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RECOMMENDED EQUIPMENT AND TECHNIQUE STANDARDIZATION FOR PREDICTION OF CARBOXYHEMOGLOBIN LEVELS FOLLOWING CARBON MONOXIDE EXPOSURES

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A rapid method is needed for determining blood carboxyhemoglobin (COHb) in military field environments. The most common method available to determine COHb utilizes a laboratory analytical procedure. Although this technique is accurate, it is time-consuming and offers none of the flexibility desired for a field environment. After a review of the literature, a technique using the concentration of carbon monoxide (CO) in expired alveolar air to indicate blood COHb was identified. Commercial equipment is available to collect alveolar air samples and determine its CO concentration. By use of a curve to correlate alveolar CO and blood COHb, the needed data can be obtained in a matter of minutes. This report describes light-weight equipment and easy procedures suited to a military field setting. The equipment, in a briefcase-sized container, is commercially available to initiate field testing.

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The author would like to express his appreciation to Dr. Richard D. Stewart for his original ideas concerning the measurement of carboxyhemoglobin by an alveolar breath technique. His pioneer research involving carbon monoxide set the stage for additional work on this technique. The guidance he gave me and his friendship spurred my efforts in this research program. In addition, special thanks are in order to Mrs. Eleanor Y. Orndorff, without whom this report would have never been completed.

INTRODUCTION

The Office of The Surgeon General (OTSG) and the U.S Army Medical Research and Development Command (USAMRDC) health hazard priority research requirements have identified a requirement for improved methods and equipment to evaluate exposure hazards in field environments. The alveolar breath method for carbon monoxide (CO) offers significant advantages over the collection of field blood samples (Stewart et al.[1]; Stewart and Stewart[2]). Two recent studies by Dalton[3] and Mossa et al.[4] have demonstrated the utility of this procedure in a military context. The alveolar breath method offers significant advantages over more traditional methods of determining carbon monoxide exposure. Measurements of carbon monoxide concentration in ambient air are often used for comparison to regulatory standards such as the 8-hr time weighted average (TWA) promulgated by the Occupational Safety and Health Administration, or as input to carboxyhemoglobin (COHb) predictors such as the COHb Coburn-Forster-Kane Equation (Coburn et al[5]). Ambient air concentrations are not true indexes of exposure, however. The length of exposure, exercise levels, smoking history, basal metabolic activity, etc., all influence final COHb values. Using symptoms to determine prior exposure is also problematic. Often coma can occur without warning symptoms. Mild symptoms such as dizziness, headache, weakness, fatigue, and shortness of breath are not unique to CO exposure.

Several instrument manufacturers have produced CO monitors/indicators that are adaptable to the accurate measurement of COHb. The equipment discussed in this report has been evaluated for several variables, including ruggedness, size, weight, and simplicity of operation. Procedures for collecting alveolar breath samples and calculating COHb values are described in concise, direct, and easily understood terms. Because alveolar breath samples can be collected in minutes and blood samples need not be sent to a laboratory for analysis, the procedure will allow military preventive medicine personnel to sample at many locations and provide immediate recommendations for personnel protection, if appropriate. Existing COHb evaluation methods are done predominantly in laboratories. Although accurate, they are time-consuming and involve taking blood samples. These procedures are inconvenient for mobile field activities.

SUMMARY OF LITERATURE REVIEWED

As early as 1948, Sjostrand[6] made rough correlations between the CO content of alveolar breath and COHb. In 1958, Jones[7] ascertained the relationship between blood COHb saturation and the partial pressure of alveolar CO during breath holding. Simultaneous blood samples and end-expired air samples were taken to compare the two. The breath was held for 20 seconds to allow alveolar air to equilibrate with pulmonary blood CO. The analysis was reproducible within ± 3.8 percent of a given mean CO meter reading and within ± 4.7 percent of a given mean CO partial pressure. However, carbon dioxide (CO_2) was found to interfere with the analysis. Concentrations of CO were found to be slightly higher when CO_2 interfered. Instruments were subsequently corrected to eliminate response to CO_2.

In 1962, Ringold et al.[8] validated the accuracy of the correlation between COHb percentages in blood and alveolar air. Here the breath was also held, with a procedure to discard unequilibrated lung gas from pulmonary dead space. They resolved the difficulties posed by the loss of CO from rubber and polyethylene bags and identified the need for a filter to remove CO_2 and water vapor. From 1976 to 1984, five important studies were conducted that incorporated the measurement of alveolar air to determine COHb: Rawbone et al.[9], Stewart et al.[10], Wald et al.[11], West[12], and Dalton[3]. Stewart dealt with COHb concentrations received by firefighters in on-the-job situations after prolonged exposures to CO in burning buildings. Alveolar air samples were checked for accuracy by gas chromatography (an average difference in the two methods of 1.2 ppm over the range of 1.4 to 132 ppm was established). The studies of Rawbone et al.[9], Wald et al.[10], and West[12] sampled large populations of cigarette smokers. Their research concluded that 20-second breath retention would allow maximum equilibrium of CO levels, that CO concentrations in alveolar air were highly correlated with COHb levels, and that the alveolar air technique was both simple and reproducible for epidemiological studies. The study by Dalton was significant in having been conducted in a military setting; CO values measured in blood and alveolar breath correlated well. This study recommended that the alveolar breath method for determining COHb be recognized as valid for military settings.

ADAPTATION FOR MILITARY USE

The military's concern for CO hazards dates back many years. Combustion by-products from weapons and gasoline engine exhausts in poorly ventilated areas frequently contain potentially lethal CO concentrations. Prudent sampling of CO has been attempted, but in field situations this is restricted to general area or breathing zone CO concentrations. These do not address the medically important question of actual COHb concentration within the personnel at risk.

The alveolar breath technique would allow easy determination of COHb concentrations. This method would be available for use by medical personnel who routinely monitor CO hazards, i.e., preventive medicine teams. Also, due to the simplicity of the procedures, this equipment can be located in areas where nonmedical personnel could easily use it. Procedural training would be minimal (less than an hour) and CO could be monitored at unit level. This would not only increase awareness of the dangers of CO exposure but would give immediate information to commanders on local CO hazards.

EQUIPMENT SPECIFICATIONS

The following are proposed specifications for the design and function of a militarily adequate instrument to detect and display [in parts per million (ppm)] CO gas in expired (alveolar) breath. Emphasis is placed on size, weight, and ruggedness without having this detract from the equipment's reliability. This device could be called an analyzer, indicator, detector, or monitor but will here be referred to as the "instrument."

1. PHYSICAL - Portable CO instrument with the following physical characteristics.

a. SIZE: Portable "small" or "pocket-size" (including all parts essential for normal operation) with a volume not more than of 30 cubic inches.

b. WEIGHT: Weight (including battery) not more than 15 ounces without carrying cases and straps.

c. CONSTRUCTION/RUGGEDNESS: Construction from high-impact materials, sufficiently durable to withstand routine transporting, handling and use in a military field environment.

2. PERFORMANCE CHARACTERISTICS - Portable CO instrument with the following performance requirements:

a. VISUAL READOUT: Liquid Crystal Display (LCD) readout.

b. WARM-UP PERIOD: Ability to warm up and become operational within 5 minutes (nominal).

c. RANGE: Ability to register CO concentrations (in air) in the range of 0-199 ppm.

d. REPRODUCIBILITY: Difference no greater than ± 2 percent of the actual value for calibration concentration of 50 ppm.

e. MINIMUM DETECTABLE SENSITIVITY: Ability to detect CO at 1 ppm.

f. SPAN DRIFT: Instrumental span drift of no more than ± 2 percent of the 80 percent value of the range cited above for an 8-hour operating period.

g. ACCURACY: CO concentration readings within ± 2 percent of the actual value.

h. RESPONSE TIME: Rise time to a stable value equivalent to 90 percent of the true value within 60 seconds or less.

i. LINEARITY: Linear within ± 2 percent of full scale.

j. ZERO DRIFT: Not to exceed ± 3 percent of the 80 percent value of the military specification range for an 8-our operating period.

k. POWER SOURCE: Nine volt (NEDA 1604A or equivalent) alkaline battery.

l. BATTERY LIFE: At least 800 hours of continuous use.

m. ATTITUDE INSENSITIVITY: A span of no more than ± 3 ppm in attitude sensitivity.

n. EASE OF OPERATION: Simplicity such that untrained users can operate, calibrate, and perform simple user maintenance procedures on the instrument with the operating manual as the only reference.

o. INSTRUCTION MANUALS: As a minimum, inclusion of step-by-step procedures for turn-on and warm-up, calibration and sampling postures plus user trouble shooting and routine maintenance; a parts list, accessory items list, and electrical schematic.

3. ENVIRONMENTAL EFFECTS - Portable CO instruments performing satisfactorily under the following ambient conditions.

a. TEMPERATURE RANGE: Ability to meet all performance specifications within an ambient temperature range of 0^{o} to 40^{o} C.

b. OPERATING HUMIDITY RANGE: Ability to meet all performance specifications within an ambient relative humidity range of 10 percent to 90 percent while continuously sampling for 4 hours without maintenance.

4. INTERFERING GASES - Many gases may interfere with the sensing mechanisms of CO instruments, and this is dependent on the operating principle of the instrument. Users must be informed of those interferences that may affect the readings. The interferences need to be identified in the operating manual. Users should be cognizant of interfering gases when using the instrument.

a. The following information concerning interfering gases represents readings on the MiniCO 1000® Carbon Monoxide Indicator.

Common Interferents	Concentrations in ppm Equivalent to 1 ppm CO
Methane (CH_4)	20,000
Ammonia (NH_3)	55
Hydrogen (H_2)	34
Propane (C_3H_8)	15
Nitrogen Dioxide (NO_2)	2.6
Sulfur Dioxide (SO_2)	1.9
Ethylene (C_2H_4)	0.7
Acetylene (C_2H_2)	0.7
Nitric Oxide (NO)	0.3
Ethyl Alcohol (C_2H_5OH)	0.3
Hydrogen Sulfide (H_2S)	0.1

b. None of the gases listed are normally found in expired breath except ethyl alcohol although the others could occur in immediate environments of the individuals being tested. The required filter adapter removes ethyl alcohol from the breath. To reduce the possibility of contamination from the interferents associated with particular work areas, personnel should be removed from the immediate areas before testing. This is further explained in the next section of this report.

EVALUATION

To find a suitable instrument for monitoring CO in alveolar breath, it was necessary to locate industrial hygiene (IH) equipment manufacturers and their products. The Instrument Society of America (67 Alexander Drive, Post Office Box 12277, Research Triangle Park, NC 27709) provided a listing of several promising products. The manufacturers were called and each one was asked to send brochures, supply photographs, general descriptions, and detailed specifications. Four responded with useful information: MDA Scientific, Inc., 405 Barclay Boulevard, Lincolnshire, IL 60069; National Draeger, Inc., 101 Technology Drive, Pittsburgh, PA 15230; Reliability Technology Corporation, 616 Beatty Road, Monroeville, PA 15146; and Catalyst Research Corporation, 3706 Crondall Lane, Owings Mills, MD 21117.

Because the CO monitor was intended for military use, a list of selection criteria was developed. The decision process was supplemented with advice from industrial hygienists, medical equipment technicians, and other knowledgeable preventive medicine personnel. Key specifications were considered in terms of a simply calibrated, operated, and maintained monitor. Ruggedness, size, and weight were evaluated. Although there may be minor changes in the future design of this equipment to make operation or calibration easier, it is quite satisfactory in its present form.

Experience has shown that just getting the equipment into the users' hands does not ensure that it will be used properly. An insufficient operating budget can limit the reordering of consumables necessary for continued use of the equipment. Two such items are mouthpiece tubing and CO span gas. Both must be purchased separately and stocked so as not to sideline the monitoring equipment. Rubber tubing (1/8-inch inner diameter), a common stock item in a medical treatment facility, can be used as mouthpiece tubing by cutting 3-inch sections and sanitizing by steam sterilization or boiling. A supply of bottled CO span gas must be kept on hand for calibration.

Four candidate monitors were matched with their intended use, the MiniCO 1000® (Catalyst Research Corporation, 3706 Crondall Lane, Owings Mills, MD 21117) CO analyzer was chosen. This monitor closely meets the desired specifications. It is 4 5/8 inches high by 2 1/2 inches wide by 1 1/2 inches deep, and weighs 9 ounces. Its range is from 0 to 500 ppm. Warm-up time, response time, and reproducibility all meet or exceed the desired criteria as well as the specifications for span drift and zero drift. Two of these monitors were purchased for trial testing. The operating procedures, although easily understood by equipment technicians, were rewritten in a simpler format. Minor modifications were made to simplify sampling procedures, and the monitors were subjected to routine and thorough familiarization testing. Over 200 randomly chosen subjects were given the alveolar breath test to determine COHb. This testing, although not statistically based, enabled small procedural difficulties to be corrected. Prior to this, several agencies and organizations including the Navy Industrial Hygiene Association, U.S. Army Natick Research Development and Engineering Center, and participants of the Tri-Service Pulmonary Research Review and Analysis had been given a detailed briefing on the equipment and procedures. They had all found the equipment and procedures suited to their individual needs.

EQUIPMENT

The following equipment list comprises the basic items that must be on hand to support use of the alveolar breath technique.

1. CO instrument with carrying case: A sturdy carrying case offers protection from weather and shock. Foam-padded cases are excellent. (See instrument specifications.)

2. Collection bag/balloon: Soft rubber balloons are best for the collection of alveolar breath. They expand easily with minimum lung pressure and hold samples for extended time periods.

3. Stopwatch: A stopwatch is preferable but any watch with a sweep second hand will enable the tester to approximate the 20-second time period.

4. Rubber tubing, pure latex, amber, 5/16 inches outer diameter, 1/8 inches inner diameter: This tubing has two uses: for calibration, approximately 8 inches of tubing are necessary to connect the flow regulator from the CO span gas cylinder to the monitoring instrument. This tubing can be of laboratory quality. In addition, several 3-inch sections of sanitary tubing are needed as mouthpieces. These sections are disposable and intended for one use only. They should be packaged separately and stored to prevent contamination.

5. Flashlight, penlight, small: This is needed at night to illuminate the liquid crystal display readout.

6. Filter adapter: This device attaches to the collection balloon, connecting the filled balloon to the CO monitor. It contains a filter to protect the monitor from water vapor.

7. Calibration span gas, CO, (50 ppm): Span gas could be of any known concentration, but 50 ppm was chosen because it is in the middle of the correlation chart. For daily field calibrations, a 24-liter pressurized bottle, fit into the carrying case, is ideal.

8. Pressure regulator: This controls the flow of span gas during instrument calibration. It is also used to check the amount of gas remaining in the pressurized bottle.

9. Check valve: This one-way valve, attached to the sanitary mouthpiece tube, permits alveolar air to enter the filter adapter and balloon but not to escape. An arrow on the check valve indicates the direction of alveolar breath flow into the filter adapter.

10. Calibration screwdriver: A small screwdriver is needed for field calibrations of the CO monitor.

11. Correlation chart ppm/COHb : The CO monitor displays the alveolar breath CO concentration in ppm. Conversion to COHb is conveniently accomplished through use of the correlation chart.

12. Instruction manual: Calibration guidelines plus maintenance and trouble shooting information should be included in this manual (provided by manufacturer).

13. The MiniCO 1000® Carbon Monoxide Analyzer is shown in Figure 1.

ALVEOLAR BREATH COLLECTION PROCEDURES

The alveolar breath collection procedures below are slightly modified versions of those of Stewart et al.[1] in their COHb sampling. Different situations may dictate variances in procedures. Generally, however, individuals selected for testing should be relocated as much as possible to sites away from CO exposure (Dalton[3]). In military settings this might be outside of motor maintenance buildings or outside of a helicopter's rotor wash area. Convenience and accessibility of a CO-free area are factors to be considered in sampling site selection.

Elevated baseline blood COHb percent levels, due to such CO sources as smoking, are very possible and must be considered when one determines exposures to CO. Such baseline COHb levels may remain relatively consistent, or they might show a decrease as CO excretion increases with time. Baseline COHb percent levels may then be used to recalculate the COHb concentrations from the hazardous site exposures. Pre-exposure levels have been recorded as high as 16.1 percent COHb for cigarette smokers and 20 percent COHb for cigar smokers (Denniston et al.[13]).

INSTRUCTION FOR TAKING A BREATH SAMPLE
(FOR PERSONS BEING TESTED)

1. Read the complete directions before beginning procedure.

2. Take a deep breath and exhale completely at normal speed.

3. Take a deep breath and hold it for 20 seconds.

4. Exhale about one-half of the air in the lungs at a normal speed then blow all the air that is left in the lungs through the tube and filter adapter and into the balloon.

5. At the end of the breath, hand the balloon and device to the technician and then breath normally. (The balloon will not deflate since it is protected by the closed check valve.)

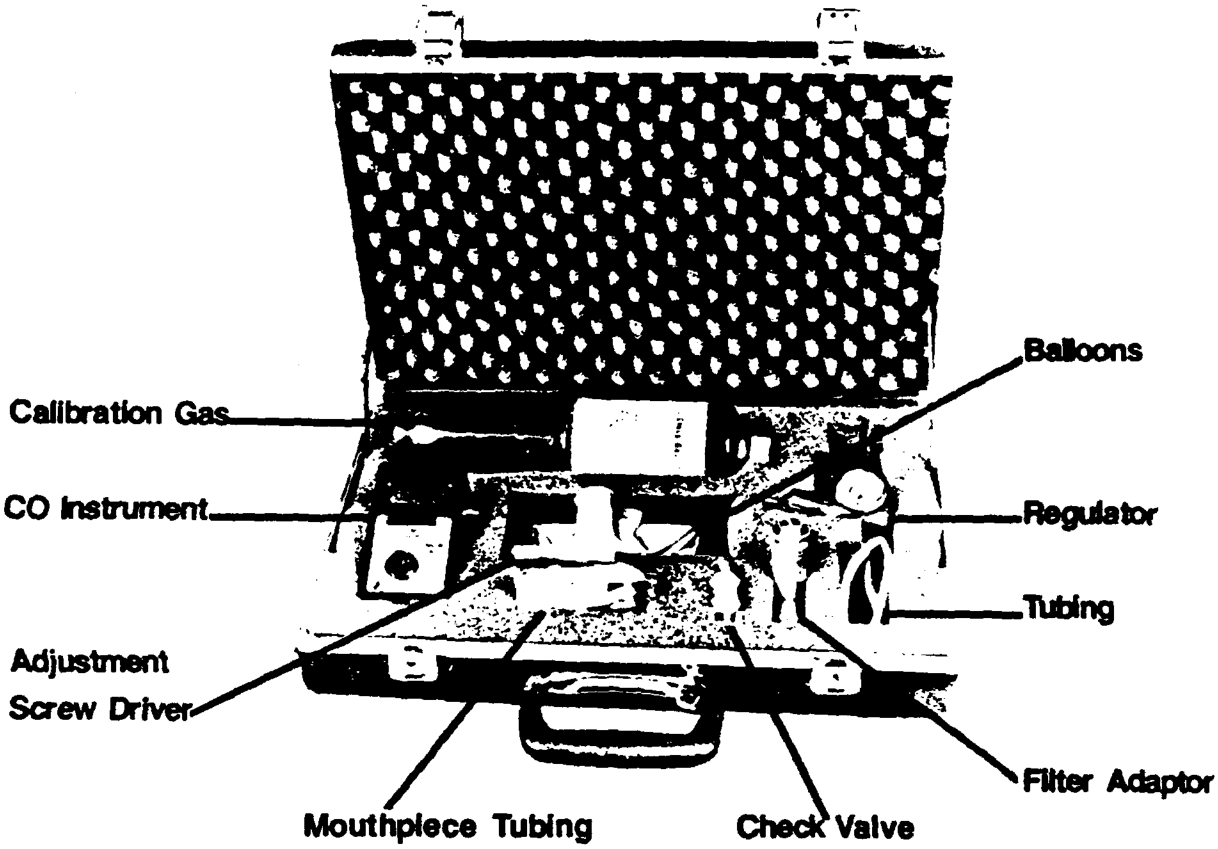

FIGURE 1. COMPLETE KIT CARBON MONOXIDE INSTRUMENT WITH ACCESSORIES

PROCEDURES FOR DETERMINING COHb
(FOR PERSONS ADMINISTERING THE TEST)

1. Turn on the CO instrument and allow for an adequate warm-up time (up to 5 minutes)

2. Perform a battery check in accordance with the instrument instruction manual.

3. Zero the CO instrument per manufacturer's instructions.

4. With the appropriate regulator, attach the hose and connector from the 50 ppm gas bottle to the CO instrument (Figure 2).

5. Adjust the regulator valve on the 50-ppm span gas bottle to the open/flow position and allow the CO gas to enter the CO instrument.

6. Allow 2 minutes for proper response time and observe the LCD readout.

7. Calibrate the CO equipment, using the proper adjustment screwdriver, if necessary, until the LCD readout matches the concentration of CO in the span gas.

8. Stop the gas flow and disconnect the span gas from the instrument.

9. Have the person being tested read the instructions carefully prior to beginning the procedure.

10. Have the subject take a deep breath and exhale completely at normal speed.

11. Have the subject take a second deep breath and hold that breath for 20 seconds. (Using the stop watch, monitor this time period and call off the time in 5-second intervals to help keep the subject posted, and to reinforce his/her progress.)

12. At the end of this 20-second breath holding period, have the subject exhale approximately one-half of the air in the lungs at normal speed (this air is wasted air and not needed in the test), then forcefully blow the remaining air in the lungs through the rubber tube (for sanitary reasons use a sanitized piece of tubing after each test) into the filter adapter and balloon/bag.

13. Using the filter adapter, attach the balloon/bag onto the CO instrument and read the LCD for the concentration of CO in ppm.

14. Match the readout which is in ppm to the correlation chart (Figure 3) (chart is also represented graphically in Figure 4).

15. This test procedure should be completed within 2 minutes.

FIGURE 2. CO INSTRUMENT WITH CALIBRATION SETUP

BREATH CO/CARBOXYHEMOGLOBIN CORRELATION CHART

MiniCO ppm		% COHB	MiniCO ppm		% COHB	MiniCO ppm		% COHB
2	=		35	=	7.475	68	=	13.127
3	=		36	=	7.672	69	=	13.279
4	=		37	=	7.866	70	=	13.429
5	=		38	=	8.057	71	=	13.579
6	=		39	=	8.246	72	=	13.727
7	=		40	=	8.434	73	=	13.875
8	=	1.14	41	=	8.620	74	=	14.022
9	=	1.432	42	=	8.804	75	=	14.169
10	=	1.714	43	=	8.987	76	=	14.314
11	=	1.99	44	=	9.169	77	=	14.459
12	=	2.262	45	=	9.349	78	=	14.603
13	=	2.528	46	=	9.527	79	=	14.746
14	=	2.789	47	=	9.703	80	=	14.888
15	=	3.046	48	=	9.879	81	=	15.029
16	=	3.298	49	=	10.05	82	=	15.170
17	=	3.546	50	=	10.225	83	=	15.310
18	=	3.791	51	=	10.396	84	=	15.450
19	=	4.031	52	=	10.556	85	=	15.588
20	=	4.268	53	=	10.734	86	=	15.726
21	=	4.501	54	=	10.902	87	=	15.863
22	=	4.731	55	=	11.068	88	=	16.000
23	=	4.958	56	=	11.233	89	=	16.136
24	=	5.182	57	=	11.396	90	=	16.271
25	=	5.404	58	=	11.559	91	=	16.406
26	=	5.622	59	=	11.721	92	=	16.540
27	=	5.837	60	=	11.881	93	=	16.073
28	=	6.051	61	=	12.040	94	=	16.806
29	=	6.262	62	=	12.199	95	=	16.938
30	=	6.470	63	=	12.356	96	=	17.069
31	=	6.675	64	=	12.512	97	=	17.200
32	=	6.879	65	=	12.667	98	=	17.331
33	=	7.081	66	=	12.975	99	=	17.460
34	=	7.279	67	=	12.975	100	=	17.590

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Figure 3.

BREATH CO/CARBOXYHEMOGLOBIN CORRELATION CHART

TO USE CHART: Determine the PPM level of carbon monoxide in individual's breath by using the MiniCO carbon monoxide analyzer. Locate the number on the vertical axis of the chart. The estimated blood carboxyhemoglobin level is determined by drawing an imaginary line over to the curve and then down to the proper % on the horizontal axis.

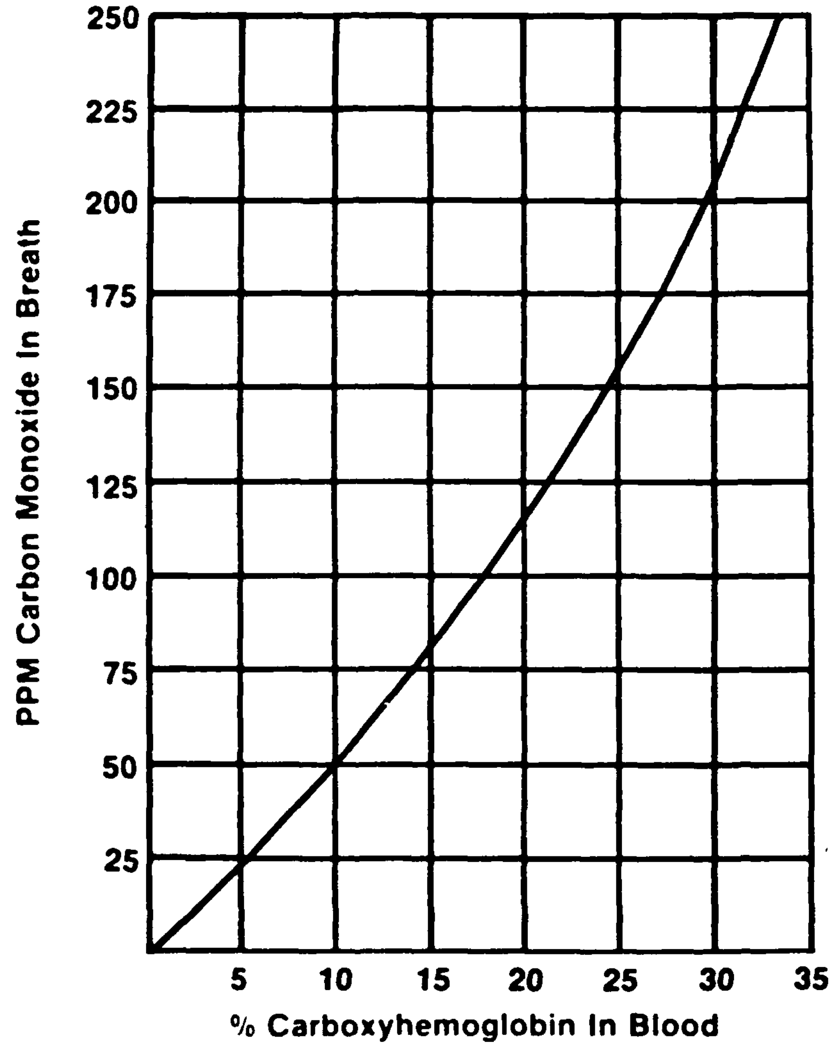

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Figure 4.

DISCUSSION

The alveolar breath technique for determining COHb would be extremely useful as a routine preventive medicine monitoring surveillance procedure. Many situations require quick and accurate COHb analysis to include: military tentage with forced air heaters, motor pool areas with poor ventilation systems, and an array of situations involving vehicles and structures where CO is generated. To date the only portable field sampling equipment for CO available within military preventive medicine are monitors that sample general and specific area air concentrations. This type of sampling specifies the amount of CO in the surrounding area and cannot identify the COHb of the affected population.

The scientific literature did not contain corrections to the alveolar breath measurement procedure for measurements made at other than sea level. The partial pressure of CO will decrease with increasing altitude. Although the gas laws could allow an estimate of the correlation factor to be applied, actual measurement of blood COHb and alveolar CO should be performed at various altitudes.

Blood samples, stationary clinical equipment, and highly trained personnel are involved in the present methods of determining COHb. The inordinate amount of time required to complete this analysis is unacceptable when human lives are considered. Death by CO pcisoning is a very real concern, and use of this alveolar breath technique could provide military preventive medicine with an effective tool to identify hazardous situations before employee health is put at risk. The alveolar breath technique is needed and its use would greatly enhance the capability of the U.S. Army Medical Department in the field of COHb determinations.

CONCLUSIONS

This method of sampling the CO content of alveolar air to determine COHb is quick, easy to administer, and accurate. Technology now allows instrumentation to be lightweight and miniaturized, thereby providing for easy transport and operation. With a CO instrument that meets or exceeds the provided specifications and the necessary accessory equipment, the procedures described in this report will enable users to conveniently and reliably measure COHb levels of personnel exposed to concentrations of CO.

RECOMMENDATIONS

1. Additional research should be performed with the alveolar breath method of determining COHb to address the effect of variations in altitude (or atmospheric pressure).

2. A lighted LED readout on the CO indicator would be convenient for night operations. This modification could be easily accomplished by the equipment manufacturer.

3. In a garrison setting a 200 cu ft (5664 liter) cylinder of calibration span gas should be used, but in a field environment a small 24 liter canister would be the most convenient.

4. The alveolar breath method of determining COHb should be incorporated into the military preventive medicine methods. This would allow better medical responses to situations where CO hazards are present or suspected. Both garrison preventive medicine sections and field preventive medicine teams would benefit from the use of this procedure.

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