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Changes in blood carboxyhemoglobin during simulated saturation diving to 50 ATA

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Rodkey, F. L., L. W. Raymond, H. A. Collison, and J. D. O'Neal. 1974. Changes in blood carboxyhemoglobin during simulated saturation diving to 50 ATA. Undersea Biomed. Res. 1(2):197-201.–Carboxyhemoglobin measurements were made on six men during a simulated saturation dive to 50 ATA in helium-oxygen mixtures. All subjects, habitual smokers and nonsmokers, reached the same COHb after 24 hours in the chamber and their COHb % increased at the rate of 0.29 percent saturation per day during pressurization and bottom time. Average COHb increased from 0.6 to 3.2% in 10 days of confinement before decompression was started and decreased to 0.7% at the end of 17 days decompression. Rates of CO accumulation during pressurization and bottom time were calculated and found to be 183% of the endogenous CO production rate calculated through the decompression period. Implications of these data in relation to heme turnover and hemolysis are discussed.

hyperbaria
helium-oxygen
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carboxyhemoglobin
endogenous carbon monoxide
hemolysis

During April and May 1973 a simulated saturation dive was conducted at the Taylor Diving Co., Belle Chasse, La. Six Navy divers (2 medical officers, 2 hospital corpsmen, and 2 divers) were compressed in a helium-oxygen atmosphere by stages to 1600 feet sea water equivalent (49.5 ATA). They remained at this pressure for 8 days followed by gradual decompression to 1 atm over the next 17 days. Throughout the dive, oxygen within the chamber was maintained at 0.32 ± 0.02 ATA, CO_2 was absorbed and did not exceed 0.01 ATA. Actual gas volume was 2,465 ft^3 with an ambient temperature of 31°C and relative humidity = 70%. Changes in diver blood COHb % saturation were measured during pressurization, bottom time, and decompression. The data were used to estimate the rate of endogenous carbon monoxide formation from the changes of COHb of the diver blood which was assumed to be in a steady state near equilibrium with the chamber gas.

PROTOCOL

Fasting blood samples from each diver were obtained before compression, at intervals through the dive, and 16-20 hours after leaving the chamber. The blood samples were permitted to clot during a controlled decompression to atmospheric pressure, then centrifuged to remove serum. The clot remaining (in a stoppered glass tube) was frozen and kept in dry ice until all samples were obtained and shipped to the laboratory. Hemoglobin solutions were prepared from each clot by expressing about 2 or 3 ml of thawed clot

through a syringe orifice without needle into a 4 ml glass tube containing 1 ml of 5% Sterox SE in water. The tube was stoppered, the contents mixed by inversion on a mechanical rotor for 30 minutes, and then allowed to extract at 4°C for 24 hours. The tubes were centrifuged to obtain a clear hemoglobin solution for analysis. Duplicate measurements were made of carbon monoxide content (Collison, Rodkey, and O'Neal 1968) (Rodkey and Collison 1970) and total hemoglobin (Van Kampen and Zijlstra 1961) with minimal exposure to air. Percent saturation as COHb was calculated by Equation (1).

$$\text{COHb} = \frac{\text{CO content} \times 100}{\text{Hb}_t \times 1.39} \quad (1)$$

where CO content is expressed in ml CO (STPD)/100 ml and Hb_t is in grams hemoglobin/100 ml, each gram of hemoglobin having a CO binding capacity of 1.39 ml of CO (STPD).

RESULTS AND DISCUSSION

Values of COHb observed are presented together with the pressure profile of the dive in Fig. 1. Predive samples indicate clearly the 2 smokers and 4 nonsmokers. Twenty-four hours after entering the chamber all divers had reached a level of COHb similar to the predive nonsmoker value. Habitual smokers and nonsmokers had identical COHb values through the remainder of the dive. There was, however, a nearly linear increase in average COHb with time during compression and stay at pressure. The data show an increase of COHb = 0.285 ± 0.009 % saturation per day. Values of COHb for all divers reached those of the habitual smokers' predive samples before decompression was started.

During decompression the COHb level of all divers decreased together—slowly over the first week, but more rapidly as decompression progressed. This was an expected change since

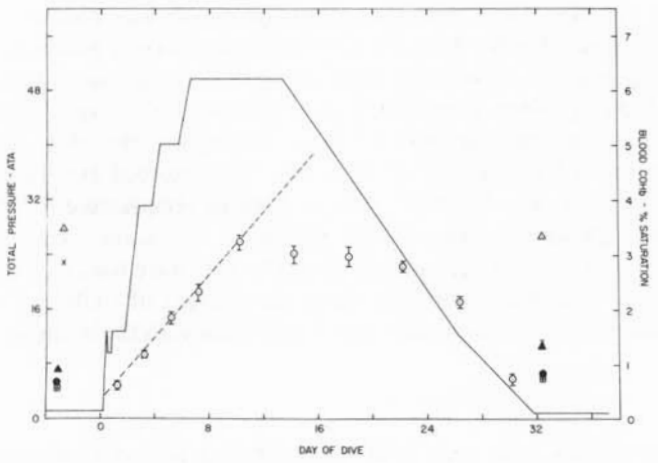

Fig. 1. Pressure profile (ordinate on left) and blood COHb changes (ordinate on right) during 50-atm. simulated dive. Symbols pre- and postdive represent individual diver COHb. Mean values of six divers are given while in the chamber and 1 standard deviation is included between the horizontal bars. The dotted line represents the change in mean COHb with time, calculated by the method of least squares, for all chamber data up to the beginning of decompression.

decompression was accomplished by a combination of venting chamber gas and addition of oxygen to maintain constant P_{O_2} of 0.32 ATA. The COHb value of 3.02 observed on Day 14 was further than had been expected below the value of 3.88% calculated at the beginning of decompression on Day 13. During the period from Day 11 to Day 13 each of the six divers breathed prepared gas mixtures (not chamber gas) for a period of 1-2 hours. The expired gas was released into the chamber gas which was vented to the outside to maintain constant chamber pressure. These respiratory experiments account for the lowered COHb by loss of CO in the expired gas. They also account for the decrease in total CO in the gas phase by dilution with the expired air while venting gas to maintain constant chamber gas pressure. Samples 16 hours postdive show the one habitual heavy smoker at his original predive level with all other subjects at or near the expected nonsmoker level.

CALCULATION OF ENDOGENOUS CO PRODUCTION

Accumulation of CO in the closed system was assumed to be due to endogenous formation by the men. No data are available concerning the CO concentration in the gas phase during the dive. The equilibrium gas CO concentration may be estimated from the measured COHb, $P_{I_{O_2}}$, and total pressure. The Haldane equation is used for this calculation in a rearranged form.

$$Pa_{CO} = \frac{(COHb) \times Pa_{O_2}}{(220)(1 - COHb)} \tag{2}$$

where Pa_{CO} is the equilibrium partial pressure of CO in the arterial blood (and the alveolae); COHb is the fractional saturation of hemoglobin with CO, 220 is the Haldane constant for human Hb at 37°, and Pa_{O_2} is the arterial oxygen tension. Since inspired oxygen tension was maintained constant at 0.32 ATA, the constant value of Pa_{O_2} was calculated from Equation 3.

$$Pa_{O_2} = (0.32)\,(760) - 55 = 188 \text{ mm Hg} \tag{3}$$

In other words, Pa_{O_2} is assumed to be 55 mm below inspired $P_{I_{O_2}}$, and represents the sum of three components: 40 mm $P_{A_{CO_2}}$, 10 mm $P(A - a)_{O_2}$, and 5 mm due to Respiratory Quotient of 0.82 (Riley, Lilienthal, Proemmel, and Franke 1946) (Clark and Lambertsen 1971). Actual Pa_{O_2} at rest was measured during decompression and ranged from 172 to 187 mm Hg.

Previous studies performed with the same Pa_{O_2} showed that observed $P_{I_{CO}}$ in the chamber was less than Pa_{CO} by 3.4×10^{-3} mm at pressure (600 fsw) and by 3.9×10^{-3} mm during decompression (Rodkey, Collison, and O'Neal 1971). Chamber gas CO concentration in ppm during compression and at bottom was therefore calculated from Equation 4.

$$CO = \frac{Pa_{CO} - 3.4 \times 10^{-3}}{(ATA \times 760) - 23} \times 10^6 \tag{4}$$

in which the P_{H_2O} of the chamber (31°C, relative humidity = 70%) is 23 mm Hg.

Total CO in the gas phase was calculated from the gas CO concentration and the STPD volume of the chamber. Total CO in the blood was estimated from the COHb percentage, assuming the CO capacity to be 13.76 ml CO/Kg body weight or 13.76 × 539.3 Kg = 7,420 ml STPD for the 6 subjects.

TABLE 1

Accumulation of carbon monoxide during pressurization and at depth

Day of Dive	Pressure ATA	Blood COHb %	CO in Blood ml STPD	CO in Gas ml STPD	Total ml STPD	Accumulation Rate ml STPD/day
1	13.1	0.61	45	150	195	–
3	31.3	1.28	95	549	644	225
5	40.4	1.86	138	1055	1193	249
7	49.5	2.32	172	1394	1566	228
10	49.5	3.22	239	2065	2304	234
						Av 234

Table 1 shows the accumulation of CO as measured in the divers' blood and calculated in the gas phase. The average rate of accumulation, 234 ml CO/day, would correspond to an endogenous rate of 19.4 μm/Kg · day or a daily destruction of 3.15% of the total diver CO capacity. This value is approximately twice the normal rate of endogenous CO formation at 1 atm. No correction has been made for gas lost in the locks used to transfer materials in and out of the chamber. Thus the CO accumulation rate may underestimate endogenous production by 5-10%.

TABLE 2

Endogenous carbon monoxide formation during decompression

Day of Dive	Pressure ATA	Blood COHb %	CO in Chamber ppm	$\dot{V}$CO mM CO/day
14	47.3	3.02	0.63	–
18	35.5	2.98	0.83	5.76
22	24.0	2.80	1.13	6.00
26	12.4	2.15	1.58	5.53
30	3.4	0.73	(0.92)	–
				Av 5.76

Data from the decompression phase of the dive were used to calculate endogenous CO formation by the method previously reported (Rodkey, Umstead, Engle, and Rubenstein 1974). The results given in Table 2 show an average of 5.76 mM/day from Day 14 to Day 26[1]. This value corresponds to 10.7 μM/Kg ··day or 1.74% of the total CO capacity per day. The rate during decompression is similar to that found in 6 normal male subjects (Berk, Rodkey, Blaschke, Collison, and Waggoner 1974) at atmospheric pressure, 8.5 ± 0.5 μM/Kg ··day or 1.5 ± 0.1% of total CO capacity per day (mean ± S.E.). It corresponds to 129 ml STPD of CO per day, or 55% of the rate of accumulation calculated during pressurization.

[1] Data obtained beyond Day 26 were not included in this calculation because medical considerations caused some of the subjects to be given higher oxygen concentrations near Day 30. Such treatment prevents accurate estimation of Pa_{O_2} and hence PI_{CO} from which the chamber gas content of CO is derived.

Endogenous carbon monoxide production by man is generally accepted to reflect total heme turnover, mostly from hemoglobin (Coburn, Williams, and Kahn 1966) (Logue, Rosse, Smith, Saltzman, and Gutterman 1971). Normal subjects at atmospheric pressure without evidence of hemolysis produce CO equivalent to about 1.5% of their total CO-binding capacity per day. The value of endogenous CO produced during the decompression phase is essentially normal. A nearly two-fold increase in CO production is implied from the rate of accumulation during pressurization and at depth. Clinical data obtained on the subjects did not indicate gross hemolysis. An increase of CO production to double normal, however, would not cause measurable hematological changes in the periods involved. Addition of CO with the helium used in pressurization would certainly contribute to the rate of accumulation. The excess accumulation (over the endogenous rate during decompression) could be accounted for by a contamination of 0.1 to 0.2 ppm CO in the helium supply. Actual measurements of the CO in the particular helium used were not available. Many measurements on similar supplies from the same source have been about .01 to .02 ppm. Hence a CO contamination of the helium supply is probably not the source of the CO accumulated in the chamber during pressurization. The data therefore suggests a moderate increase of CO formation during pressurization insufficient to produce clinically observable hematological changes.

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