Rapid Estimation of Carboxyhemoglobin Level in Fire Fighters

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- The analysis of expired breath with a portable electrochemical cell after carbon monoxide exposure provides a practical field method for the rapid estimation of carboxyhemoglobin. A fire fighter can collect and analyze his own breath sample for CO, an operation that requires 1½ minutes. This simple technique has the accuracy necessary to determine compliance with the regulations governing occupational exposure to CO.

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ORIG. CONTRIB.

OF THE occupational groups at risk of exposure to carbon monoxide, fire fighters are subjected repeatedly to the highest, most hazardous concentrations of the gas. Smoke can contain CO in concentrations of 0.1% to 10%, and a few deep breaths of it can elevate the blood carboxyhemoglobin (COHb) to levels that produce a severe hypoxic stress on the cardiovascular system (Table). The stress of this CO-induced hypoxia is further intensified when it is superimposed on the stress of maximum physical exertion, heat stress, pulmonary insult from a myriad of toxic inhalants, and possible underlying coronary heart disease. The complexity of the matter is compounded further when a fire fighter is reexposed to CO on multiple occasions during a 24-hour tour of duty, permitting the accumulation of an excessive, occasionally lethal, quantity of COHb.

Efforts to develop a suitable on-the-job method that will detect a toxic amount of COHb before a hazardous concentration has been reached have not been successful to date, to our knowledge. To prevent injury from CO and other smoke constituents, heavy reliance has been placed on the routine use of respirators. Nevertheless, over 10,000 fire fighters are overcome by toxic gases each year.

What is needed is a practical field method to determine COHb accurately and rapidly. Ideally, the analytical equipment should be portable so that it could be used at the scene of a fire. The method should also be simple enough so that it could be performed by a nonchemist technician.

This communication reports the results of a study in which fire fighters were trained to use a rapid electrochemical technique to measure the CO in their expired breath and then estimate the magnitude of their exposure to the gas.

EXPERIMENTAL METHOD

One hundred seventy fire fighters of the First Battalion, Milwaukee Fire Department, volunteered to participate in this study. Two Emergency Medical Technicians from each shift were given six hours of instruction in the collection of breath samples, sample analysis, and the interpretation of breath-CO data.

To collect the breath samples the subjects were instructed to hold their breath for 20 seconds, then discard the first portion of their expired breath and collect the last portion (alveolar) in a 5-liter Saran bag (Fig 1). The breath samples were immediately analysed in a properly calibrated breath analyzer (model 2100 Ecolyzer), a 4-kg portable instrument whose operating principle is based on the electrochemical oxidation of CO at a Teflon-bonded diffusion electrode. The elapsed time for breath sample collection and analysis averaged 1½ minutes.

To establish the breath CO-blood COHb relationship presented in Fig 2, 71 paired alveolar breath and venous blood samples were collected from 56 fire fighters for CO and COHb analysis. Thereafter, the alveolar breath CO was used to estimate blood COHb. The theoretical relationship between the amount of CO in the expired breath and the COHb in the blood shown in Fig 2 was derived as follows: The Haldane equation expresses the relationship between COHb, CO tension, oxyhemoglobin, oxygen tension, and the affinity of CO for hemoglobin (M) in a blood sample at equilibrium.

\[
\frac{\text{COHb}}{\text{O}_2\text{Hb}} = \frac{\text{M}(\text{Pco}_2)}{\text{P}_2\text{O}}
\]  

(1)

During the 20 seconds of breath holding, the tension of CO in the alveoli approximates the CO tension in the pulmonary capillaries. The oxygen tension stabilizes at approximately 80 mm Hg in Milwaukee. With this information, the Haldane equation can be solved for alveolar CO concentration in parts per million:

\[
\text{CO}_2 = \frac{\text{COHb} (\text{Pco}_2)}{\text{O}_2\text{Hb} (\text{F}_2\text{O}) (\text{M})} \times 10^4
\]  

(2)

where CO₂ is the alveolar CO in parts per million; COHb is the percentage of carboxyhemoglobin bound to oxyhemoglobin.

<table>
<thead>
<tr>
<th>Carbon Monoxide Concentration</th>
<th>Increase in Blood Carboxyhemoglobin (COHb) Level During Heavy Exertion*</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 sec</td>
<td>30 sec</td>
</tr>
<tr>
<td>1,000 ppm (0.1%)</td>
<td>0.2</td>
</tr>
<tr>
<td>10,000 ppm (1%)</td>
<td>2.5</td>
</tr>
<tr>
<td>20,000 ppm (2%)</td>
<td>5</td>
</tr>
<tr>
<td>50,000 ppm (5%)</td>
<td>12.5</td>
</tr>
<tr>
<td>100,000 ppm (10%)</td>
<td>25</td>
</tr>
</tbody>
</table>

*"Heavy exertion": Laboratory demanding alveolar ventilation rate of 30 liters/min. Blood COHb calculated as described by Stewart et al.

COHb in Fire Fighters—Stewart et al
Fig 1.—Firefighter collecting alveolar breath sample in polyethylene bag, using 20-second breath-holding technique. Second fireman analyzes breath sample with portable CO monitor. Instrument reads "50 ppm," which indicates blood-COHb saturation of 9%.

Fig 2.—After 20 seconds of breath holding, predictable relationship exists between alveolar CO and COHb. The equation for this relationship is given in text. M is affinity of hemoglobin for CO.

boxyhemoglobin saturation; O₂Hb is the percentage of oxyhemoglobin; Pₐ is the barometric pressure in millimeters of mercury; M is the affinity of hemoglobin for CO; and Pco₂ is the oxygen tension in the pulmonary capillaries in millimeters of mercury. In the calculations, M was assigned a value of 210; Pco₂, was assigned a value of 80.

The calibration of the breath analyzer was checked each day by the emergency medical technicians, using a compressed air-CO mixture. This calibration was re-checked five times a week by a technician from The Medical College of Wisconsin.

RESULTS

The emergency medical technicians were able to analyze breath samples for CO, using the breath analyzer after the three training sessions. The COHb levels after the first fire fighting episode of a 24-hour tour of duty were as follows: In 55 nonsmoking fire fighters, the mean COHb level was 5.0% (range, 1.4% to 9.1%). The five highest COHb values in this group were 7.9%, 8.4%, 8.6%, 8.6%, and 9.1%. In the remaining 56 cigarette smokers, the mean COHb level was 7.0% (range, 2.9% to 18.0%). The five highest COHb values were 10.4%, 10.7%, 11.8%, 12.4%, and 13.0%. The nonsmoking firemen had COHb saturations comparable to those of heavy cigarette smokers, while five of the cigarette smokers had COHb elevations above 10% saturation.

As an accuracy check on the breath analyzer method, the CO in a random number of breath samples was determined by gas chromatography. The average difference in the results between the two methods was 1.2 ppm over the range of 1.4 to 132 ppm, confirming the accuracy of this electrochemical method. Using the CO-
COHb relationship shown in Fig 2, the standard error of estimating COHb, given a breath CO concentration of 8 or 50 ppm, was ± 0.5% COHb saturation.

The fire fighters enthusiastically endorsed this method for estimating their COHb body burden. They quickly learned the proper breath collection procedure and did not resent spending the few minutes required to perform the COHb screening test.

**COMMENT**

There are compelling reasons why fire fighters who are exposed to potentially toxic concentrations of CO each day should be screened for the presence of elevated blood COHb each time exposure occurs. With any increase in COHb and the resultant decrease in blood oxygen-carrying capacity, there is a compensatory increase in cardiac output and a diversion of blood to those organs most sensitive to oxygen lack. Therefore, a means to detect toxic amounts of absorbed CO is required if unnecessary cardiac stress is to be prevented.

To be of greatest value, any COHb detection method employed should be available for use immediately following each exposure to CO. This permits the prompt initiation of oxygen therapy in cases of overexposure. In addition, the method should be rapid, accurate, economical, and noninvasive.

The described electrochemical breath analysis performed by the firemen themselves meets these criteria. The portability of the instrument and its self-contained power supply for eight hours of operation make possible at-the-site analyses with the frequency necessary to define the cumulative CO exposure.

While the CO-COHb relationship shown in Fig 2 should be applicable to the majority of geographical locations, a more precise CO-COHb correlation curve can be constructed using the equation given. Both barometric pressure and altitude, with their effect on the partial pressure of oxygen in the pulmonary capillaries, are important determinants.

From the standpoint of having firemen perform their own analyses, the only disadvantage of this electrochemical method is that the period of calibration checks be made. Fortunately, the linearity of the sensor response necessitates only a one-point calibration procedure. In field use this can be achieved easily each day, using a commercial compressed air-CO standard.

Sjöstrand was the first to demonstrate that COHb saturation could be estimated from alveolar CO concentration. The relationship between COHb and the magnitude of exposure was carefully set forth by Coburn, who utilized breath CO as a measure of endogenous CO production. Prior to this study, the best equation for the COHb-CO relationship was that presented by Peterson and Stewart. However, the expired breath method failed to gain in popularity because a practical field method could not be devised. Efforts to monitor individual CO exposures continued to rely on rapid blood COHb methods, none of which were ideal for use in the field. The development of a portable electrochemical cell to make Sjöstrand's CO breath measurement on samples collected, using the 20-second breath-taking technique of Jones et al, should now provide that long sought after biological test of CO exposure for all occupational groups.

The current monitoring of environmental exposure for American industry set forth in the NIOSH Criteria and Recommended Standard for Occupational Exposure to CO recommends breathing zone measurements to define average and peak exposure concentrations "at least annually" and COHb determinations only when needed to evaluate "borderline exposure." With the technology available in 1972, this was an acceptable surveillance program. However, all recognized its salient weakness: an absolute inability to detect CO overexposure in occupational groups such as fire fighters in time to effectively combat hypoxic stress. The use of the described rapid electrochemical method of breath analysis remedies this defect in the surveillance program. The quantity of CO absorbed by any workman can be determined by breath analysis performed with a frequency necessary to define the magnitude of the CO exposure.

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Jack E. Peterson, MD, suggested the use of the Ecolizer breath analyzer, and Energetics Science, Inc, Elmsford, New York, provided the Ecolizer, and the Fire Fighters of the First Battalion, Milwaukee Fire Department, volunteered to evaluate this screening test.

**References**