PULSE OXIMETRY FAILS TO ACCURATELY DETECT LOW LEVELS OF ARTERIAL HEMOGLOBIN OXYGEN SATURATION IN DOGS

Avner Sidi, MD, William Rush, BA,* Nikolaus Gravenstein, MD,*† Bruce Ruiz,* David A. Paulus, MD,*‡ and Richard F. Davis, MD**

Sidi A, Rush W, Gravenstein N, Ruiz B, Paulus DA, Davis RF. Pulse oximetry fails to accurately detect low levels of arterial hemoglobin oxygen saturation in dogs.

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ABSTRACT. The accuracy of two commercially available pulse oximeters (the Ohmeda Biox 3700, software version "J," and the Nellcor N-100) in detecting low levels of arterial hemoglobin oxygen saturation (SaO_2) was evaluated in 10 dogs in which hypoxia was induced by stopping the fresh gas flow into the anesthesia machine circle system. Measurements made in vivo with the pulse oximeters, with detectors placed on the tongue, were compared with measurements made in vitro using an IL 282 CO-Oximeter as SaO_2 decreased toward zero. Measurements from the two oximeters correlated poorly over the range from 0 to 100% SaO_2 ($r = 0.69$). In this range, the correlation between Nellcor N-100 measurements and those of the CO-Oximeter had an r of 0.82, a regression line slope of 0.82, and a y intercept of 14.8; the correlation between the Ohmeda Biox 3700 and the CO-Oximeter had an r of 0.83, a regression line slope of 0.66, and a y intercept of 32.7. The correlation with the CO-Oximeter was similar for both the Ohmeda and the Nellcor pulse oximeters at an SaO_2 of 80% or more. However, when SaO_2 was less than 80%, measurements by pulse oximetry correlated less well with CO-Oximeter measurements ($r = 0.62$, slope = 0.64, and y intercept = 21.0 for Nellcor; $r = 0.71$, slope = 0.67, and y intercept = 32.4 for Ohmeda). When SaO_2 was less than 60%, both oximeters inaccurately indicated the co-oximetry values ($r = 0.36$ and y intercept = 26.1 for the Nellcor; $r = 0.48$ and y intercept = 33.2 for the Ohmeda). In this animal model, with pulse oximeter measurements obtained from the tongue and with rapidly decreasing SaO_2, measurements of SaO_2 by pulse oximetry become inaccurate in comparison with co-oximetry measurements at low levels of SaO_2.

KEY WORDS. Oxygen: saturation. Equipment: pulse oximeters. Measurement techniques: oximetry. Monitoring: oxygen.

Continuous measurement of arterial oxygenation by pulse oximetry has become a widely used monitoring technique during anesthesia and intensive care. The values obtained by in vivo pulse oximetry have been found to correlate well with those obtained by in vitro co-oximetry (using blood samples drawn simultaneously) when arterial hemoglobin oxygen saturation (SaO_2) values range from 80 to 100% [1]. However, little information exists regarding correlation of these two methods when SaO_2 is less than 80%, even though accurate measurements at the middle and lower ranges are crucial, especially in patients at a high risk for desaturation (e.g., those with congenital heart or pulmonary disease or those being resuscitated from cardiopulmonary arrest). Using in vitro co-oximetry for confirmation, we evaluated the accuracy of two commercially available pulse oximeters, the Nellcor N-100 (Nellcor, Hayward, CA) and the Ohmeda Biox 3700, software version "J" (Ohmeda, Boulder, CO), with the detectors

From the *Department of Anesthesiology and the †Department of Neurosurgery, College of Medicine, and the ‡Department of Mechanical Engineering, College of Engineering, University of Florida, Gainesville, FL.

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Address correspondence to Dr Davis, Editorial Office, Department of Anesthesiology, Box J-254, J. Hillis Miller Health Center, Gainesville, FL 32610-0254.

placed on the tongue of anesthetized dogs rendered hypoxemic by ventilation with a hypoxic gas mixture.

METHODS AND MATERIALS

All relevant institutional policies regarding the care and use of experimental animals were followed. We anesthetized 10 dogs with intravenous thiamylal (an initial bolus of 16 mg/kg followed by a continuous infusion of 1–4 mg/kg/hr). After orotracheal intubation, we controlled ventilation mechanically to keep the arterial carbon dioxide tension between 35 and 45 mm Hg and the arterial oxygen tension between 80 and 150 mm Hg. The aorta was catheterized from the femoral artery. For each dog, the detectors of two pulse oximeters (Ohmeda Biox 3700, software version "J," detector no. 8122-003 S/N 9698, Ohmeda, and Nellcor Model N-100, Digitoxisensor D-25, Nellcor) were placed on the tongue for continuous measurement of hemoglobin SaO_2. Heart rate was monitored by an electrocardiogram, which was recorded continuously.

Progressive hypoxemia was created gradually by stopping all flow of fresh gas to the anesthesia machine circle system and ventilator while the two pulse oximeters recorded SaO_2. Aortic blood was sampled at approximately 5% intervals of change in SaO_2 as displayed by a pulse oximeter (the first instrument to show that decrease being used as the marker); the values displayed by both pulse oximeters during blood sampling were recorded. To provide a relatively uniform distribution of SaO_2 values (over the 0 to 100% range), samples were collected and SaO_2 values recorded during both desaturation and reoxygenation. Blood samples were collected in heparinized, 3-ml syringes to calculate oxyhemoglobin percentage ($\%HbO_2$), arterial oxygen content, and concentrations of carboxyhemoglobin and methemoglobin with a CO-Oximeter (IL 282 CO-Oximeter, Instrumentation Laboratory, Lexington, MA). After blood was sampled, all visible bubbles were removed from the syringe, and it was tightly capped and placed in ice until analysis, which was not longer than 30 minutes from the time of sampling. Thus, for each dog, 8 to 36 measurements were obtained in vivo with both pulse oximeters (SaO_2) and in vitro by the CO-Oximeter ($\%HbO_2$) from blood sampled nearly simultaneously.

The photoplethysmographic waveform detected and displayed by the Ohmeda oximeter represents changes in blood volume of the vascular system if no other factors (e.g., motion artifact) are involved. The waveform adjusts automatically according to the magnitude of the pulse signal. The message "low quality signal" that appears above waveforms of low-amplitude signals indicates that SaO_2 and pulse rate readings may be invalid, possibly because of poor perfusion. Values obtained from the Nellcor pulse oximeter while the device was "pulse searching" were not included in the study, because no SaO_2 value is displayed during that time.

Using least-squares linear regression analysis, we compared measurements obtained by pulse oximetry with those obtained by co-oximetry. For four ranges of SaO_2—from 0 to 100%, from 80% or greater to 100%, from 0 to less than 80%, and from 0 to less than 60%—measurements from the Nellcor and the Ohmeda oximeters were compared with one another and with values from the CO-Oximeter by regression analysis, which gave the predicted slopes and y intercepts of the regression lines [2]. The analysis was performed by SAS software (SAS Proc Reg, SAS Institute, Cary, NC); $P < 0.05$ was considered significant. Pulse oximeter data (SaO_2) are also presented as mean values ($\pm$ SD) of the difference between the CO-Oximeter value ($\%HbO_2$) and the SaO_2 for each pulse oximeter over 10% bands of $\%HbO_2$.

RESULTS

In our experiment, the message "low quality signal" was displayed intermittently in 5 dogs. Of a total of 206 values obtained with the Ohmeda device, 56 "low quality signal" values were obtained, and these were analyzed statistically as a separate group. For SaO_2 values ranging from 0 to 100%, the pulse oximeter measurements correlated well with those of the CO-Oximeter (Fig 1, Table 1): $r = 0.82$ for Nellcor and $r = 0.83$ for Ohmeda. However, the slope of the regression line (0.82 for Nellcor and 0.66 for Ohmeda) and its y intercept (14.8 for Nellcor and 32.7 for Ohmeda) indicate that both instruments tended to overestimate SaO_2. The degree of overestimation was greater with the Ohmeda (see Table 1), as indicated by the significant difference in slope and intercept ($P < 0.05$ for both). The regression between the "low quality signal" data points from the Ohmeda instrument and the corresponding CO-Oximeter values had a significantly greater y intercept and a lower slope than the good quality signal data points (see Table 1) or the Nellcor values (Fig 2). Even with the "low quality signal" indication, the pulse rate indicated by the oximeter agreed with the heart rate indicated by the electrocardiogram.

The difference between the pulse oximeter reading of SaO_2 and the CO-Oximeter reading of HbO_2 was calculated directly as $SaO_2 - \%HbO_2$ for each data set. Mean values ($\pm$ SD) of these differences for each pulse oximeter were obtained using the absolute value of the observed difference to show actual variability about a

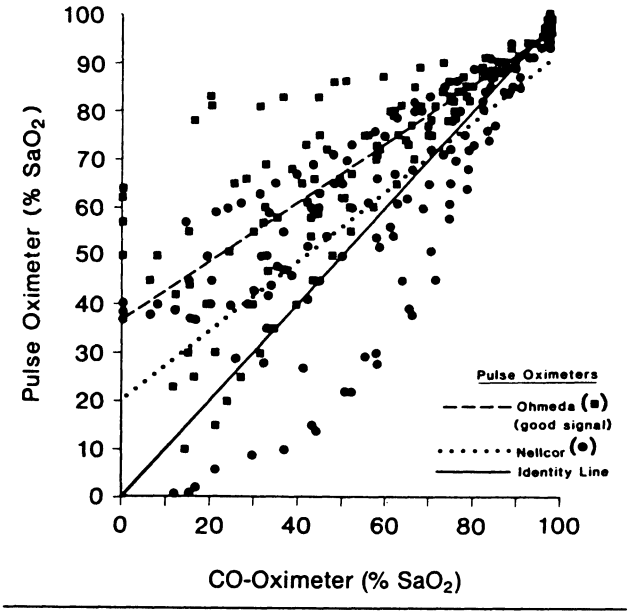

Fig 1. Linear regression analysis of the relationship between measurements of arterial hemoglobin oxygen saturation (SaO_2) *obtained from both Ohmeda Biox 3700 pulse oximeter* (squares) *and Nellcor Model N-100 pulse oximeter* (circle) *as compared with corresponding values obtained with an IL 282 CO-Oximeter. Ohmeda versus CO-Oximeter regression line is dashed; Nellcor versus CO-Oximeter regression line is dotted; line of identity is solid. See Table 1 for regression values.*

zero difference. These values are shown in Table 2 according to HbO_2 percentile bands. Differences markedly increased as $\%HbO_2$ decreased.

For SaO_2 values ranging from 0 to less than 80%, the regression coefficient of both instruments was less than for the full range of values (0.71 for Ohmeda and 0.62 for Nellcor). With each instrument, the scatter of the data about the line of identity appeared to increase as SaO_2 decreased. For SaO_2 values ranging from 0 to less than 60%, both oximeters were inaccurate (r = 0.36 and y intercept = 26.1 for Nellcor; r = 0.48 and y intercept = 33.2 for the Ohmeda). At SaO_2 values of 80% or greater, statistically significant differences in slope and y intercept values did not occur when either pulse oximeter was compared with the CO-Oximeter (see Table 1). The concentrations of carboxyhemoglobin and methemoglobin indicated by the CO-Oximeter averaged 0.9 ± 0.03% (range 0 to 1.9%) and 1.1 ± 0.03% (range 0.3 to 2.4%), respectively. Moreover, the values did not increase as SaO_2 decreased.

Table 1. Linear Regression Analysis of Arterial Oxygen Saturation Values Derived by Pulse Oximetry and Co-oximetry[a]

	Arterial Oxygen Saturation		
Oximeter	0–100%	>80%	<80%
Ohmeda (good signal strength)			
Pairs of data (n)	150	42	108
r	0.83	0.93	0.71
Slope	0.66	1.06	0.67
y intercept	32.7	27.9	32.4
Ohmeda (low quality signal)[b]			
Pairs of data	56	18	32
r	0.93	0.51	0.89
Slope	0.49[c]	0.44	0.53[c]
y intercept	48.4[c]	52.0[c]	46.9[c]
Nellcor			
Pairs of data (n)	190	58	132
r	0.82	0.79	0.62
Slope	0.82[d]	1.07	0.64
y intercept	14.8[d]	−7.5	21.0[d]

[a] Ohmeda Biox 3700 pulse oximeter, Nellcor pulse oximeter Model N-100, and IL 282 CO-Oximeter were used.
[b] The Ohmeda pulse oximeter will display the message "low quality signal" during conditions producing low pulse volume.
[c] $P < 0.05$ when the regression value between the Ohmeda with a "low quality signal" indication and the CO-Oximeter is compared with that between the Ohmeda (without that indication) and the CO-Oximeter.
[d] $P < 0.05$ when the regression value between the Nellcor and the CO-Oximeter is compared with that between the Ohmeda (good signal strength) and the CO-Oximeter at the same range of arterial saturation.

DISCUSSION

In this investigation, at SaO_2 values of less than 60%, the correlation between pulse oximetry and co-oximetry was poor, whereas at an SaO_2 of greater than 80% the correlation was better. This agrees partially with what is specified in the operating manuals of both instruments.*† In the range of 60 to 100% SaO_2, accuracy of about 3% (±SD) is claimed; at less than 60%, accuracy is not specified.

One factor that may contribute to the discrepancy between pulse oximeter and CO-Oximeter measurements is the difference in spectrophotometric methods used to detect SaO_2. The pulse oximeter transmits light at two different wavelengths: 660 nm and approximately 900 nm (940 nm for Ohmeda and 925 nm for Nellcor). The lower wavelength represents the point of near maximal difference between the light absorbance properties of deoxyhemoglobin and HbO_2, whereas the higher wavelength corresponds to a spectral region

*Ohmeda Biox 3700 pulse oximeter operating/maintenance manual. P/N 1118-300 Revision D. Boulder, CO: BOC Health Care, 1985:9, 20–30.
†Instruction Manual. Nellcor pulse oximeter Model N-100. Revised. Hayward, CA: Nellcor, 1984: Section 5:8.

Table 2. Difference Between Pulse Oximeter Measurement of Arterial Oxygen Saturation and CO-Oximeter Measurement Shown by HbO_2 Percentile[a]

HbO_2 Percentile	Difference	
	Ohmeda[b]	Nellcor[c]
0–9	47 ± 12	36 ± 4
10–19	28 ± 18	23 ± 10
20–29	30 ± 19	17 ± 11
30–39	21 ± 15	17 ± 10
40–49	24 ± 12	15 ± 9
50–59	16 ± 8	16 ± 10
60–69	13 ± 5	12 ± 8
70–79	8 ± 3	10 ± 7
80–89	4 ± 2	5 ± 4
90–100	1 ± 1	3 ± 3

[a] Values shown are the mean (±SD) of the differences between the pulse oximeter and the CO-Oximeter (pulse oximeter value minus CO-Oximeter value). Mean values were calculated by using the absolute value of the individual differences.
[b] Ohmeda Biox 3700 pulse oximeter.
[c] Nellcor pulse oximeter model N-100.

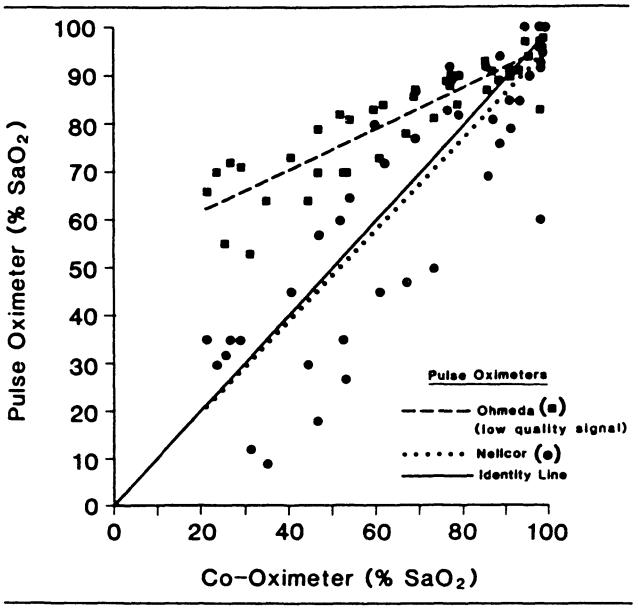

Fig 2. Linear regression analysis of the relationship between measurements of arterial hemoglobin oxygen saturation (SaO_2) *obtained simultaneously from a Nellcor Model N-100 pulse oximeter* (circles) *and an Ohmeda Biox 3700 pulse oximeter* (squares) *displaying the "low quality signal" indication as compared with corresponding values obtained with an IL 282 CO-Oximeter. Nellcor versus CO-Oximeter regression line is dashed; Ohmeda versus CO-Oximeter regression line is dotted; line of identity is solid.*

where relative absorption of deoxyhemoglobin and HbO_2 remains stable with changing wavelength; here, however, the extinction due to HbO_2 is greater than that due to hemoglobin [1,3]. In pulse oximetry, light is directed through a pulsating arterial bed to a detector that distinguishes the relative pulsatile absorbances of the two wavelengths. The pulsatile absorbance difference between the two wavelengths is then used to calculate SaO_2. In contrast, the CO-Oximeter measures steady-state (nonpulsatile) transmission of four wavelengths totally different from those of the pulse oximeters, i.e., 535, 585, 594, and 626 nm, to obtain percent concentrations of hemoglobin, HbO_2, carboxyhemoglobin, and methemoglobin.*

The dogs in our study were desaturated continuously and were not stabilized at any given level of desaturation. With incremental, steady-state desaturation, CO-Oximeter and Nellcor pulse oximeter values correlated closely overall in another study [4], although apparent scatter of data points from the regression line increased as SaO_2 decreased below 60%. Apparently, in that study, the CO-Oximeter $\%HbO_2$ was corrected to a "functional" SaO_2. The $\%HbO_2$ from the CO-Oximeter is the amount of HbO_2 relative to the total amount of hemoglobin ($\%HbO_2t$), including species not available for oxygenation (methemoglobin and carboxyhemoglobin).* In contrast, the pulse oximeter calculates SaO_2 as the amount of HbO_2 relative only to the amount of hemoglobin available for oxygenation ($\%HbO_2a$). The relationship between these two methods is given by the equation:*

$$\%HbO_2t = \%HbO_2a\left[1 - \frac{(\%COHb + \%MetHb)}{100}\right],$$

where %COHb is percent carboxyhemoglobin and %MetHb is percent methemoglobin. The amount of carboxyhemoglobin and methemoglobin encountered in our study would not have produced the difference between $\%HbO_2$ and SaO_2 observed in our study.

The non–steady-state conditions of the present investigation were associated with significant differences between the pulse oximeter and the CO-Oximeter values. When SaO_2 declines rapidly, any delay between the pulse oximeter reading and the sampling of blood for CO-Oximeter measurement would bias the results in favor of an overestimation of SaO_2 by the pulse oximeter, as would desaturation in the CO-Oximeter blood sample before analysis. Also, any delay caused by the time required for blood circulation from the aortic sampling site to the pulse oximeter measurement site would, during rapidly decreasing SaO_2, bias results toward an overestimation of the more proximal measure-

* Operator's Manual. IL 282 Co-Oximeter. 79282. Lexington, MA: Instrumentation Laboratory, 1980:1.1, 1.2, 9.1–9.3.

ment (CO-Oximeter) by the more distal measurement (pulse oximeter). The rate of decline of oxygen tension in iced whole-blood samples is insufficient to have significantly affected SaO_2 of blood sampled before analysis in this study [5,6]. Both pulse oximeters update the display of SaO_2 measurements at six-second intervals, and the blood sample was obtained within this time interval. Because the time required for blood circulation from the external jugular vein to the carotid artery in the dog is reported to be 3.0 to 4.4 seconds [7], which is a briefer interval than that required for updating the display on a pulse oximeter, the delay between aortic blood sampling and pulse oximetry measurement at the tongue would be slight. Because of these considerations we believe that the non–steady-state study design of our study was not in itself a significant cause of the difference between SaO_2 and $\%HbO_2$.

Our data were obtained from pulse oximeter probes fixed to the tongue, which clinically is not a widely used monitoring site. Whether the pulse oximeter readings from the tongue of the dog differ significantly from readings from the finger, toe, ear, or nose of humans is not known. However, clinical use of pulse oximetry in urgent situations such as cardiopulmonary arrest or neonatal resuscitation [8] requires accuracy in dynamic non–steady-state conditions and makes these results particularly relevant.

Carboxyhemoglobin or methemoglobin could adversely affect the accuracy of pulse oximeters; however, concentrations of these hemoglobin species as detected by the CO-Oximeter did not vary in any dog during hypoxia. Although the CO-Oximeter can be calibrated for canine hemoglobin (as was done in this study), the pulse oximeter cannot; thus, any difference in the spectrophotometric properties of HbO_2 and deoxyhemoglobin in human and canine blood would adversely affect oximeter measurements in canine studies using instruments calibrated for human hemoglobin. However, the light absorbance properties of canine and human oxyhemoglobin and deoxyhemoglobin are similar at 660 and 940 nm [5,9]. Therefore, a measurement error in pulse oximetry caused by canine hemoglobin would be unlikely to significantly affect the results of this study.

It has been known since 1980 that a pulse oximeter (Minolta Model 101) may overestimate SaO_2 at values lower than 90%, the y intercept being about 40 compared with in vitro oximetry (Radiometer Model OSM2 hemoximeter) in human volunteers at the range of 70 to 100% hemoglobin oxygen saturation [10]. The apparent cause for the overestimation in that instrument, and perhaps also in other similar instruments, is "multiple-light scattering." The original pulse oximeters calculated SaO_2 of hemoglobin by using the Beer-Lambert law [3], which relates the logarithm of the transmission of light through an absorbing material to the optical density. That principle applies to hemoglobin solutions but is not strictly applicable to whole blood and is less applicable to blood in tissue. The differences in optical density between whole-blood and hemoglobin solutions have been attributed to light scattering caused by refraction at the interface between red blood cells and plasma and against other cells. The greatest oxygen dependence of total scattering occurred at 660 nm, the wavelength at which the greatest difference occurs between the absorption coefficients of deoxyhemoglobin and HbO_2 [11]. The relationship between this scattering and saturation is almost linear. By adopting the light-scattering particle theory, Shimada and Yoshiya derived [12] a new equation for calculation of saturation. By modifying a pulse oximeter to incorporate this new equation, they obtained SaO_2 values that correlated better with pulse oximeter values obtained in vitro in volunteers.

The difference between the readings of the two pulse oximeters in our study (see Table 1 and Fig 1) may be attributable to inherent differences between the instruments. For example, the infrared wavelengths used by the devices are different: 925 nm with Nellcor and 940 nm with Ohmeda. Also, when the AC signal produced by the pulsatile light absorbance is less than 0.5% of the DC light absorbance the pulse oximeter indicates an artifactually high SaO_2 [12]. This may be the reason that the Ohmeda "low quality signal" data points are less accurate than those of the other devices (see Table 1).

Despite its widespread clinical popularity, measurement of SaO_2 by pulse oximetry has significant limitations at the lower range of saturation in the dog, and these limitations may be clinically important. The results reported here indicate that further investigation is needed to determine the accuracy of pulse oximetry at low SaO_2 levels in humans, especially during non–steady-state conditions. Until such studies are completed, we urge cautious interpretation of pulse oximetry data, especially in dynamic clinical situations involving arterial desaturation.

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