gas mixtures via a technique previously described [6]. In the first study group of 3 subjects, 18 desaturation events were recorded. The mean measured SaO_2 was 52.97 ± 2.18%. The mean difference between SaO_2 and SpO_2 from two forehead sensors tested simultaneously was 5.41 ± 2.18% and 13.56 ± 6.7%.

In a group of 10 subjects tested at a later time the mean measured SaO_2 was 54.76 ± 5.39%. Again, two forehead sensors were tested at the same time. For one sensor 60 desaturation events were recorded, with a mean difference from measured SaO_2 of 8.88 ± 5.47%. For the other forehead sensor 54 desaturation events were recorded. The mean difference between SaO_2 and SpO_2 was 1.11 ± 8.85%.

The relatively large errors between SpO_2 and SaO_2 have several causes. Severinghaus and Naifeh [6] noted that errors at low levels are due in part to lack of suitable calibration data. This is because, at an oxygen saturation of less than 70%, development of an accurate formula is hampered by the relationship between saturation and the optical signals at the two wavelengths usually used, which are not linear or logarithmic, but variable. Another factor may be the qualitative differences in the production of the forehead sensor. Lack of adequate plateau times for equilibrium to take place also may play a role.

The forehead pulse oximeter sensor for noninvasively determining SaO_2 deserves more study. Further modification and refinement are needed to calculate low saturation and to secure the sensor on the forehead before this method can become an acceptable alternative to the common finger or ear-lobe sensors.

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