The Effect of Carbon Monoxide Inhalation on Pulse Oximetry and Transcutaneous $P_O_2$

Steven J. Barker, Ph.D., M.D.,* Kevin K. Tremper, Ph.D., M.D.*

Five dogs were anesthetized, intubated, and ventilated with various mixtures of oxygen, nitrogen, and carbon monoxide. Each dog was monitored with arterial and pulmonary artery catheters, a transcutaneous $P_O_2$ analyzer, and two pulse oximeters. An IL-282 Co-oximeter was used to periodically measure arterial oxyhemoglobin ($O_2Hb$) and carboxyhemoglobin (COHb) as percentages of the total hemoglobin. The $P_{aO_2}$, $P_{aCO_2}$, and $pH$, were measured in the same blood specimens using standard electrodes. When the inspired oxygen concentration was reduced in the absence of COHb, the pulse oximeter saturation ($SpO_2$) estimated $O_2Hb$ with reasonable accuracy. COHb levels were then varied slowly from 0–75% in each dog. As the COHb level increased and oxyhemoglobin decreased, both pulse oximeters continued to read an oxygen saturation of greater than 90%, while the actual $O_2Hb$ fell below 30%. In the presence of COHb, the $SpO_2$ is approximately the sum of $O_2Hb$ and $O_2Hb$, and, thus, may seriously overestimate $O_2Hb$. The pulse oximeter, as the sole indicator of blood oxygenation, should, therefore, be used with caution in patients with recent carbon monoxide exposure. On the other hand, transcutaneous $P_O_2$ falls linearly as COHb increases, and reaches about one-fifth of its initial value at the highest COHb levels despite the maintenance of constant arterial $P_O_2$. (Key words: Blood, hemoglobin: carboxyhemoglobin; saturation. Gases, nonanesthetic: carbon monoxide. Measurement techniques: pulse oximetry; transcutaneous. Monitoring: oxygen.)

Noninvasive monitoring of oxygenation in the operating room is rapidly becoming a standard of anesthetic practice. The pulse oximeter is easy to use, and provides a rapid, continuous estimate of arterial oxygen saturation.1,2 Transcutaneous oxygen tension ($P_{tcO_2}$) is a noninvasive indicator of oxygen delivery to peripheral tissues, and reflects changes in both arterial oxygen tension and perfusion.3,4 Each of these techniques has its own advantages and disadvantages, and both clearly have a role in the operating room and intensive care unit.

The pulse oximeter estimates arterial hemoglobin saturation by measuring the light absorbance of perfused tissue (finger, ear, etc.) at two wavelengths, 660 and 940 nm. The device then computes the difference between the maximum and minimum absorbance at each wavelength to generate a "pulse-added" absorbance signal. The ratio of the pulse-added absorbances at the two wavelengths is used to estimate the oxygen saturation ($SpO_2$), using an empirical algorithm built into the oximeter software. This algorithm was created by measuring pulse-added absorbances in healthy, awake volunteers breathing various gas mixtures. These absorbances were then correlated with actual oxygen saturations ($O_2Hb$) as determined by arterial blood sampling and a co-oximeter.1

A laboratory co-oximeter, such as the Instrumentation Laboratories IL-282 (Lexington, MA), measures the light absorbance of blood samples at six or more discrete wavelengths. Using these data and the known absorbance spectra of the various hemoglobin species, the co-oximeter calculates the concentration of each species as a fraction of the total hemoglobin. It can thus determine the amounts of reduced hemoglobin (Hb), oxymyoglobin ($O_2Hb$), methemoglobin (MetHb), and carboxyhemoglobin (COHb). The pulse oximeter, with absorbance measurements at only two wavelengths, cannot discriminate between more than two species, i.e., reduced and oxyhemoglobin. If a third species, such as carboxyhemoglobin (COHb), is present, it is not clear a priori what the pulse oximeter $SpO_2$ will actually measure. The present study is aimed at determining the behavior of the pulse oximeter in the presence of COHb, which may constitute 50% or more of the total hemoglobin in patients with acute inhalation injuries. We are also interested in the effect of COHb upon $P_{tcO_2}$. Since the latter is an indication of oxygen delivery to tissue, we expect it to fall with increasing COHb despite adequate arterial oxygen tension.

Methods

Five mongrel dogs were used in this study. Each dog was anesthetized with intravenous sodium pentobarbital, 30 mg/kg. Following tracheal intubation, they were ventilated to maintain normocapnia ($pCO_2 = 35–40$ mmHg). Femoral artery and pulmonary artery catheters were inserted and pressures were monitored continuously. Two Novametrix model 807 transcutaneous $P_O_2$ probes were

* Associate Professor of Anesthesiology.
Received from the Department of Anesthesiology, University of California, Irvine Medical Center, Orange, California. Accepted for publication December 1, 1986.
Address reprint requests to Dr. Barker: Department of Anesthesiology, UCI Medical Center, Mail Route 81A, 101 City Drive South, Orange, California 92668.
applied to shaved skin on the chest, after calibration as suggested by the manufacturer. Two pulse oximeters (Nellcor N-100 and Ohmeda Biox-III) were used, with their probes applied to the tongue. This location of the oximeter probes resulted in a very low incidence of "low perfusion" alarm or low signal strength.

Inspired oxygen fraction (FiO₂) was slowly varied from 1.0–0.12 at several constant levels of COHb for each dog. COHb was controlled by the administration of precisely known quantities of carbon monoxide into the circle breathing system. COHb was measured in arterial blood samples by an IL-282 Co-oximeter, which was also used to determine the total hemoglobin and the actual oxygen saturation (O₂Hb). The co-oximeter was adapted to dog blood using additional electronics and calibration standards supplied by the manufacturer. Each data set was recorded when steady-state conditions were maintained for at least 15 min. Data included hemodynamic values (heart rate, blood pressure, PA pressure, cardiac output), PtcO₂, SpO₂ from the two pulse oximeters, arterial blood gases (Radiometer model ABL-2), and co-oximeter values of total hemoglobin, O₂Hb, and COHb.

First, we must verify the validity of using in dogs a pulse oximeter whose empirical calibration was developed in humans. To this end, we varied FiO₂ slowly from 1.0–0.10 without carbon monoxide for each dog. We recorded SpO₂ from the pulse oximeters and O₂Hb by IL-282 from arterial samples. The resulting plot of SpO₂ versus O₂Hb, shown in figure 1, yields a linear regression with a correlation coefficient of 0.99 and a precision of 2.2%. (Precision is defined as the standard deviation of

![Graph 1](image1.png)

**Fig. 1. SpO₂ versus O₂Hb without carbon monoxide. Line of identity is shown. Correlation coefficient r = .99, bias = 4.5, precision = 2.2. These data and previous studies show good function of pulse oximeters in dogs.**

![Graph 2](image2.png)

**Fig. 2. SpO₂ and O₂Hb versus carboxyhemoglobin (COHb) at FiO₂ = 1.0. SpO₂ consistently overestimates saturation in the presence of COHb. At COHb = 70%, SpO₂ is still roughly 90%, while O₂Hb has fallen to 50%.**

![Graph 3](image3.png)

**Fig. 3. SpO₂ and O₂Hb versus carboxyhemoglobin (COHb) at FiO₂ = 0.2. The balance of the gas mixture is nitrogen. These data show the same trends as figure 2; see table 1 for linear regression results.**

| Table 1. Linear Regression Statistics (Figures 2–4) |
|---------------------------------|-----|-----|-----------------|
|                                | r   | Slope | Intercept       | Standard Error of the Estimate* |
| Fig. 2, FiO₂ = 1.0             |     |       |                 |                               |
| O₂Hb vs. COHb                  | -0.99| -1.05 | 103.5           | 2.92                           |
| SpO₂ vs. COHb                  | -0.53| -0.10 | 99.3            | 3.32                           |
| Fig. 3, FiO₂ = 0.2             |     |       |                 |                               |
| O₂Hb vs. COHb                  | -0.93| -1.03 | 84.0            | 7.97                           |
| SpO₂ vs. COHb                  | -0.16| -0.05 | 94.1            | 6.99                           |
| Fig. 4, FiO₂ = 0.2             |     |       |                 |                               |
| PtcO₂ vs. COHb                 | -0.99| -1.24 | 1.05            | 0.088                          |

* Defined as the standard deviation of the differences between the Y-values and the linear regression predictions.
the differences between the SpO2 and O2Hb values.) Previous studies in dogs have shown similar correlations.6

Results

Results obtained by the Nellcor pulse oximeter when carbon monoxide was added to the gas mixture are shown in figures 2 and 3. Similar results were obtained with the Ohmeda-Biox. Figure 2 shows both SpO2 and O2Hb plotted versus percentage of carboxyhemoglobin (COHb) for FIO2 = 1.0. (Inspired carbon monoxide concentration never exceeded 0.1%.) Figure 3 is a similar plot for FIO2 = 0.2, with the balance of the gas mixture made up by nitrogen. In both of these plots, SpO2 from the pulse oximeter shows little dependence upon COHb, while the actual O2Hb falls linearly with increasing COHb. Correlation coefficients and linear regression data for the best-fit straight lines shown in figures 2 and 3 are given in table 1.

Data obtained from the transcutaneous P2O2 probes during carbon monoxide inhalation are shown in figure 4. The ratio of PtcO2 to its initial value (before the introduction of carbon monoxide) is plotted versus COHb. Although these data show considerable scatter, the trend is clear: PtcO2 falls almost linearly with increasing COHb (r = -0.95). See table 1 for linear regression results.

Discussion

The data presented here show that, in the presence of elevated carboxyhemoglobin levels, the pulse oximeter overestimates arterial hemoglobin saturation. Since absorbance is measured at only two wavelengths, the pulse oximeter is unable to distinguish three or more hemoglobin species. However, it was not clear before this study to what degree the SpO2 would overestimate O2Hb. It is interesting that the SpO2 values in figures 2 and 3 approximate the sums of the O2Hb and COHb values. Note also that, even at COHb levels of 70%, which would be lethal in most humans, the pulse oximeter still reports a saturation of 90% or greater. On the other hand, the transcutaneous P2O2 has decreased to approximately one-fifth of its initial value when this COHb level is reached (fig. 4). The decrease in PtcO2 with increasing COHb appears to be linear (linear regression slope = -1.24, standard error of the estimate = 0.088). This reflects the fact that PtcO2 is determined by oxygen delivery to peripheral tissue, and the latter is continuously decreasing as oxyhemoglobin is replaced by carboxyhemoglobin.

The fact that SpO2 overestimates O2Hb in the presence of COHb implies that the pulse oximeter should be used with caution in patients with a possible recent history of carbon monoxide inhalation. A smaller discrepancy may also occur in heavy smokers, whose COHb levels have been measured in the 10–20% range. In view of these results, we may speculate that a pulse oximeter measurement error will also occur in the presence of methemoglobin. As the absorbance spectrum of methemoglobin is very different from that of carboxyhemoglobin, the magnitude of this error remains to be determined.

References