

FIREGROUND USE OF AN EMERGENCY ESCAPE RESPIRATOR

David C. Cone, MD, Carin M. Van Gelder, MD, Donald MacMillan, PA-C, MA, EMT-P

ABSTRACT

Introduction. Firefighters who become lost, disoriented, or trapped in a burning building may die after running out of air in their self-contained breathing apparatus (SCBA). An emergency escape device has been developed that attaches to the firefighter's mask in place of the SCBA regulator. The device filters out particulate matter and a number of hazardous components of smoke (but does not provide oxygen), providing additional time to escape after the firefighter runs out of SCBA air. **Objective.** To field-test the device under realistic fire conditions to 1) ascertain whether it provides adequate protection from carbon monoxide (CO) and 2) examine firefighters' impressions of the device and its use. **Methods.** A wood-frame house was fitted with atmospheric monitors, and levels of CO, oxygen, and hydrogen cyanide were continuously recorded. After informed consent was obtained, firefighters wearing the escape device instead of their usual SCBA regulators entered the burning structure and spent 10 minutes breathing through the device. A breath CO analyzer was used to estimate (± 3 ppm) each subject's carboxyhemoglobin level immediately upon exiting the building, vital signs and pulse oximetry were assessed, and each firefighter was asked for general impressions of the device. **Results.** Thirteen subjects were enrolled (all male, mean age

42.5 years, mean weight 94 kg). The mean peak CO level at the floor in the rooms where the subjects were located was 546 ppm, and ceiling CO measurements ranged from 679 ppm to the meters' maximum of 1,000 ppm, indicating substantial CO exposure. The firefighters' mean carboxyhemoglobin level was 1.15% (range 0.8%–2.1%) immediately after exit. All pulse oximetry readings were 95% or greater. No subject reported problems or concerns regarding the device, no symptoms suggestive of smoke inhalation or toxicity were reported, and all subjects expressed interest in carrying the device while on duty. **Conclusion.** The emergency escape device provides excellent protection from CO in realistic fire scenarios with substantial exposure to toxic gases, and the firefighters studied had a positive impression of the device and its use. **Key words:** carbon monoxide; fires; respiratory protective devices

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INTRODUCTION

Firefighters who become lost, disoriented, or trapped in a burning building are at significant risk of death due to running out of air in their self-contained breathing apparatus (SCBA). Firefighters work in immediately dangerous to life and health (IDLH) environments with high levels of hazardous gases and particulates, and breathing this toxic air for even a brief period of time can be fatal. For example, monitoring during interior structural firefighting in typical residential buildings shows significantly elevated carbon monoxide (CO) levels^{1,2} (frequently greater than 1,500 ppm³); smoke inhalation also causes exposure to dozens of other chemicals,⁴ including hydrogen cyanide (HCN),⁵ acrolein,^{1,3} formaldehyde,³ hydrogen chloride,^{1,3,6} sulfuric acid,³ benzene,⁶ and particulates.^{1,7} SCBA provides breathing air under positive pressure through a face mask, preventing inhalation of these and other toxins. However, the amount of air carried is limited and, particularly when performing strenuous physical activity, an SCBA cylinder can be depleted in 15 to 20 minutes. If the SCBA runs out of air and the firefighter is unable to escape the hazardous environment, he or she must remove the SCBA regulator from the mask and begin breathing the ambient air, often with fatal results.⁸

An emergency escape device has been developed that is placed on the firefighter's mask in place of the air cylinder regulator once the cylinder has been depleted. The device filters the ambient air, providing breathable air for up to 15 minutes, according to the manufacturer. The purpose of this study was to field-test the device under realistic fire conditions, in order

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Address correspondence and reprint requests to: David C. Cone, MD, Yale University School of Medicine, Department of Emergency Medicine, 464 Congress Avenue, New Haven, CT 06519. e-mail: david.cone@yale.edu

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to ascertain whether it provides adequate protection from CO, and to assess firefighters' impressions of the device and its use.

METHODS

Study Design

This was a prospective field trial of an emergency escape device for firefighters. Methods used were generally similar to those reported in our earlier study of threats to life in residential structure fires,⁹ with the addition of automated data logging of meter data in place of the manual data recording used in the earlier trial.

Study Setting and Population

The study was conducted at a "live burn" firefighter training exercise. A large three-story wood-frame house that was going to be demolished was the study site.

Air meters (GasAlertMicro 5, Honeywell/BW Technologies, Calgary, Alberta, Canada) were placed at various locations in the second floor of the building, to allow for monitoring of CO, oxygen (O₂), and HCN levels. These meters logged data continuously, for download to a laptop computer at the completion of the exercise. The room in which each meter was located was color-coded using paint on the entry door or window, to allow for tracking of each study firefighter (e.g., "Evolution 2, FF Smith, Blue room") and ensure that the ambient air data from the meter in the room in which each study firefighter worked could be matched to that firefighter's data.

Throughout the day, fire crews rotated through multiple live-burn evolutions, to practice fire attack, building ventilation, search and rescue, and overhaul. Each evolution involved a fire that was set in one room of the house and allowed to reach realistic proportions for a typical residential structure fire before the crews entered the building. Typical home contents were used as fire fuel, including mattresses, bedding, dressers full of clothes, computers, and plastic toys. A total of six evolutions were run, each taking approximately 45 minutes.

The study firefighters were all members of career fire departments, from California, Connecticut, Indiana, Maryland, Michigan, New Jersey, New York, and Texas. Demographic data collected on the study firefighters included sex, age, smoking history, and, for smokers, time of last cigarette. Breath CO levels were collected with a breath CO analyzer (The COB, FSP Instruments, Inc., Hoboken, NJ) to estimate (± 3 ppm) baseline carboxyhemoglobin (COHb) levels on all study firefighters shortly before the first burn evolution was begun, and baseline vital signs were also collected.

Study Protocol

The emergency escape device (Last Chance Rescue Filter, Essex PB&R Corp., St. Louis, MO) is a cylindrical, 3 × 5-inch filter cartridge that attaches to the firefighter's face mask, in place of the SCBA regulator. The device uses a combination of mechanical filtering and catalytic surfaces to remove components of smoke from the air. The first stage is a 0.5- μ m N95 mechanical filter, the second stage is an activated charcoal filter, and the third stage is a catalytic surface that converts CO to carbon dioxide (CO₂). The manufacturer provides test data on its Web site (www.lastchancefilter.com) indicating adequate protection from CO₂, HCN, hydrogen sulfide, sulfur dioxide, and acrolein.

Study firefighters (one to four per evolution) each wore an emergency escape device instead of their usual SCBA regulators. A safety crew of two firefighters using SCBA accompanied each study firefighter into the building and remained with that study firefighter throughout the evolution. Another safety firefighter on SCBA remained at the door or window through which each study firefighter entered, to assist with his escape from the building if necessary. All firefighters, including the incident commander, safety officer, and researchers (DCC, CMVG) were in radio contact at all times, and all wore their standard full personal protective equipment (helmet, hood, jacket, gloves, pants, and boots). The safety firefighters did not have fire attack/suppression, ventilation, search/rescue, or overhaul roles; their only assignment was to ensure the safety of the study firefighter. All participating firefighters, including the other crews working each evolution, were aware of the study and the need to help ensure the safety of the study firefighters. Each study firefighter wore his usual SCBA, and could replace the emergency escape device with the SCBA regulator and breathe cylinder air if an emergency arose, such as becoming trapped in debris in the building.

In the first evolution, the study firefighter entered the building with his regular SCBA regulator in place, and changed over to the escape device to evaluate the ease of making this change-over. In the subsequent evolution, each study firefighter entered the building wearing the emergency escape device and immediately moved to the area of the live fire (either the fire room itself, the hallway just outside the fire room, or another nearby area), to ensure exposure to realistic heat and air conditions. In four evolutions, the study firefighter simply remained in the fire area; in the remaining evolutions, the study firefighter performed light to strenuous work (such as crawling or chopping holes in the wall with an axe) to simulate the heavy physical activity of a trapped firefighter attempting to escape a burning building.

The incident commander, using a digital stopwatch, ordered the study firefighters out of the building

exactly 10 minutes after entry. The study firefighters proceeded directly to the rehabilitation area, approximately 25 feet from the building, where each subject's COHb level and pulse oximetry were immediately (within 30 seconds after exiting the building) measured by the study investigators, before any gear was removed. A set of vital signs was also recorded for each study firefighter, and each subject was asked for general impressions of the device in an unstructured manner, as well as for information about what he did during the 10 minutes in the burning building.

Analytical Methods

Data were downloaded from the meters into an Excel (Microsoft Corp., Redmond, WA) spreadsheet at the conclusion of the exercise (after all evolutions were complete) and matched to the study firefighter by evolution number and room color. Simple descriptive statistics were used to analyze the data.

Human Subject Committee Review

The Yale University Human Investigative Committee approved this study. Written informed consent was obtained from all participants prior to data collection.

RESULTS

Fifteen emergency escape devices were supplied by the manufacturer, but the integrity of the packaging of two had been compromised; these two were not used. Thirteen subjects were thus enrolled, with the following demographic characteristics: all were male, their mean age was 42.5 years (range 33–54 years), and their mean weight was 94 kg (range 73–132 kg).

Data from the building monitoring meters are shown in Table 1. The mean peak CO level at the floor in the rooms where the subjects were located was 546 ppm. Ceiling measurements ranged from 769 ppm to the meters' maximum of 1,000 ppm, indicating substantial CO exposure. Several ceiling measurements were lost because of melted sampling tubing. Simultaneous O₂ measurements showed mean minimum ceiling levels of 13.2%, whereas HCN measurements showed mean peak ceiling levels of 20.8 ppm, with a maximum reading of meter's maximum of 30 ppm.

The study firefighters' mean estimated blood COHb level was 1.15% (range 0.8%–2.1%) immediately after exit. Table 2 shows each firefighter's baseline and postevolution COHb level, postevolution pulse oximetry, vital signs, and activities during the evolution. The mean increase in heart rate was 46 bpm, suggesting that the firefighters were under significant cardiovascular stress during the evolutions. All pulse oximetry readings were 95% or greater.

Firefighter impressions of the device were positive. Two of the 13 reported that breathing through the device (which requires generating a negative pressure)

felt different from breathing on an SCBA mask (which involves positive pressure), but both reported that they adjusted to this very quickly, and that it did not interfere with their activities or distract them. No firefighter reported any problems or concerns with the device, and all 13 indicated that they would want to carry one at all times when working.

DISCUSSION

Public safety providers of all types (emergency medical services [EMS], fire, and police) work in environments with a variety of hazards, and much attention has been focused on improving provider safety while on the job. Firefighter deaths (100 annually) and injury/illness (50,000–100,000 cases annually) while in the line of duty are most commonly associated with responding to and returning from calls, physical training, and fireground activities. Almost half of firefighter line-of-duty deaths (LODDs) from 1995 to 2004 were due to sudden cardiac death.¹⁰ Health (fitness/wellness) (54%), personal protective equipment (PPE) (19%), and human error (19%) constitute the major contributing factors to LODDs.¹¹ Actual fire suppression accounts for only 1% to 5% of firefighter activities, but creates the highest risk of death from coronary disease.¹² In more than 40% of LODDs, firefighters who died from coronary heart disease were smokers.¹³

The National Institute for Occupational Safety and Health (NIOSH) specifically targets smoke exposure in recommending that fire departments "control exposure to carbon monoxide and other fire contaminants through proper management of the fire scene and proper use of respiratory protection"¹⁴ during fire suppression and training. The National Fire Protection Association regularly updates standards (NFPA 1404, 1500) regarding the use of respiratory protection.^{15,16}

Despite nearly universal use of SCBA during fire attack and most other "interior" operations, firefighters still occasionally sustain exposure to smoke and CO.² In 2006, for example, 4,330 cases of firefighter smoke or gas inhalation or respiratory distress were reported¹⁷; undoubtedly many others were not reported. Elevated levels of CO have been seen in firefighters who remove their SCBA during overhaul before air monitoring confirms that the air is safe to breathe.^{2,18} This premature removal of SCBA is a particularly common and well-known problem,^{3,19} despite longstanding Occupational and Safety Health Administration (OSHA) regulations prohibiting the removal of SCBA while still in a hazardous environment²⁰ and national standards requiring air monitoring prior to removing SCBA.¹⁶ In addition to CO, other toxins are present during overhaul that can similarly endanger firefighters who do not wear their SCBA.²¹ A firefighter who becomes trapped during overhaul, perhaps by the

TABLE 1. Room Data

| FF | Evolution | CO (ppm) (Floor) | | | CO (ppm) (Ceiling) | | | O ₂ (%) (Floor) | | | O ₂ (%) (Ceiling) | | | HCN (ppm) (Floor) | | | HCN (ppm) (Ceiling) | | |
|----|-----------|------------------|--------------|--------------|--------------------|--------------|--------------|----------------------------|------|------|------------------------------|------|------|-------------------|------|-----------|---------------------|-----------|-----------|
| | | In | Out | Peak | In | Out | Peak | In | Out | Low | In | Out | Low | In | Out | Peak | In | Out | Peak |
| 1 | 1 | 0 | 1,000 | 1,000 | NR | NR | NR | 20.9 | 20.1 | 19.5 | NR | NR | NR | 0 | 17.8 | 30 | NR | NR | NR |
| 2 | 1 | 982 | 44 | 982 | NR | NR | NR | 20.3 | 20.9 | 20.2 | NR | NR | NR | 25 | 1 | 25 | NR | NR | NR |
| 3 | 2 | 283 | 77 | 283 | NR | NR | NR | 20.6 | 20.9 | 20.9 | 20.9 | 20.4 | 12.4 | 5 | 0 | 5 | 0 | 0.5 | 28.4 |
| 4 | 2 | 177 | 64 | 432 | 1,000 | 1,000 | 1,000 | 20.9 | 20.9 | 20.5 | 16.3 | 19.6 | 9.1 | 2.7 | 0 | 3.6 | 15 | 7.3 | 30 |
| 5 | 2 | 177 | 64 | 432 | 1,000 | 1,000 | 1,000 | 20.9 | 20.9 | 20.5 | 16.3 | 19.6 | 9.1 | 2.7 | 0 | 3.6 | 15 | 7.3 | 30 |
| 6 | 2 | 283 | 37 | 283 | NR | NR | NR | 20.6 | 20.9 | 20.6 | 20.9 | 20.4 | 12.4 | 5 | 0 | 5 | 0 | 0.5 | 28.3 |
| 7 | 3 | 1,000 | 22 | 1,000 | NR | NR | NR | 20.3 | 20.9 | 20.2 | 14.5 | 8.7 | 8.7 | 18 | 0 | 18 | 30 | 30 | 30 |
| 8 | 3 | 22 | 50 | 585 | 1,000 | 947 | 1,000 | 20.9 | 20.9 | 20.9 | 19.3 | 19.5 | 19.2 | 0 | 0 | 4.6 | 3.4 | 2.7 | 6 |
| 9 | 3 | 1,000 | 22 | 1,000 | NR | NR | NR | 20.3 | 20.9 | 20.2 | 14.5 | 8.7 | 8.7 | 18 | 0 | 18 | 30 | 30 | 30 |
| 10 | 4 | 23 | 25 | 38 | 762 | 691 | 679 | 20.9 | 20.9 | 20.9 | 19.8 | 19.9 | 19.8 | 0 | 0 | 0 | 1.7 | 1.3 | 2.2 |
| 11 | 4 | 24 | 8 | 28 | NR | NR | NR | 20.9 | 20.9 | 20.9 | NR | NR | NR | 0 | 0 | 0 | NR | NR | NR |
| 12 | 4 | 23 | 25 | 38 | 762 | 691 | 679 | 20.9 | 20.9 | 20.9 | 19.8 | 19.9 | 19.8 | 0 | 0 | 0 | 1.7 | 1.3 | 2.2 |
| 13 | 5 | 1,000 | 266 | 1,000 | NR | NR | NR | 20.2 | 20.4 | 19.0 | NR | NR | NR | 19 | 3 | 30 | NR | NR | NR |

In = reading at the time of firefighter entry; out = reading at the time of firefighter exit.

Numbers in **boldface** represent the meters' maximum.

CO = carbon monoxide; FF = firefighter; HCN = hydrogen cyanide; NR = no reading (melted air sampling tubing); O₂ = oxygen.

collapse of a wall or ceiling that the firefighter is "pulling" to look for hidden fire, may be exposed to a toxic atmosphere even though the bulk of the fire has been extinguished.

Amounts and types of toxic gases and particulate matter in smoke vary widely, but several are known to have cardiovascular effects and potentially cause cardiac ischemia. Specifically, moderate to severe CO exposure causes significant cardiac morbidity and mortality.^{22,23} One study found that in 24% of firefighter deaths where CO levels could be determined, they were elevated.¹³ Carbon monoxide levels measured at the hospital or in the postmortem stage are often lower than true field levels because of removal of

the victim to ambient air and treatment with O₂.^{13,24} A highly publicized 2007 article showed that in patients with known coronary artery disease, exposure to dilute diesel fuel exhaust induces myocardial ischemia, producing ST-segment depression.²⁵ Diesel exhaust contains particulate matter and CO, which may contribute to ischemia in several ways. Particulate matter induces oxidative injury and inflammation and may contribute to the development of atherosclerosis.²⁶

Our data demonstrate that under realistic IDLH conditions, the emergency escape device offers firefighters excellent protection against CO, while not impeding their ability to perform physical activity, as would be needed to escape a burning structure after running

TABLE 2. Firefighter Physiologic Data

| FF | Weight (lb) | Evolution | COHb (%) | | Pulse Oximetry (%) | Heart Rate (bpm) | | Blood Pressure (mmHg) | | Respiratory Rate (breaths/min) | | Activity during Evolution |
|----|-------------|-----------|----------|------|--------------------|------------------|------|-----------------------|--------|--------------------------------|------|------------------------------------|
| | | | Pre | Post | Post | Pre | Post | Pre | Post | Pre | Post | |
| 1 | 200 | 1 | 0.6 | 0.8 | 96 | 88 | 124 | 148/90 | 150/82 | 20 | 32 | Crawling, sitting, breaking window |
| 2 | 160 | 1 | 0 | 1.0 | 98 | 104 | 120 | 150/88 | 152/88 | 16 | 24 | Sitting |
| 3 | 210 | 2 | 0.6 | 2.1 | 99 | 84 | 120 | 116/86 | 152/78 | 12 | 20 | Moving between rooms |
| 4 | 290 | 2 | 0.6 | 0.8 | 97 | 72 | 98 | 128/88 | 170/78 | 20 | 20 | Sitting |
| 5 | 165 | 2 | 0.8 | 1.5 | 96 | 80 | 100 | 138/84 | 154/94 | 16 | 12 | Sitting |
| 6 | 230 | 2 | 0.6 | 1.8 | 97 | 88 | 130 | 148/82 | 138/90 | 20 | 16 | Sitting |
| 7 | 180 | 3 | 0.6 | 1.5 | 95 | 76 | 150 | 160/88 | 158/86 | 20 | 24 | Walking upright |
| 8 | 218 | 3 | 0.6 | 0.8 | 100 | 80 | 139 | 116/84 | 122/88 | 20 | 20 | Moving around |
| 9 | 215 | 3 | 0.8 | 0.8 | 96 | 80 | 150 | 142/82 | 132/92 | 20 | 24 | Chopping walls with axe |
| 10 | 238 | 4 | 0.8 | 0.8 | 95 | 72 | 139 | 136/86 | 168/80 | 16 | 20 | Sitting, breaking window |
| 11 | 210 | 4 | 0.8 | 1.0 | 98 | 72 | 113 | 142/74 | 160/82 | 20 | 20 | Doing push-ups |
| 12 | 190 | 4 | 0.6 | 0.8 | 98 | 88 | 139 | 140/78 | 162/78 | 16 | 24 | Walking upright |
| 13 | 200 | 5 | 0.6 | 1.3 | 96 | 68 | 122 | 126/88 | 156/94 | 16 | 24 | Crawling, sitting |

Pre = baseline readings taken at the start of the day; post = reading taken immediately after the firefighter exited the burning building.

COHb = carboxyhemoglobin; FF = firefighter.

out of SCBA air. In order to be of use in the rare and unanticipated out-of-air scenario, a firefighter would need to carry the device in his or her gear at all times. While the manufacturer reports a shelf life of 5.5 years, the fact that two of our 15 test units had compromised packaging raises the concern that carrying the device every day may necessitate frequent inspections of the packaging.

It is also extremely important to note that this device does not supply O₂; it simply filters the ambient air through a combination of mechanical filtering and catalytic devices. Hence, a firefighter breathing through this device in an O₂-depleted atmosphere will not be protected from this aspect of the IDLH environment.^{24,27} EMS personnel treating firefighters rescued after use of this device should consider the possibility of exposure to an O₂-deficient breathing atmosphere.

LIMITATIONS

There are two primary limitations to this study. First, only COHb was measured. The ability of the respirator to protect firefighters from other toxins was not tested because of the lack of noninvasive, portable monitoring devices. The manufacturer reports that the device provides adequate protection from acrolein, HCN, and hydrogen chloride, but we were unable to test this. The manufacturer of the breath CO analyzer reports that noninvasive HCN monitoring will be available shortly, which will allow for studies assessing the ability of this device and others to protect from HCN. Aside from elevated heart rate, which is likely attributable to the work performed, we can report that no subjects reported signs or symptoms suggestive of toxicity with any of the other agents that the device is designed to filter.

Second, the number of subjects enrolled was limited by the number of respirators available, and by the 10-minute limit established as a safety factor. The manufacturer reports that the devices provide adequate filtering for 15 minutes, but it did not seem prudent to test the device to the failure point.

Two other limitations bear mentioning. Because of the nature of the abandoned building, O₂ levels during the fires may not have been as low as might be seen in an actual structure fire. Also, we were unable to record the temperature of the air inhaled through the escape device; however, no subjects reported problems with excessively hot inspired air.

CONCLUSIONS

The emergency escape device provides excellent protection from CO in realistic fire conditions with substantial exposure to toxic gases, and the firefighters

studied had a positive impression of the device and its use. Additional testing to confirm adequate protection from other components of smoke would be helpful.

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