

Effects of a Nosecup on Inspired Carbon Dioxide Concentration and Service Time in Selected Open-Circuit Self-Contained Breathing Apparatus

Nina Turner, David Beeckman, and Thomas Hodous

National Institute for Occupational Safety and Health,
Division of Safety Research,
944 Chestnut Ridge Road,
Morgantown, West Virginia 26505

Abstract

The effect of nose cups on respirator performance in three National Fire Protection Association-compliant 60-minute open-circuit positive-pressure self-contained breathing apparatus (SCBA) was investigated. Six men performed a continuous, variable work rate treadmill protocol which consisted of three exercise periods of 5 minutes at a high intensity work rate, 15 minutes at a moderate work rate, and 10 minutes at a low work rate while wearing an SCBA without a facepiece. Average oxygen consumption ($\dot{V}_{O_2}$), minute ventilation ($\dot{V}_E$), and expired peak flow (PF_E) were 338 ± 0.13 , 79.1 ± 10.6 , and 254.4 ± 29.1 for the high intensity work rate; 2.21 ± 0.09 , 48.7 ± 5.1 , and 182.4 ± 36.3 for the moderate work rate; and 1.00 ± 0.09 , 25.8 ± 7.2 , and 113.6 ± 32.4 for the low work rate, respectively (all units $L \cdot \text{min}^{-1}$, STPD, and mean $\pm$ S.D.). The same exercise tests were then performed with subjects wearing three different model SCBAs with and without a nosecup. Time to alarm, minimum and average inspired CO_2 concentration, tidal volume, and breathing frequency were measured for each test. Time to alarm was significantly reduced without versus with a nosecup [30.0 min (without) versus 34.1 min (with), $p < 0.05$]. Minimum and average inspired CO_2 concentrations, as well as the volume of reinspired CO_2 , were significantly greater without a nosecup than with a nosecup across all work rates ($p < 0.005$). Inspired minute volume was significantly greater ($p < 0.05$) without a nosecup ($86.6 \pm 12.5 L \cdot \text{min}^{-1}$) than with ($76.5 \pm 12.7 L \cdot \text{min}^{-1}$) during the high intensity work rate but not during the moderate or low intensity work rate. These findings may have significant implications regarding nosecup use and testing conditions for those involved in updating NFPA fire service SCBA regulations.

Introduction

Open-circuit self-contained breathing apparatus (SCBAs) used in the fire service have been reported to have air cylinder service times that vary inversely with the volume of facepiece dead space (Raven, 1989). This concern has received enough attention that in 1989, a subcommittee of the National Fire Protection Association (NFPA) considered proposing legislation which would require the mandatory use of a noseclip with all respirator facepieces used by the fire service. The proposal was based on manufacturers' promotional literature claiming increases in service time of 25% using a noseclip, anecdotal evidence from users, and several studies which have demonstrated dead space-induced increases in ventilation; however, the actual magnitude of the effects of noseclips is not known. The objective of this study was to quantify the effect of a noseclip on inspired CO₂ concentration, ventilation, and service time in three different manufacturers' NFPA-approved SCBAs.

The effects of dead space on physiological variables were recognized as early as 1948 (Stannard and Russ, 1948) and were addressed again in an early NIOSH document (James, 1971). As facepiece dead space increases, the concentration of inspired CO₂ and volume of re-inspired CO₂ both increase. Most of the research in this area has not been performed on actual SCBAs; dead space or inspired CO₂ concentrations have been experimentally increased in order to simulate wearing an SCBA facepiece. Warkander (1988) summarized data from four such studies (Bartlett et al., 1972; Clark et al., 1980; Jones et al., 1971; Kelman and Watson, 1973) and found that for each liter of added dead space, ventilation may be expected to be increased an average of 53%. He

concluded that ventilatory demand can be predicted to increase 10 to 40% with commercially available breathing devices (dust masks to full facepiece), with a corresponding reduction in air cylinder service time for SCBAs.

Only one study (Raven, 1989) investigated one full facepiece and noseclip combination using fire fighters and measured inspired CO₂, service time, and ventilation. Minute ventilation, inspired CO₂ concentration and volume of re-inspired CO₂ with a noseclip were significantly lower across all work rates. Service time was improved by as little as 7.9% (1 minute) and as much as 11.4% (2 minutes). Raven stated that this was far lower than the improvements predicted with noseclips in some SCBA manufacturers' promotional literature.

Both Raven's study (1989) and the present study used the method of Dahlback et al. (1987) to determine re-inspired CO₂ concentrations and dead space volumes. This method employs a modification of the Bohr equation, where dead space (V_{DS}) multiplied by end tidal CO₂ ($F_A CO_2$) equals inspired tidal volume (V_{TI}) multiplied by the inspired fraction of CO₂ ($F_I CO_2$), and the product is equal to the volume of re-inspired CO₂ ($V_I CO_2$):

$$V_{DS} \cdot F_A CO_2 = V_{TI} \cdot F_I CO_2 = V_I CO_2$$

The present study investigated several open-circuit SCBAs commonly used by the fire service with and without a noseclip to discover if the findings of Raven hold for these devices.

Materials and Methods

The subjects for this study were six nonsmoking men between the ages of 18 and 35 years. Two were experienced SCBA users, and four were inexperienced.

Prior to inclusion in the study, all subjects signed a consent form, completed a medical history questionnaire, and received a resting 12-lead electrocardiograph and spirometry. Each subject also completed a graded exercise test on a treadmill using a modified Balke protocol (Balke and Ware, 1959). Maximum aerobic capacity was determined by

measuring maximum oxygen consumption ($\dot{V}O_{2max}$) using an MMC Horizon, Advanced Exercise System 5, metabolic cart (SensorMedics, Yorba Linda, CA).

Following these screening procedures, subjects were placed into one of three body weight categories. The rationale for these body weight categories and the energy expenditures for the variable work rate protocol is described in a previous study (Turner et al., 1995). The treadmill speed and grade combinations for the variable work rate protocol are presented by body weight group in Table 1. Subject

characteristics are shown by body weight group in Table 2.

SCBAs selected for this study consisted of three different manufacturers' National Fire Protection Association-compliant 60-minute open-circuit positive pressure SCBA. Only SCBAs which are certified by NIOSH to be used either with or without a noseclip were tested. Relevant open-circuit SCBA performance variables were continuously monitored; data were sampled at 60 Hz and logged by a Hewlett-Packard Vectra QS-20 IBM-compatible computer. Inspired dry bulb temperatures were measured using a fast-response Type T copper-constantan thermocouple. Inspired and expired pressures were measured using a Validyne differential pressure transducer and carrier demodulator (Northridge, CA). Tidal volumes and flow rates were measured and calculated, respectively, using a Sensormedics Ventilation Measurements Module turbine (Yorba Linda, CA). Inspired CO₂ and O₂ concentrations were measured by Ametek CD-3 and S-3A/II analyzers, respectively (Pittsburgh, PA). All exercise was performed on a Quinton 645 programmable treadmill (Seattle, WA).

Instrumentation of each SCBA was accomplished by drilling small holes in the facepiece lens and noseclip, as pictured in Figure 1. The gas sampling line was placed in the center, so that the tip of the line was approximately 1 cm from the tip of the nose for both the with and without noseclip (NC) conditions. The temperature/pressure line and the sample return line were placed 2 cm on either side of the gas sample line. The turbine volume transducer was

inserted into the breathing hose at the point where the facepiece attached to the hose. The dead space of the turbine was approximately 75 ml, and the diameter of the turbine casing (2.5 cm) was identical to that of the breathing hose for each SCBA.

There are three distinct measurements of inspired gas concentration which can be made during the human subject testing of respirators: (1) minimum inspired, (2) maximum inspired, and (3) average inspired concentration. However, measurement of the first two quantities does not reveal the actual concentration inhaled by the user because it fails to take into account apparatus dead space. The measurement of average inspired gas concentration does take apparatus dead space into account but requires more instrumentation and modification to the apparatus being tested. Instantaneous inspired flow rates are required for the accurate measurement of average inspired gas concentrations and may only be obtained through insertion of a flow measurement device into the breathing line of the SCBA. Both flow-weighted and time-weighted average inspired CO₂ concentrations were measured in the current study; however, the flow-weighted concentrations were found to be inaccurate due to respirator-induced variations in turbine response time and therefore will not be reported.

Each subject performed the variable work rate test first wearing only the Model A SCBA harness and cylinder (control test) and then while wearing one of three different fire service SCBA with and without a noseclip, for a total of six respirator tests. Test order was randomized for each subject. Test

Table 1. Durations and treadmill speed and grade combinations for the variable work rate protocol by body weight group.

Body Weight Group (kg)	Target Work Rate ^A					
	3.0 L • min ⁻¹ (5 min)		2.0 L • min ⁻¹ (15 min)		0.5 L • min ⁻¹ (10 min) ^B	
	Speed Grade		Speed Grade		Speed Grade	
	(mph)	(%)	(mph)	(%)	(mph)	(%)
80-86.5	3.5	13.5	3.5	6.5	2.0	0.0
87-92.5	3.5	12.0	3.5	5.5	2.0	0.0
93-100	3.5	11.0	3.5	4.5	2.0	0.0

^A Oxygen consumption

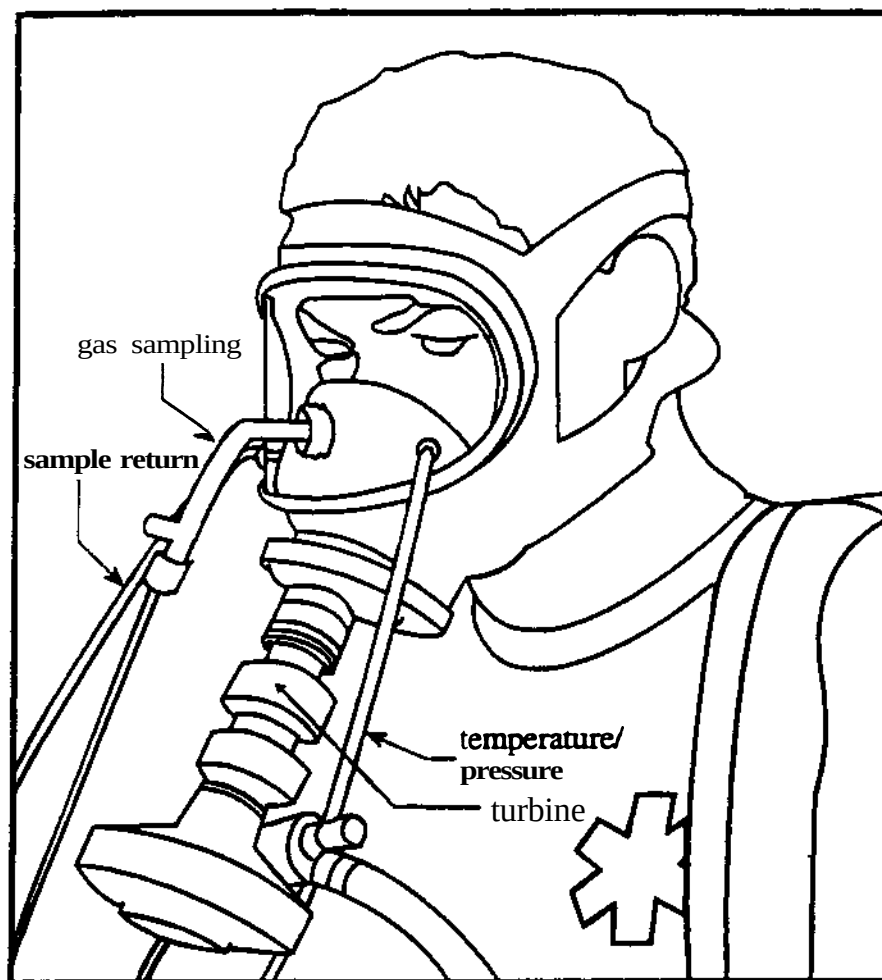
^B Repeat the 30-minute protocol for a 60-minute apparatus

Table 2. Mean and S.D. of subject characteristics (n=6).

Body Weight Group (kg)	Age (yrs)	Ht (cm)	Wt (kg)	$\dot{V}O_{2\max}^A$ (ml · kg ⁻¹ · min ⁻¹)	$\dot{V}_{E\max}^B$ (L · min ⁻¹)
80–86.5 (n = 2)	27.0 ±9.9	184.0 ±1.3	80.1 ±0.8	51.5 ±2.4	129.1 ±2.6
87–92.5 (n = 2)	21.5 ±2.1	184.0 ±5.7	90.0 ±2.7	45.5 ±0.3	111.6 14.1
93–100 (n = 2)	31.0 ±1.4	188.0 ±4.2	99.2 ±4.0	42.2 ±2.2	98.1 ±7.6

^A Maximum oxygen consumption (STPD)

^B Maximum minute ventilation (STPD)

**Figure 1. SCBA facepiece and nosecup instrumentation.**

duration was measured as the time to the sounding of the first-stage regulator **alarm**, and the same regulator was used within each SCBA model. The amount of air remaining in each cylinder at the time of alarm was recorded.

Data were collected using custom software that phased the various signals into a breathing waveform, located minimum and maximum values, and calculated average inspired gas concentrations by integration versus flow rates. Five to fifteen breaths

were obtained for each minute, and minute averages were calculated and stored. Representative CO₂ curves were also obtained using a high-speed chart recorder for later analysis. Data from the last two minutes of each work period were used in the analysis. Data were analyzed using a 2-way analysis of variance (ANOVA) with repeated measures (SCBA Model by Nosecup). Multiple comparisons were made using the Student-Newman-Keuls test (SigmaStat, San Rafael, CA).

Results

The results of the 30-minute control test (SCBA cylinder, no **facepiece**) are presented in Table 3 by body weight group. The observed V_{O₂} values are slightly greater than the target values because of the additional weight of the SCBA (approximately 17 kg). The absolute V_{O₂} and V_{CO₂} were identical among the three body weight groups. These energy expenditures represent 82, 54, and 24% of all subjects' V_{O₂} max for the high, moderate, and low intensity work rates, respectively. While there was greater variability in minute ventilation (V_E) among the three body weight groups, overall test time-weighted averages of V_E were quite similar (44.7, 48.6, and 44.3 L • min⁻¹ for the lightest to the heaviest body weight group, respectively). Expired tidal volume (VTE) and peak expiratory flows (PFE) for the control test are also shown in Table 3.

The time to alarm data collected during the variable work rate protocol when three different SCBA models were worn without and with a **nosecup** are presented in Table 4. Time to alarm was measured as the first sounding of the first-stage regulator alarm. These alarms were found to be very consistent; the means and standard deviations of the cylinder pressure remaining at the time of alarm for models A, B, and C were 1160 ± 40, 1075 ± 60, and 1170 ± 40 psi, respectively. Mean cylinder pressure at the time of alarm was not significantly different across SCBA models for the without NC condition (1133.3 ± 59.4 psi) as compared to the with NC condition (1127.8 ± 73.2 psi). Time to alarm was

significantly greater with a nose cup than without (p < 0.05). SCBA model B showed the smallest increase in time to alarm (7.5%), and the average increase across all three SCBA models was 4.1 min, or 14.0%.

Physiological data from the variable work rate protocol when three different SCBAs were worn with and without a nose cup are shown in Table 5. Inspired minute ventilation (V_I, STPD) was significantly reduced (p < 0.05) with the use of a nose cup for the high intensity work rate but not for the moderate or low intensity work rate. Both minimum and average inspired CO₂ concentrations were significantly lower (p < 0.005) with a nose cup across all work rates, as was the volume of re-inspired CO₂ per breath. There were no statistically significant differences in either inspired tidal volume (V_{TI}, STPD) or breathing frequency between the with and without nose cup conditions.

In order to explore the differences in V_I more thoroughly, data for every five minutes were graphed versus time for the with and without NC conditions (Figure 2), and a separate repeated measures ANOVA was performed. Significant differences in V_I were observed for minutes 5 and 20. Areas under the two curves were calculated in order to estimate the total amount of air used (SigmaPlot, San Rafael, CA) and equaled 1701 and 1663 liters for the with and without NC conditions, respectively.

Discussion

The results of the current study, although they were obtained using a variable work rate protocol, can be compared with those of Raven (1989). In that

study, inspired CO₂ during exercise while using a nose cup declined 0.87% (2.08% to 1.21%) at 40 L • min⁻¹, and 0.61% (1.43% to 0.82%) at

Table 3. Mean and S.D. of control data for the variable work rate protocol by body weight group (n=6).

Target $\dot{V}_{O_2}$ (L • min ⁻¹)	Observed $\dot{V}_{O_2}$ (L • min ⁻¹)	$\dot{V}_{CO_2}$ ^A (L • min ⁻¹)	$\dot{V}_E$ ^B (L • min ⁻¹)	$\dot{V}_{TE}$ ^C (L)	P_{FE} ^D (L • min ⁻¹)
80–86.5 kg (n=2)					
3.0	3.3 ±0.2	3.7 ±0.4	80.8 ±13.6	2.2 ±0.1	285.6 ±57.7
2.0	2.2 ±0.1	2.0 ±0.1	47.7 ±8.5	1.4 ±0.1	211.2 ±33.9
0.5	0.9 ±0.1	0.8 ±0.1	22.2 ±2.6	0.8 ±0.1	112.8 ±30.6
87–92.5 kg (n=2)					
3.0	3.3 ±0.1	3.6 ±0.1	76.6 ±5.5	2.1 ±0.1	249.6 ±6.8
2.0	2.3 ±0.1	2.1 ±0.1	51.0 ±6.1	1.3 ±0.1	194.4 ±3.4
0.5	1.0 ±0.1	1.0 ±0.2	31.0 ±12.6	0.9 ±0.1	146.4 ±10.2
93–100 kg (n=2)					
3.0	3.5 ±0.2	3.5 ±0.1	75.4 ±1.0	2.8 ±0.4	228.0 ±23.8
2.0	2.2 ±0.1	1.9 ±0.1	47.4 ±1.0	1.7 ±0.1	141.6 ±10.2
0.5	1.0 ±0.1	0.9 ±0.1	24.2 ±1.1	1.0 ±0.1	81.6 ±6.8

^A CO₂ production (STPD)^B Minute ventilation (STPD)^C Expired tidal volume (STPD)^D Peak expiratory flow rate (STPD)**Table 4. Time to alarm (Mean and S.D.) for the variable work rate protocol by respirator model without and with a noseclip (NC).**

SCBA Model	Time to Alarm (min)		
	Without NC	With NC	% Increase
A	28.4 ±5.4	33.6* ±3.8	18.3
B	30.5 ±6.0	32.8* ±5.8	7.5
C	31.0 ±6.0	36.0* ±4.9	16.1

* With NC time significantly greater than Without NC (p<0.05)

Table 5. Mean and S.D. of respirator data for the variable work rate protocol by work rate without and with a nose cup (NC).

Variable	High Intensity		Moderate Intensity		Low Intensity	
	Without NC	With NC	Without NC	With NC	Without NC	With NC
$V_{IA} (L \cdot \min^{-1})$	86.6 ±12.5	76.5* ±12.7	59.6 ±6.8	53.8 ±6.6	32.8 ±6.8	30.3 ±7.5
$F_{ICO_{2min}}^B$ (%)	0.25 ±0.06	0.04** ±0.02	0.58 ±0.10	0.07** ±0.02	1.17 ±0.13	0.18** ±0.04
$F_{ICO_{2ave}}^C$ (%)	2.00 ±0.44	1.30** ±0.32	2.11 ±0.43	1.27** ±0.28	2.24 ±0.38	1.38** ±0.31
$V_{ICO_2}^D$ (ml · breath ⁻¹)	59.9 ±16.5	36.5** ±7.5	48.2 ±15.2	27.1** ±4.8	33.6 ±7.3	18.4** ±3.7
V_T^E (liters)	3.0 ±0.5	2.9 ±0.5	2.3 ±0.6	2.2 ±0.5	1.5 ±0.2	1.3 ±0.2
Frequency (breaths · min ⁻¹)	29.6 ±5.8	27.2 ±5.0	27.2 ±5.0	25.6 ±5.8	21.9 ±3.5	22.8 ±6.2

* With NC significantly lower than Without NC ($p < 0.05$)

** With NC significantly lower than Without NC ($p < 0.005$)

A Inspired minute ventilation (STPD)

B Minimum inspired CO₂ concentration (± standard error of mean)

C Average inspired CO₂ concentration

D Volume of re-inspired CO₂ (STPD)

E Inspired tidal volume (STPD)

80 L · min⁻¹. The study found that with a nose cup the group-averaged air bottle service time increased 2.0 minutes (11.4%) at a minute ventilation of 40 L · min⁻¹, 1.0 minute (7.9%) at 60 L · min⁻¹, and 1.0 minute (10%) at 80 L · min⁻¹. In contrast, the current study demonstrated an average improvement of 14.0%, or 4.1 minutes for a test of 30 minutes duration, across three different manufacturers' SCBAs.

In addition, Raven (1989) calculated a quantity described as "total air saved," which was equal to the difference in mean $\dot{V}_E$ (without versus with NC) multiplied by the service time obtained when using a nose cup. When the total volume of air used in the current study was divided by the time to alarm, mean minute ventilations for the entire test were 55.4 and 49.9 L · min⁻¹ for the without and with NC conditions, respectively. Therefore, the quantity "total air saved" across all three SCBAs was calculated to be approximately 188 liters when a nose cup was used for the current variable work rate protocol.

Current NIOSH respirator certification testing requires that inspired CO₂ concentrations in open-circuit SCBAs will be measured during a breathing machine test at a minute ventilation of 10.5 L · min⁻¹ (NIOSH, 1995, 42CFR Part 84.97). The reason for this choice of ventilation, stated in a report by the U.S. Bureau of Mines (Kloos and Lamonica, 1966), is as follows:

Since dead-space air is a fixed volume, an increase in tidal volume will dilute the CO₂ in the dead space and give a lower average concentration of CO₂ in the inspired air. The sedentary rate, therefore, provided the most severe breathing condition for this CO₂ test on self-contained breathing apparatus.

However, results from one very recent study demonstrate that dead space is not necessarily a fixed volume but can increase with increased ventilation (Warkander and Lundgren, 1995). In addition,

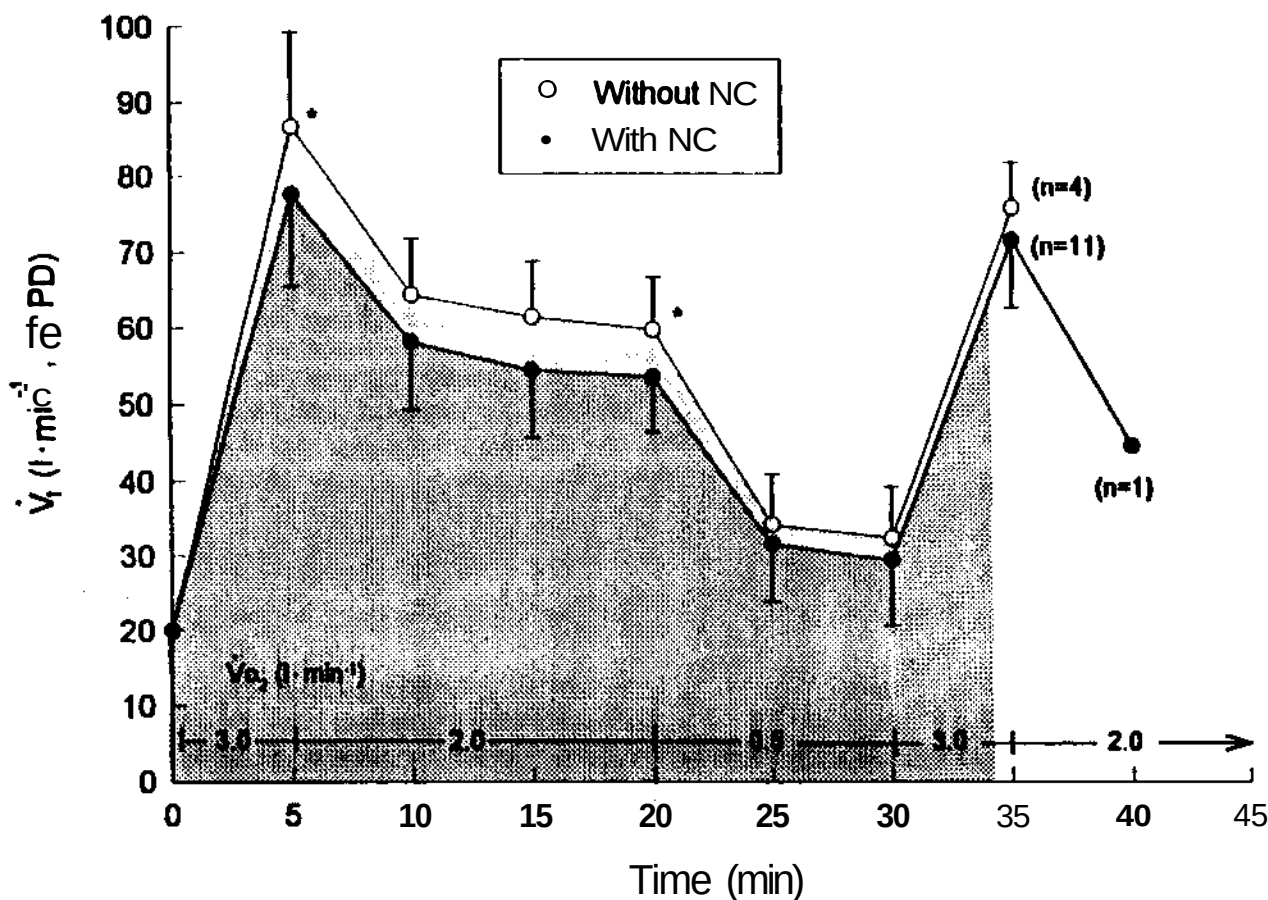


Figure 2. Inspired minute ventilation ($\dot{V}_I$) versus time for all respirator tests ($n=18$; * Without NC the inspired minute ventilation was significantly greater than With NC, $p<0.05$). Shaded areas under curves represent total breathing air used.

that study demonstrated that the highest mean inspired CO_2 concentrations do not always occur at the lowest ventilations. In the current study, average inspired CO_2 concentrations were similar across work rates within each NC condition. These findings may serve to justify testing SCBAs at more than one ventilation or at greater than resting minute ventilations, as is the case with the $50 \text{ L} \cdot \text{min}^{-1}$ test employed in the European Standard (CEN, 1989, EN 136, Part 5.6).

In conclusion, time to alarm was significantly reduced without versus with a noseclip [30.0 min (without) versus 34.1 min (with), $p<0.05$]. Minimum and average inspired CO_2 concentrations, as well as the volume of re-inspired CO_2 , were significantly greater without a noseclip than with a noseclip across all exercise intensities ($p<0.005$). These findings may have significant implications for those involved in updating NFPA regulations for the use and testing of fire service SCBAs.

Acknowledgments

The authors would like to thank Sam Terry, Tim Merinar, Doug Riffle, and Mike Commodore for their expert technical assistance with this study. The graphics assistance provided by Herb Linn and Mike Moore was also highly appreciated.

References

1. Balke, B. and R.W. Ware, "An Experimental Study of 'Physical Fitness' of Air Force Personnel," *U.S. Armed Forces Med. J.* 6:675-688 (1959).
2. Bartlett, H.L., J.L. Hodgson, and J. Kollias, "Effect of Respiratory Valve Dead Space on Pulmonary Ventilation at Rest and During Exercise," *Med. Sci. Sports* 4(3):132-137 (1972).
3. Clark, J. M., R.D. Sinclair, and J.B. Lenox, "Chemical and Nonchemical Components of Ventilation During Hypercapnic Exercise in Man," *J. Appl. Physiol: Respirat. Environ. Exer. Physiol.* 48(6):1065-1076 (1980).
4. *Code of Federal Regulations*, Title 42, Part 84, Washington, D.C.: USGPO (1995).
5. Dahlback, G. O. and L. G. Fallhagen, "A Novel Method for Measuring Dead Space in a Respiratory Protective Equipment," *J. Internat. Soc. Resp. Prot.* 5:12-17 (1987).
6. James, R. H., "Physiological Effects of Breathing Resistance and Equipment Dead Space in Respiratory Protective Devices: Status of the Problem," Department of Health, Education, and Welfare (NIOSH), Cincinnati, OH, Publication No. 77-161 (1976).
7. Jones, N. L., G. B. Levine, D. G. Robertson, and S. W. Epstein, "The Effect of Added Dead Space on the Pulmonary Response to Exercise," *Respiration* 38:389-398 (1971).
8. Kelman, G. R. and A. W. S. Watson, "Effect of Added Dead Space on Pulmonary Ventilation During Sub-Maximal, Steady-State Exercise," *Quart. J. Appl. Physiol.* 58:305-313 (1973).
9. Kloos, E.J. and J. Lamonica, "A Machine-Test Method for Measuring Carbon Dioxide in the Inspired Air of Self-Contained Breathing Apparatus," Bureau of Mines, U.S. Department of the Interior, Washington, D.C., Report 6865 (1966).
10. Raven, P., Mine Safety Appliances Company, Safety Products and Engineering Division, Final Report No. PORD024535 (February 1989).
11. Stannard, J.N. and E.M. Russ, "Estimation of Critical Dead Space in Respiratory Protective Devices," *J. Appl Physiol.* 1:326-332(1948).
12. Turner, N.L., D.C. Beeckman, and T.K. Hodous, "Evaluation of Proposed Methods to Update Human Testing of Self-Contained Breathing Apparatus," *Am. Ind. Hyg. Assoc. J.* 56 (December 1995).
13. Warkander, D.E., "Effect of Added Dead-Space and Inspired CO₂ on Ventilation (air usage) in Humans as it Pertains to the Endurance and Performance of Protective Breathing Gear: A Literature Review," Center for Research in Special Environments, Dept. of Physiology, State University of New York, Buffalo, NY (April 1988).
14. Warkander, D.E. and C.E.G. Lundgren, "Dead Space in the Breathing Apparatus; Interaction with Ventilation," *Ergonomics* 38(9): 1745-1758 (1995).