Effects of Carboxyhemoglobin on Pulse Oximetry in Humans

Chikara TASHIRO, Yoo Hee KOO*, Kazuo FUKUMITSU, Katsuji TOMI, Takashi MASHIMO and Ikuto YOSHIYA

Carboxyhemoglobin (HbCO)-induced reading errors of the Biox 3700 (version J, Ohmeda) pulse oximeter were determined in 6 healthy volunteers rendered hypoxic (Sa_{O_2} from 65–100%) by breathing mixtures of air in nitrogen. The oximeter reading (Sp_{O_2}) before and after cigarette smoking was compared with oxyhemoglobin percentage (%HbO_2). Mean HbCO levels were; 3.0 ± 1.0 (SD) % before cigarette smoking and 5.2 ± 1.7% after smoking, whereas mean methemoglobin was unchanged as 0.5 ± 0.1%. The correlations of the Sp_{O_2} (y) with %HbO_2 (x) were; y = 1.01x − 0.30 (r = 0.990, n = 21, $P<0.001$) when %HbCO was less than 2.5, and y = 1.01x + 3.21 (r = 0.964, n = 33, $P<0.001$) when %HbCO was above 5.0%. The reading error, (Sp_{O_2} − %HbO_2), could be expressed as a function of %HbCO; 1.06 × %HbCO − 2.49 (r = 0.669, n = 83, $P<0.05$). Thus, the Sp_{O_2} is approximately the sum of %HbO_2 and (%HbCO − 2.5), and overestimates %HbO_2 in the high levels of HbCO. The pulse oximeter should be used with caution in patients with the elevated level of %HbCO. (Key words: pulse oximeter, cigarrete smoking, carbon monoxide carboxyhemoglobin, oxygen saturation)

(Tashiro C, Yoo HK, Fukumitsu K et al.: Effects of carboxyhemoglobin on pulse oximetry in humans. J Anesth 2: 36–40, 1988)

The terminology in oximetry has become confusing because of the use of CO-oximeters which measure oxyhemoglobin (HbO_2), deoxyhemoglobin (Hb), carboxyhemoglobin (HbCO) and methemoglobin (MetHb) using five or more wavelengths of light, and express each as a percentage of the total hemoglobin. Before the CO-oximeter was introduced, Sa_{O_2} was defined as:

$$Sa_{O_2} = 100 \times \frac{(HbO_2)}{(HbO_2 + Hb)}$$

where each term represents a fraction of the total of four hemoglobin species shown above. This ratio has more recently been called functional Sa_{O_2}.

The CO-oximeter reports oxyhemoglobin percentage (%HbO_2) according to:

$$\%HbO_2 = 100 \times \frac{(HbO_2)}{(HbO_2 + Hb + HbCO + MetHb)}$$

This is called %HbO_2 or fractional Sa_{O_2} although no widespread agreement has been reached.

Non-invasive monitoring of arterial oxygenation is becoming standard practice during anesthesia and intensive care. The commonly-used pulse oximeters determine hemoglobin saturation by measuring light absorbance at two different wavelengths during arterial pulsation and comparing the ratio of the absorbances to an empirically derived algorithm based on clinical data of

Department of Anesthesiology, Osaka University Medical School, Osaka, 553 Japan

**Department of Anesthesiology, Hanyang University College of Medicine, Seoul, 133 Korea*

Address reprint requests to Dr. Tashiro: Department of Anesthesiology, Osaka University Medical School, Fukushima, 1-1-50, Fukushima-ku, Osaka, 553 Japan

Table 1 Total hemoglobin (THB), % carboxyhemoglobin (HbCO), % methemoglobin (metHb), systolic and diastolic arterial pressure (SAP, DAP), heart rate (HR), and the regression line of Spo_2 vs. $\%HbO_2$ before (C) and after smoking (S).

Subject		n	THb (g/dl)	%HbCO	%MetHb	SAP (torr)	DAP (torr)	HR (/min)	Spo_2 vs. $\%HbO_2$ slope	$Spo_{2\,\%HbO_2=70}$	r
1	C	7	14.8±0.7	2.1±0.1	0.4±0.1	163± 6	78± 5	67± 7	1.077	69.4	0.996
	S	7	15.6±1.1	2.6±0.1***	0.4±0.1	169± 6	89± 7*	77± 7	1.075	68.9	0.995
2	C	7	17.0±0.2	3.5±0.1	0.5±0.1	142± 8	71±12	60± 6	1.067	70.8	0.995
	S	7	17.3±0.3	6.0±0.0***	0.5±0.1	138± 6	63±10	63±11	1.080	75.2	0.999
3	C	7	13.2±0.4	2.4±0.1	0.6±0.2	146± 6	65± 5	71± 7	1.031	71.1	0.996
	S	7	13.5±1.6	3.9±0.1***	0.8±0.2	143± 5	76± 5*	89± 9**	1.052	71.0	0.992
4	C	7	15.1±1.3	2.3±0.1	0.6±0.1	167± 8	89± 3	69±10*	0.942	70.3	0.993
	S	7	15.8±0.8	5.2±0.1***	0.5±0.1	168±20	94± 8	86±10*	1.044	74.6	0.967
5	C	7	13.8±0.2	3.0±0.1	0.5±0.2	139± 2	74±11	79± 8	0.916	69.8	0.980
	S	6	13.8±0.3	5.2±0.0***	0.4±0.1	148± 8*	78±10	87± 6	1.187	69.7	0.995
6	C	7	13.5±0.5	5.0±0.1	0.6±0.1	137± 3	81± 6	76±10	1.142	70.4	0.995
	S	7	13.7±0.3	7.9±0.1***	0.5±0.1	142± 2*	82± 5	87±11	1.011	75.2	0.996
Total	C	47	14.6±1.4	3.0±1.0	0.5±0.1	148±13	76±11	70±10	1.017	70.4	0.976
	S	44	15.0±1.6	5.2±1.7***	0.5±0.2	151±16	80±12	81±13**	0.990	73.2	0.956

Mean±SD, *; $P<0.05$ **; $P<0.01$ and ***; $P<0.001$ significant from Control (Student's t-test).

Sa_{O_2}[1], while it is obscure for each type of the pulse oximeters to use either fractional or functional Sa_{O_2} as the standard. Since the pulse oximeter senses only two wavelengths and does not distinguish HbO_2 from HbCO[2], its reading (Spo_2) probably predicts the sum of $\%HbO_2$ and %HbCO with no information of HbCO levels*. It is evident that the accurate oxygen content will be derived from the total hemoglobin level (Hb + HbO_2 + HbCO + MetHb) and $\%HbO_2$.

In this study, the correlation of Spo_2 with $\%HbO_2$ is examined before and after cigarette smoking in six volunteers to clarify the effects of HbCO levels on the accuracy of the Biox 3700 pulse oximeter (Ohmeda, Boulder Co), although this device uses new algorithms for the oxygen desaturation meter[3].

Methods

Six healthy, male volunteers consented to participate in this study which had been approved by Osaka University Hospital Ethical Committee. Their mean age was 26.4 ± 4.6 (SD) yrs. They daily smoked 15–20 cigarettes and stopped smoking 12hr prior to the experiment. After an intravenous infusion route, ECG monitoring and a left radial artery catheter for blood sampling and blood pressure monitoring (Hewlett-Packard Multimonitor 78342A) had been established, a finger-probe of the Ohmeda Biox 3700 with Version J software was placed on the right index finger of each subjects. The oximeter was set to respond in the fast mode. Using a reservoir bag (20L), a non-rebreathing circuit and a face mask, the air/nitrogen mixture was delivered. A mass-spectrometer (Perkin-Elmer Medical Gas Analyzer MGA-1100) continuously measured respective fraction of O_2 and CO_2 in the mask. Inspiratory oxygen concentrations were decreased in the stair-case fashion to obtain approximate 5% decrease of the oximeter reading until the final reading reached about 70%. In each set of measurements, the oximeter reading (Spo_2) was simultaneously recorded when the arterial blood was drawn for the determination with a CO-oximeter (Corning

*; The Biochem CO/OX_{1000} non-invasive CO-Oximeter operates on three wavelengths, detecting the approximate fractional Sa_{O_2} with %HbCO.

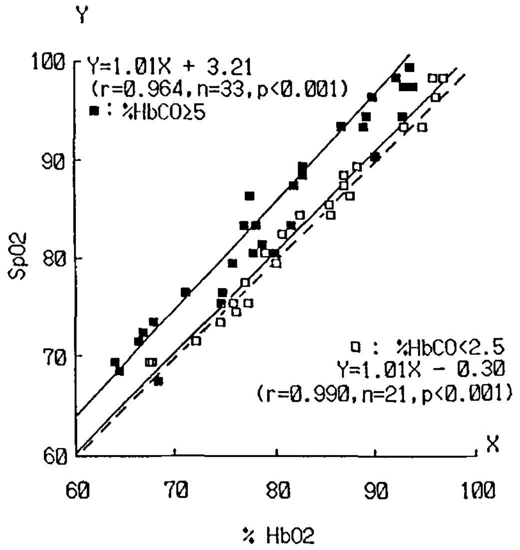

Fig. 1. The SpO_2 (y) was plotted against $\%HbO_2$ (x) in the samples of which %HbCO were less than 2.5 (open squire) or above 5 (closed squire). The regression line of the sample above 5% HbCO is obviously upward shifted from the line under 2.5% HbCO. The line of identity is shown as a dotted line.

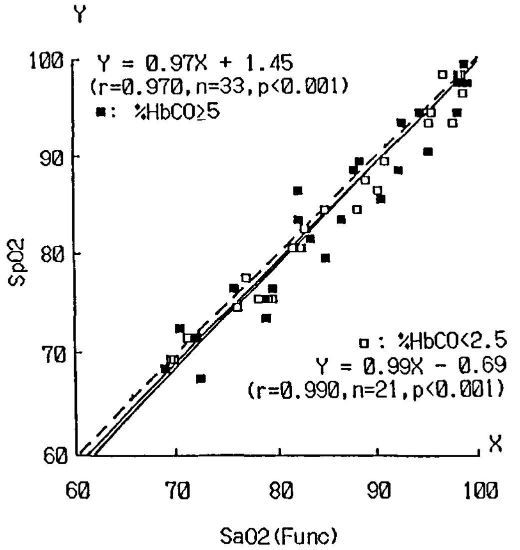

Fig. 2. The SpO_2 (y) was plotted against functional Sa_{O_2} (x) in the samples of which %HbCO were less than 2.5 (open squire) or above 5 (closed squire). Two regression lines are almost the same, and locate near the line of identity (a dotted line).

2500) and a blood gas analyzer (Corning 178). The CO-oximeter denoted % fraction of Hb, HbO_2, HbCO and MetHb to the total hemoglobin with the total hemoglobin level, and the blood gas analyzer reported theoretical or functional Sa_{O_2}. To ensure that a steady-state had been achieved, we waited until SpO_2 had been stable for 30 seconds.

After the first experiemnt, the face mask and the probe were removed. The subject was allowed to drink a cup of coffee and smoke 3 cigarettes for ten minutes. Then the same preparation and method were served as the second experiment.

Data were analyzed by using the linear regression. Significant differences were determined by the Student t-test ($P<0.05$).

Results

Forty-two blood samples were drawn from six volunteers in the first experiment (before smoking) and 41 blood samples in the second experiment (after smoking). The results were summarized in table 1. Cigarette smoking caused the significant increase of %HbCO from 3.0 ± 1.0 to 5.2 ± 1.6% ($P<0.001$), whereas THb and %MetHb levels were stable. The %HbCO and %MetHb levels during each experiment of all the subjects were almost constant as known their small standard deviation. After smoking, heart rate and arterial pressure increased in some subjects. The SpO_2 always had a better correlation coefficient with $\%HbO_2$ in each subject rather than in the total subjects (table 1). In the range of $\%HbO_2$ from 70 to 100%, each regression line of SpO_2 vs. $\%HbO_2$ was usually upward-shifted after smoking. It indicated that the SpO_2 became higher than $\%HbO_2$ when the %HbCO levels were increased.

Two groups were introduced with HbCO levels; one group consisted of $\%HbCO < 2.5$, and the other group of $\%HbCO \geq 5$. The relationships of SpO_2 with both of fractional and functional Sa_{O_2} in the two groups were shown in figure 1 and 2. The SpO_2 in the presence of $\%HbCO \geq 5$ was overestimated

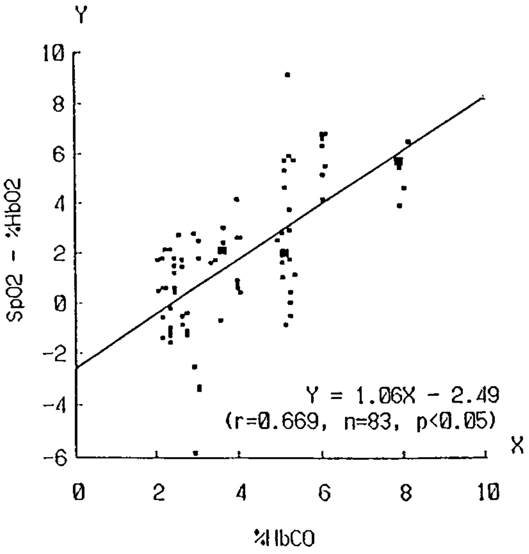

Fig. 3. The difference of $\%HbO_2$ from $\%SpO_2$ (y), ($SpO_2 - \%HbO_2$), was plotted against % HbCO (x). On the regression line, the difference becômes minimum (y=0) when the x-value is 2.4 (=2.49/1.06).

in comparison with $\%HbO_2$, while the line of %HbCO < 2.5 was close to the identity line (fig. 1). On the other hand, the regression line of SpO_2 vs. functional Sa_{O_2} in the two groups almost coincided with each other (fig. 2). In the elevated HbCO group, higher correlation coefficient of SpO_2 vs. functional Sa_{O_2} was observed in comparison with that of SpO_2 vs. $\%HbO_2$.

Discussion

This study demonstrated that the pulse oximeter overestimates arterial hemoglobin saturation in the presence of elevated carboxyhemoglobin (HbCO) levels. This result was in agreement with the previous dog's result[2], where the SpO_2 was approximately the sum of $\%HbO_2$ and %HbCO; $SpO_2 = \%HbO_2 + \%HbCO$. Therefore, when the difference of the oximeter reading (SpO_2) from $\%HbO_2$ was plotted against the level of %HbCO, the regression line was supposed as ($SpO_2 - \%HbO_2$) = %HbCO. Our calculated line was; ($SpO_2 - \%HbO_2$) = 1.06 × (%HbCO) − 2.49, r = 0.669, n = 83, $P<0.05$ (fig. 3). It indicates that, in the presence of higher HbCO levels than 2.4 (=2.49/1.06) %, the SpO_2 is overestimated in comparison with $\%HbO_2$. Since the slope of the line was approximate one, the oximeter may misunderstand a unit of %HbCO as the same unit of SpO_2. The error of the oximeter becomes minimum at 2.4% of HbCO which is around the average value of surgical patients[4]. Thus, the oximeter might be calibrated with the fractional Sa_{O_2} of humans who had the average levels of HbCO. In addition, the SpO_2 in our study was approximately close to functional Sa_{O_2} (fig. 2). It may be eligible that the SpO_2 predicts functional SaO_2. Namely, when the SpO_2 is approximately the sum of $\%HbO_2$ and %HbCO; $SpO_2 = (HbO_2 + HbCO)/(Hb + HbO_2 + HbCO)$, this equation may be approximated by the functional Sa_{O_2} in the condition of HbCO level far small from HbO_2.

It is generally considered that the pulse oximeter using two wavelengths measures arterial desaturation and cannot show the oxyhemoglobin percentage because the light absorbance of HbCO considerably resembles to that of HbO_2. Therefore, the SpO_2 will underestimate functional Sa_{O_2}[5] if it can be postulated that the SpO_2 predicts functional Sa_{O_2}. However, this underestimation will be less than one fifth of %HbCO levels in the ranges of Sa_{O_2} 60–100%[5]. On the other hand, if the SpO_2 is considered to predict fractional Sa_{O_2}, we can tell that SpO_2 is overestimated in comparison with $\%HbO_2$. For example, 90% HbO_2 in the presence of 10% HbCO means that functional Sa_{O_2} is 100%. In this case, actual SpO_2 will be 97–98% from our regression line.

The oximeter cannot distinguish dyshemoglobins (carboxyhemoglobin, methemoglobin, sulfhemoglobin) from oxyhemoglobin or deoxyhemoglobin[2,3]. Carboxyhemoglobin level is usually the highest of dyshemoglobins and it will reach above 10% in the burn or heavy-smoking patients[6,7]. The banked blood sometimes contained high amounts of HbCO[6] and the half-life of HbCO in normal man is approximate 4hr under air and 40 min under pure oxygen inhalation[7].

Therefore, the massive transfusion of carbon monoxide-rich blood may decrease $\%HbO_2$ in hypoxic patients whose half-life of HbCO are prolonged, while the oximeter readings were less changed. We should recognize that 1) the oximeter readings predict approximate functional Sa_{O_2}, and 2) the arterial oxygen content can be calculated with the total Hb level (HbO_2 + Hb + HbCO + MetHb) and $\%HbO_2$. The CO-oximeter measurement should be done in the patients who show unexplained hypoxic signs, dyshemoglobinemia or cyanosis.

Although the underestimation of arterial saturation was reported in the pulse oximeter[8,9], the SpO_2 in our study was in good agreement with functional Sa_{O_2}. However, in the presence of high levels of HbCO, the SpO_2 was overestimated in comparison with $\%HbO_2$. Baker & Tremper[2] examined the effects of carbon monoxide inhalation on the dog's pulse oximetry and concluded that the SpO_2 is approximately the sum of $\%HbO_2$ and %HbCO. We also could find that a smaller discrepancy also occurs in humans after smoking 3 cigarretes. These facts imply that the pulse oximeter should be used with caution in patients with elevated carboxyhemoglobin levels.

In conclusion, the Ohmeda Biox 3700 pulse oximeter overestimate $\%HbO_2$ or fractional Sa_{O_2} when the percent fraction of carboxyhemoglobin is increased. It will be necessary to check HbCO and MetHb levels with the CO-oximeter in order to know accurate oxygen contents in blood.

(Received Nov. 20, 1987, accepted for publication Nov. 27, 1987)

References

1. Yoshiya I, Shimada Y, Tanaka K: Spectrophotometric monitoring of arterial oxygen saturation in the fingertip. Med Biol Eng Comput 18:27–32, 1980
2. Baker SJ, Tremper KK, Hufstedler S: The effects of carbon monoxide inhalation on pulse oximetery and transcutaneous Po_2. Anesthesiology 66:677–679, 1987
3. Payne JP, Severinghaus JW: Pulse Oximetry. Springer-Verlag, Berlin, 1986, pp. 45–53
4. Stewart RD, Baretta ED, Platte LR, Stewart EB, Kalbfleisch JH, Van Yserloo B, et al.: Carboxyhemoglobin levels in American blood donors. JAMA 229:1187–1195, 1974
5. Minolta Co. Ltd.: Technical Information of Pulsox-7, 1986
6. Aronow WS, O'Donohue WJ, Freygang JF, Sketch MH: Carboxy hemoglobin levels in banked blood. Chest 87:684–685, 1985
7. Goldzimer EL, Parton ME, Kane EW: Elevated intraoperative carboxyhemoglobin levels. Anesth Analg 63:698–703, 1984
8. Berko RS, Kagle DM, Alexander CM, Giuffre M, Gross JB: Evaluation of the Ohmeda Biox 3700 Pulse Oximeter during rapid changes in arterial oxygen saturation. Anesthesiology 65:A130, 1986
9. Kagle DM, Alexander CM, Berko RS, Giuffre M, Gross JB: Evaluation of Ohmeda 3700 Pulse Oximeter: Steady-state and transient response characteristics. Anesthesiology 66:376–380, 1987