

Exposure Profile Effects on the Concentration of Freon®-113 in Exhaled Air

Demetra Dalamagas

DPR Construction, Inc., 120 SW Ankeny,
Suite 325, Portland, OR 97204-3566

Christopher C. Coffey *

Ziqing Zhuang

Robert B. Lawrence

Department of Health and Human Services, Public Health Service,
Centers for Disease Control and Prevention, National Institute for
Occupational Safety and Health, Division of Respiratory Disease Studies,
1095 Willowdale Road, Morgantown, WV 26505-2888

**) (Author to whom all correspondence should be addressed.)*

Keywords: Freon®-113, end-exhaled air, respirator performance, leak profile

Disclaimer - Mention of commercial product or trade name does not constitute endorsement by the National Institute for Occupational Safety and Health.

Abstract

End-exhaled breath concentrations of 1,1,2-trichloro-1,2,2-trifluoroethane (Freon®-113) have been used as a measure of respirator performance. This study investigated whether end-exhaled breath concentration is significantly affected by the "leak profile" and thereby not representative of the concentration to which the wearer was exposed. Four subjects participated in three different phases. End-exhaled air samples were collected and analyzed after each 30-minute test. Phase 1 consisted of four scenarios supplying: (a) 500 ppm Freon®-113 only during the first minute, (b) 500 ppm exposure only during the last minute, (c) 33 ppm during the first 15 minutes, and (d) 33 ppm during the last 15 minutes. Phase 2 consisted of supplying 500 ppm in two scenarios: (a) during the first six minutes and (b) during the last six minutes. Phase 3 consisted of two scenarios supplying: (a) 500 ppm for two minutes at the beginning, middle, and end of the test and (b) 100 ppm continuously. For two subjects in phase 1, the means of scenario b were statistically higher than those for the other three scenarios; this could have been attributed to high intra-subject end-exhaled breath concentration variability. No significant difference was found between subject means for the scenarios in phases 2 and 3. A significance level of $\alpha = 0.05$ was used for all analyses. It was concluded that different exposure scenarios, having identical time-weighted exposures, produced consistent end-exhaled breath concentrations and Freon®-113 can be used as a measure of air-purifying respirator performance.

Introduction

In 1998, the National Institute for Occupational Safety and Health (NIOSH) conducted a study designed to compare the fit factors from six quantitative fit-test methods against a measure of a respirator's performance under laboratory conditions (Coffee, *et al.*, 1998a; Coffee, *et al.*, 1998b). Respirator performance was assessed by exposing a subject to 1,1,2-trichloro-1,2,2-trifluoroethane (Freon®-113) during a simulated workplace test. The concentration of Freon®-113 in a subject's exhaled breath was reflective of the actual dose they received while wearing respirators in a known concentration of Freon®-113. Supported by the pharmacokinetic properties of Freon®-113, airborne exposure to the vapor was determined experimentally, by measuring end-exhaled air levels rather than relying on in-facepiece sampling. This eliminated or

minimized the documented biases inherent with current in-facepiece sampling techniques and hardware such as probe location and depth (Oestenstad, *et al.*, 1990), particle loss (Hewett, *et al.*, 1993), and the relationship of leak sites and facial characteristics (Liau, *et al.*, 1982; Myers, *et al.*, 1986). The total Freon[®]-113 exposure dose was calculated from concentration measurements of a subject's end-exhaled air. Therefore, it could be determined whether an increase in fit factor resulted in better protection (*i.e.*, lower total Freon[®]-113 exposure dose) during a simulated healthcare workplace protection-factor test.

Other researchers have investigated the uptake, distribution, and elimination of Freon[®]-113 in exhaled air (Woolen, *et al.*, 1990; Auton and Wollen, 1991; Decker and Crutchfield, 1993). Because none of these studies provided information on how different exposure scenarios, having identical 30-minute time-weighted average concentrations, would affect the end-exhaled breath concentration, a limited investigation was conducted on whether end-exhaled breath concentration may be due to the leak profile and not representative of the concentration to which the wearer was exposed. End-exhaled breath concentrations from identical time-weighted average concentrations, acquired through two different exposure scenarios, during a 30-minute exposure test were determined (Coffee, *et al.*, 1998b). During the first scenario, the subject breathed 500 ppm Freon[®]-113 for the first six minutes of the simulated workplace test and clean air for the remaining 24 minutes. During the second scenario, the subject breathed clean air for the first 24 minutes of the simulated workplace test and 500 ppm Freon[®]-113 for the last six minutes. The end-exhaled breath was analyzed 30 minutes after the subject completed the simulated workplace test, and it was determined that the Freon[®]-113 concentration in a subject's end-exhaled air was only slightly affected by various exposure scenarios. The purpose of the current study was to investigate the effects of exposure scenario on end-exhaled breath concentration using a wider range of exposure scenarios and a larger group of subjects than the previous study.

Methods

Exposure Scenarios

The study consisted of 3 phases having a total of 8 exposure scenarios (Table 1). Each scenario was a 30-minute test in which the subject performed simulated workplace movements (Table 2). These simulated workplace movements were not selected to specifically duplicate the movements in any particular job or industry but were intended to be representative of movements made in various jobs and industries, including the healthcare industry. While executing the movements, each subject wore a flexible cup, covering the nose and mouth (nose cup), connected to a system that supplied either Grade D quality breathing air or Grade D quality breathing air containing Freon[®]-113 and 15 to 20 mg/m³ corn oil aerosol (Freon[®]-113 delivery system) as shown in Figure 1 (Compressed Gas Association, 1989). The various Freon[®]-113 exposure limits are 1,000 ppm as an 8-hour time-weighted average. All of the exposures in this study are well below that level.

Phase 1:

Phase 1 of the study consisted of 4 exposure scenarios. The first exposure scenario (SE) consisted of the subjects breathing Grade D air for the first 29 minutes and then Grade D air containing 15 to 20 mg/m³ of corn oil and 500 ppm Freon[®]-113 for the final minute of the test. The second scenario (SB) was the reverse of SE, *i.e.*, the subjects breathed Grade D air containing 15 to 20 mg/m³ of corn oil and 500 ppm Freon[®]-113 for the first minute and Grade D air for the last 29 minutes. The third exposure scenario (LE) consisted of the subject breathing Grade D air for the first 15 minutes and then breathing Grade D air containing 15 to 20 mg/m³ of corn oil and 33 ppm Freon[®]-113 for the last 15 minutes of the test. The fourth scenario (LB) consisted of the subjects breathing Grade D air containing 15 to 20 mg/m³ of corn oil and 33 ppm Freon[®]-113 for the first 15 minutes of the test and Grade D air for the remainder of the time. In these scenarios, the 30-minute time-weighted average concentration of Freon[®]-113 was 17 ppm.

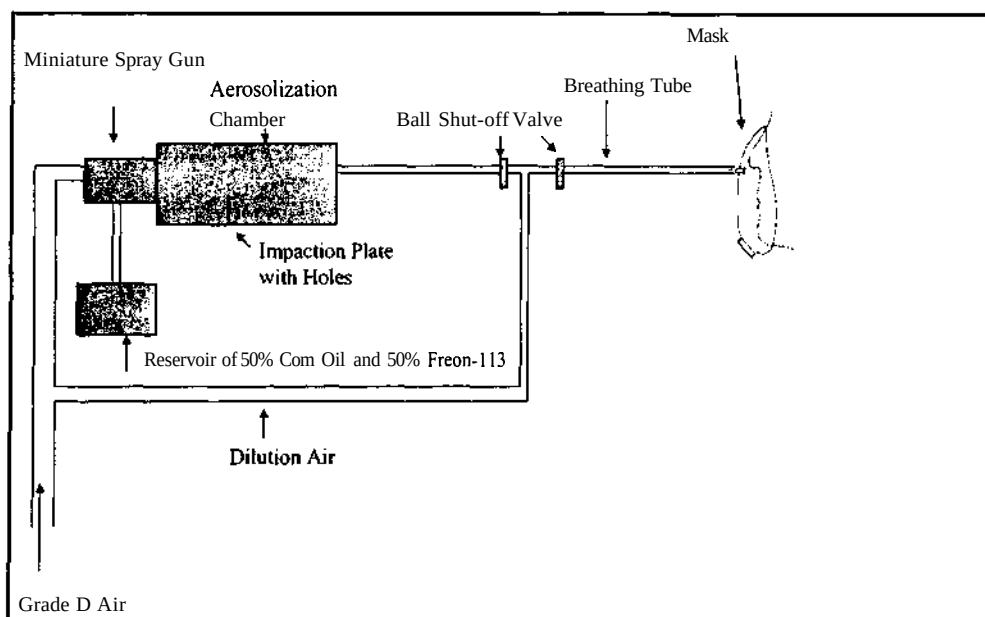


Figure 1. Freon®-113 Delivery System

Table 1. Experimental Design Summary

Phase	Scenario	Exposure Description
1	Short End (SE)	Grade D Air -0 to 29 minutes 500 ppm Freon®-113 - 29 to 30 minutes
1	Short Beginning (SB)	500 ppm Freon®-113 - 0 to 1 minute Grade D Air -1 to 30 minutes
1	Long End (LE)	Grade D Air - 0 to 15 minutes 33 ppm Freon®-113 - 15 to 30 minutes
1	Long Beginning (LB)	33 ppm Freon®-113 - 0 to 15 minutes Grade D Air -15 to 30 minutes
2	Beginning (BEG)	500 ppm Freon®-113 - 0 to 6 minutes Grade D Air -6 to 30 minutes
2	End (END)	Grade D Air -0 to 24 minutes 500 ppm Freon®-113 - 24 to 30 minutes
3	Intermittent (INT)	500 ppm Freon®-113 - 0 to 2 minutes Grade D Air - 2 to 12 minutes 500 ppm Freon®-113 - 12 to 14 minutes Grade D Air - 14 to 27 minutes 500 ppm Freon®-113 - 27 to 29 minutes Grade D Air -29 to 30 minutes
3	Continuous (CON)	100 ppm Freon®-113 - 0 to 30 minutes

Table 2. Simulated Workplace Motions

Motion	Duration (Minutes)	Motion	Duration (Minutes)
Hang IV Bag	1	Reach side to side	2
Bending	2	Reaching overhead	2
Insert Syringe into IV Bag	1	Talking aloud while sitting	2
Carrying Weight	2	Nodding and Turning Head	2
Twisting and Turning Head	2	Reaching Overhead	1
Open and Close Door	1	Stand and talking aloud	1
Talking aloud	3	Control Panel Motions	1
Bending	3		
Turning head	2	Walking	1

Phase 2

Two exposure scenarios composed phase 2. The first exposure profile (BEG) consisted of the subject being supplied Grade D air containing 15 to 20 mg/m³ of corn oil and 500 ppm Freon[®]-113 to breathe for the first 6 minutes of the test and Grade D air to breathe for the remaining 24 minutes. The second (END) involved the subject being supplied with Grade D air to breathe for the first 24 minutes and Grade D air containing 15 to 20 mg/m³ of corn oil and 500 ppm Freon[®]-113 for the last 6 minutes. Both of these exposure scenarios provided a 30-minute time-weighted average concentration of 100 ppm Freon[®]-113 to the subject.

The scenarios in phases 1 and 2 were selected because they represented the most extreme cases of faceseal leakage possible during two simulated workplace tests with the same subject and respirator. The respirator provided only partial or no protection for a period time at the beginning of one test and at the end of the other and complete protection the remainder of the time.

Phase 3

Phase 3 consisted of two exposure scenarios. In the first scenario (INT), subjects were supplied Grade D air, containing 15 to 20 mg/m³ of corn oil and 500 ppm Freon[®]-113, to breathe at the following times: 0 to 2 minutes, 14 to 16 minutes, and 28 to 30 minutes. During the other 24 minutes of the test, the subjects breathed Grade D air. The second scenario (CON) consisted of the subject being supplied Grade D air, containing 15 to 20 mg/m³ of corn oil and 100 ppm Freon[®]-113, to breathe for the entire 30 minutes of the test. The 30-minute time-weighted average concentration for these two scenarios was 100 ppm. Each of the 8 scenarios was repeated in triplicate with the subject providing end-exhaled air samples after each test.

These scenarios were selected because it cannot be predicted how a particular respirator will on a wearer either during a simulated workplace test or at a worksite. One way to ascertain potential exposure is for the majority of the exposure to occur only when a leak is produced by certain movements of the wearer. When the leak-producing movement is not being made, the respirator has an adequate seal and very little exposure occurs. The INT scenario simulates a small number of large leaks causing the exposure. Another method

to determine is for the exposure to occur due to the respirator's "fundamental fit" (*i.e.*, the amount of leakage present when the wearer holds his/her head still, looking forward, and breathing normally). In this scenario, any leaks caused by movement do not contribute significantly to the exposure. The CON scenario simulates exposure caused by a fairly poor "fundamental fit."

Subjects

Twelve subjects (four in each phase) were used in this study; 7 females and 5 males. The test subjects were experienced in wearing respirators and performing simulated workplace movements and were medically cleared for participation using NIOSH Human Subject Review Board approved procedures. Each subject was provided with verbal instructions on the proper donning of the dose delivery nose cup used in the testing and on the movements to be used during the exposure scenario tests.

End-Exhaled Air Sampling

To collect the end-exhaled air, a subject first inhaled deeply and held his/her breath for approximately 10 seconds. He/she put on a nose clip (Vacu•Med, catalog number 1008, Ventura, CA) and exhaling as long and as hard as possible into a sampling apparatus (Figure 2). The apparatus consisted of a Vacu•Med 1026 cardboard mouthpiece, Vacu•Med 1084 adapter, Vacu•Med 1011 Clean Bor tubing, K270 K-valve, T-version, and a silicone stopper equipped with a fitting, tubing, and clamp which fit into the K-valve. The sampling apparatus collected only the last 25 ml of expiration. End-exhaled air samples were collected at 25, 30, and 35 minutes after the exposure test ended.

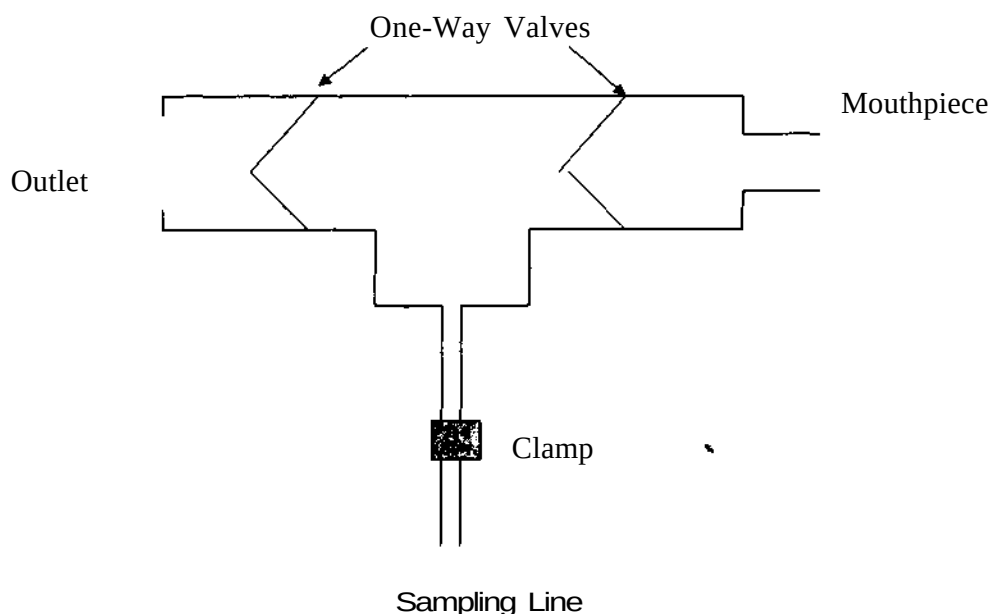


Figure 2. End-exhaled Air Sampling Device.

The sample was then injected into the gas sampling valve system of a Hewlett-Packard 5890 gas chromatograph equipped with a G1223A electron capture detector (Agilent Technologies, Inc., Palo Alto, CA). The lower limit of detection was determined to 0.005 ppm and the lower limit of quantification was 0.010 ppm. The coefficient of variation (CV) for the end-exhaled air sampling was 15% with the gas chromatograph having a CV of 3%.

Data Analysis

The gas chromatograph was calibrated and Freon[®]-113 peak areas transformed into Freon[®]-113, end-exhaled breath concentrations (ppm) as in our 1998 study (Coffee, *et al.*, 1998b). Statistical analysis was performed on the end-exhaled air concentrations by using the Statistical Analysis System (SAS) software (SAS Institute, Research Triangle, NC). A general linear models procedure (GLM proc) was performed on the data and Duncan's Multiple Range test for variance was performed to compare the mean, end-exhaled breath Freon[®]-113 concentration of each scenario for each subject. The four exposure scenarios in phase 1 were compared to each other as were the two scenarios in phases 2 and 3. Three different models were used having end-exhaled breath concentration of Freon[®]-113 as the dependent variable. The first model used the scenario as the independent variable. For this model, a mean Freon[®]-113 end-exhaled concentration was calculated from the three end-exhaled breath samples taken at 25, 30, and 35 minutes after the exposure was stopped and used as the dependent variable. The second model used was a first-order model with two independent variables (*i.e.*, scenario and end-exhaled breath sampling time). The data for each of the subjects was analyzed independently in the first two models. The third model employed was a first-order model with three independent variables (*i.e.*, scenario, subject, and end-exhaled breath sampling time) and with the data from all the subjects in a particular scenario combined. A significance level of $\alpha=0.05$ was used in all cases.

RESULTS AND DISCUSSION

Tables 3 through 5 contain the results of the various comparisons between scenarios using the first model. The phase 1 comparison of the LE, SE, LB, and SB scenarios did not reveal any significant differences between the mean concentrations of each scenario except between the SE and LB scenarios for subjects 5 and 45 (Table 3). In phases 2 and 3 (Tables 4 and 5), there were no significant differences between the two scenarios for all four subjects in each phase.

The second model produced slightly different results. The most notable differences with the second model came in comparing phase 1 scenarios (Table 3). No significant difference was found between the mean end-exhaled breath concentrations of all four scenarios for subject 1. Subject 8 had one significant difference while subjects 5 and 45 now had three significant differences. For subject 5, the mean end-exhaled breath concentration was significantly different between scenarios: SE and LB, SE and LE, and SB and LB. A significant difference was found between the LE and SE and LB scenarios for subject 8. For subject 45, the mean end-exhaled breath concentration was significantly different between scenarios: SE and SB, LB and LE, and SE and LE. There was no significant differences between the CON and INT scenarios for all four subjects participating in phase 2 (Table 4). For the END and BEG scenarios, three of the four subjects did not have any significant differences (Table 5). For subject 26, there was a significant difference. For all four subjects the mean end-exhaled air concentration for the END scenario was consistently higher than for the BEG scenario.

End-exhaled breath sampling time was not significant for any of the subjects. No significant interaction was found between scenario and end-exhaled breath sampling time in model 2 for any of the scenarios. Only the model for subject 1 had no significant terms. Scenario was significant for subjects 5, 8, and 45. No significant terms were found for any of the phase 2 interaction terms using model 2. For the phase 3 data, only the scenario was significant for subject 26.

When the third model (Table 6) was used, the only significant difference was found between the SE and the other 3 scenarios. The mean end-exhaled breath concentration for the END scenario was found to be significantly higher than for the BEG scenario. As with models 1 and 2, the CON and INT scenarios were not found to be significantly different. The model had different significant terms depending upon the phase. For phase 1, both subject and scenario were significant; for phase 2, scenario and end-exhaled breath sampling time; for phase 3 only subject.

Table 3. Summary of Duncan groupings for phase 1 scenarios

Subject	Scenario	Mean End-Exhaled Breath Freon®-113 Concentration (ppm) (n=9)	Duncan Grouping ^a	
			Model 1 ^b	Model 2 ^c
1	LE	0.67	A	A
1	SE	0.63	A	A
1	SB	0.57	A	A
1	LB	0.56	A	A
5	SE	0.78	A	A
5	SB	0.74	A,B	A,B
5	LB	0.57	A,B	C
5	LE	0.42	B	B,C
8	LE	0.76	A	A
8	SB	0.70	A	A,B
8	SE	0.69	A	A
8	LB	0.54	A	B
45	SE	0.92	A	A
45	LB	0.89	A,B	A,B
45	SB	0.69	A,B	B,C
45	LE	0.51	B	C

^a Statistical comparisons were made for each subject; means with the same superscript letter are not significantly different ($p > 0.05$).

^bModel 1: End-exhaled breath Freon®-113 concentration = scenario.

^cModel 2: End-exhaled breath Freon®-113 concentration = scenario + sampling time.

The fact that the time (25, 30, or 35 minutes post-exposure) of the end-exhaled breath sample, duration, and nature of the Freon®-113 administration did not confound the end-exhaled breath concentration data in this study has been evidenced in other studies. Pharmacokinetic studies of Freon®-113 suggest that it has an average desaturation half-life of 13 minutes (Woolen, *et al.*, 1990; Auton and Wollen, 1991). Decker and Crutchfield fit a two compartment (central and peripheral) model to their breath desaturation curves (plot of exhaled breath concentration versus time) (Decker and Crutchfield, 1993). A compartment is composed of the parts of the body having similar pharmacokinetic properties. They defined the central compartment as the one into which a vapor is directly absorbed, including certain fractions of the blood and tissues having large amounts of blood vessels.

The peripheral compartment was defined as those tissues that only communicated with the ambient environment through the central compartment. In their study, the average desaturation half-life was 4.5 for

Table 4. Summary of Duncan groupings for phase 2 scenarios

Subject	Scenario	Mean End-Exhaled Breath Freon®-113 Concentration (ppm) (n=9)	Duncan Grouping ^a	
			Model 1 ^b	Model 2 ^c
4	INT	1.23	A	A
4	CON	1.44	A	A
10	INT	1.15	A	A
10	CON	1.15	A	A
19	INT	0.93	A	A
19	CON	1.24	A	A
29	INT	2.01	A	A
29	CON	1.63	A	A

^a Statistical comparisons were made for each subject; means with the same superscript letter are not significantly different ($p > 0.05$).

^bModel 1: End-exhaled breath Freon®-113 concentration = scenario.

^cModel 2: End-exhaled breath Freon®-113 concentration = scenario + sampling time.

Table 5. Summary of Duncan groupings for phase 3 scenarios

Subject	Scenario	Mean End-Exhaled Breath Freon®-113 Concentration (ppm) (n=9)	Duncan Grouping ^a	
			Model 1 ^b	Model 2 ^c
3	END	1.51	A	A
3	BEG	1.34	A	A
16	END	1.94	A	A
16	BEG	1.37	A	A
22	END	1.57	A	A
22	BEG	1.57	A	A
26	END	1.83	A	A
26	BEG	1.04	A	B

^a Statistical comparisons were made for each subject; means with the same superscript letter are not significantly different ($p > 0.05$).

Table 6. Summary of Duncan Groupings using model 3.

Phase	Scenario	Mean End-Exhaled Breath Freon®-113 Concentration (ppm) (n=36)	Duncan Grouping ^a
1	SE	0.80	A
1	SB	0.67	B
1	LB	0.64	B
1	LE	0.59	B
2	END	1.70	A
2	BEG	1.33	B
3	CON	1.37	A
3	INT	1.28	A

^a Statistical comparisons were made for each subject; means with the same superscript letter are not significantly different ($p > 0.05$).

^bModel 1: End-exhaled breath Freon®-113 concentration = scenario.

^cModel 2: End-exhaled breath Freon®-113 concentration = scenario + sampling time.

the central and 51 minutes for the peripheral with breath desaturation curves reaching a plateau at 30 minutes post-exposure and remaining constant for 60 minutes (Decker and Crutchfield, 1993). They stated the first 20 minutes of the breath desaturation curve represents the transferring of Freon®-113 from the central compartment to the exhaled breath, while the remaining portion of the curve was due to the Freon®-113 being transferred from the peripheral to the central compartment and then to the exhaled breath at a constant rate.

Because this current study consisted of a Freon®-113 exposure during a 30-minute simulated workplace test, followed by at least 25 minutes of no exposure before the first breath sample, the longest time between exposure and sample collection would be 54 minutes (SB scenario) and the shortest would be 25 minutes (SE scenario). Starting end-exhaled breath sampling at 25 minutes after test completion should have allowed the samples to be taken when the Freon®-113 was being transferred from the peripheral compartment to the exhaled breath at a stable rate, regardless of the exposure scenario.

With the first model data analysis, the only subjects to have a significant difference in end-exhaled breath concentrations for any scenario were subjects 5 and 45 in phase 1. For both subjects, the end-exhaled breath concentrations for the LE (33ppm Freon®-113 administered during the last 15 minutes) scenario were significantly lower than for the SE scenario (a high concentration administered during the last minute). One possible explanation for this is that for low solubility gases and vapors, such as Freon®-113, in a two-compartment model, a higher concentration is found in the exhaled air after a short exposure than after a longer one (Fiserova-Bergerova, *et al.*, 1984; Fiserova-Bergerova, *et al.*, 1980). Another explanation is that taking the first end-exhaled breath sample at 25 minutes did not allow enough time for the Freon®-113 in these subjects' exhaled breath to reach a stable concentration. Delaying the collection time may yield more consistent results since the Freon®-113 would have longer to reach a stable concentration in the end-exhaled breath.

The wide variation noted among these subjects' end-exhaled breath concentrations (Figure 3) may have also affected the results. This variation may have a number of sources. If the subject did not provide a complete end-exhaled breath sample each time (he/she did not consistently exhale as long and hard as possible), then

it would be possible for the Freon®-113 to be diluted with relatively clean air from the upper airways. Another source of the variability could be differences in physiological factors between tests (e.g., changes in cardiac output due to a subject's emotional state, health, or how vigorously the movements were performed; body temperature; and changes in the amount of mucus in the lungs due to allergies or colds).

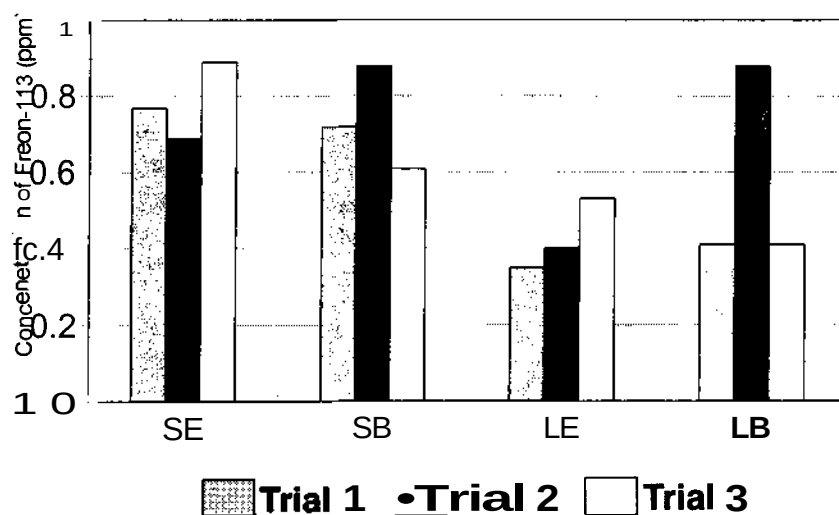


Figure 3. Comparison of phase 1 scenario mean of 25, 30 and 35 minute post-exposure end-exhaled breath concentrations of Freon®-113 for a typical subject.

The variability in the end-exhaled breath samples could also be due to the inherent variability of the end-exhaled breath sampler and the Freon®-113 delivery device. Alternate means of delivering the Freon®-113 exposure and collecting and analyzing the end-exhaled breath samples may reduce the variability. One alternate method for delivering the Freon®-113 exposure would be a modified anesthesiology machine. This may reduce some of the variability by ensuring a more consistent and accurate administration of the Freon®-113 since it is a closed system, with precise dosing, and a finely regulated and controlled flow rate. The use of evacuated minicans, for collecting larger exhaled breath samples, and the use of a preconcentrator to trap the Freon®-113 and introduce it rapidly to the gas chromatograph, may reduce the variability that was seen in this study.

Regardless of the cause, the variability among the end-exhaled breath samples of the same subject affect the results of the Duncan procedure. For different scenarios to produce end-exhaled breath concentrations which are significantly different, the difference between the means of the end-exhaled breath concentrations must exceed a least significant range (Walpole, *et al.*, 1998). A high degree of variance in breath concentrations causes the least significant range to be large and requires the observed difference between mean end-exhaled breath concentrations to be even larger before being significantly different.

CONCLUSIONS

The different exposure scenarios designed in this study were intended to represent the possible ways in which leaks might occur during a simulated workplace test, designed to compare fit factors to a measure of exposure using Freon®-113. The statistical analysis has shown that the onset, duration, and magnitude of the leaks should not bias the concentration of Freon®-113 in the end-exhaled breath samples. Different exposure scenarios having identical time-weighted average exposures produced consistent (i.e., not statistically different) Freon®-113, end-exhaled breath concentrations. The results of the study demonstrate that Freon®-113 can be used as a measure of air-purifying respirator performance. The statistical analysis also supports the concept that the end-exhaled breath sample is representative of the 30-minute time-weighted average concentration that the wearer was exposed to rather than due to the leak profile.

Because quantitative fit factors for half-facepiece respirators are, on average, lower when compared to other respirator types, the variability of the end-exhaled breath concentrations seen in this study is not an issue. Approximately the same amount of leakage is represented by a fairly wide range of fit factors (e.g., fit factors of 100 and 120 represent about the same amount of face seal leakage). The variation between end-exhaled breath concentrations of a subject using the same exposure scenario should be minimized. It should be investigated whether samples taken later than 35-minute post-exposure would reduce the variability.

Acknowledgments

The authors would like to acknowledge Dr. Sidney Soderholm, NIOSH, Health Effects Laboratory Division, for his assistance in developing the pharmacokinetic exposure profiles and Ms. Molly Pickett-Harner, NIOSH, Division of Respiratory Disease Studies, for her talented editorial assistance during the development of this manuscript.

References

- Auton, T.R. and B.H. Woollen. (1991) A physiological based mathematical model for the human inhalation pharmacokinetics of 1,1,2-trichloro-1,2,2-trifluoroethane. *Int. Arch. Occup. Environ. Health* 63:133-138.
- Coffey C.C., D.L. Campbell, W.R. Myers, Z. Zhuang, and S. Das. (1998) Comparison of six respirator fit test methods with an actual measurement of exposure in a simulated health-care environment: part I - protocol development. *Am. Ind. Hyg. Assoc. J.* 59:852-861.
- Coffey C.C., D.L. Campbell, W.R. Myers, and Z. Zhuang. (1998) Comparison of six respirator fit test methods with an actual measurement of exposure in a simulated health-care environment: part II - method comparison testing. *Am. Ind. Hyg. Assoc. J.* 59:862-870.
- Compressed Gas Association, Inc. (1989): American National Standard Commodity Specification for Air. Pamphlet G-7.1 ANSI Z86.1-1989. Compressed Gas Association, Inc., Arlington, VA.
- Decker J.A. and C.D. Crutchfield. (1993) Feasibility of a new method to determine respirator performance by biological monitoring of exhaled air. *J. Inter. Soc. Respir. Prot.* 77:6-19.
- Fiserova-Bergerova, V., J. Vlach, and J.C. Cassidy. (1980) Predictable "individual differences" in uptake and excretion of gasses and lipid soluble vapours simulation study. *Brit. J. Indust. Med.* 37:42-49.
- Fiserova-Bergerova, V., M. Tichy, and F.J. Di Carlo. (1984) Effects of biosolubility on pulmonary uptake and disposition of gasses and vapors of lipophilic chemicals. *Drug Metabolism Reviews* 75:1033-1070.

-
- Hewett P., B.G. Pallay, and J.F. Gamble. (1993) A model for correcting workplace protection factors for lung deposition and other effects. *Am. Ind. Hyg. Assoc. J.* 54:142-149.
- Liau Y., A. Bhattacharya, H. Ayer, and C. Miller. (1982) Determination of critical anthropometric parameters for design of respirators. *Am. Ind. Hyg. Assoc. J.* 43:897-899.
- Myers W.R., J. Allender, R. Plummer, and T. Stobbe. (1986) Parameters That Bias the Measurement of Airborne Concentration Within a Respirator. *Am. Ind. Hyg. Assoc. J.* 47:106-114.
- Oestenstad R.K., J.L. Perkins, and V.E. Rose. (1990) Identification of face seal leak sites on a half-mask respirator. *Am. Ind. Hyg. Assoc. J.* 51:280-284.
- Walpole, R.E., R.H. Myers, and S.L. Myers. (1998) *Probability and Statistics for Engineers and Scientists* (6th Edition). Upper Saddle River, New Jersey: Heath.
- Woolen B.H., E.A. Guest, W. Howe, J.R. Marsh, H.K. Wilson, T.R. Auton, P.G. Blain. (1990) Human inhalation pharmacokinetics of 1,1,2-trichloro-1,2,2-trifluoroethane (FC113). *Int. Arch. Occup. Environ. Health* 62:73-78.