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CAUSES OF IN-FACEPIECE SAMPLING BIAS— I. HALF-FACEPIECE RESPIRATORS*

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Abstract—A widely used technique of in-facepiece sampling has been shown to provide unrepresentative sampling in half-facepiece respirators. These experiments were conducted on a manikin test system using acetone vapour as a test agent. The magnitude of the sampling bias was non-uniform and appears to be a function of several sampling, facepiece and human parameters. These include the location and depth of the sampling probe, the position of the face-seal leak (nose vs chin, etc.), an interaction of breathing pattern (nose vs mouth) with the position of the face-seal leak, and the particular design of half-facepiece. These results clearly demonstrate that during inhalation inboard face-seal leakage does not mix uniformly within the cavity of a half-facepiece respirator. This leads to the collection of unrepresentative samples. The uses and interpretations of in-facepiece sampling data are discussed with regard to the effect of these large, non-uniform sampling biases. Within the constraints and design of the experiments, leak geometry, multiple leaks and volumetrically different leak rates were not found to be significant problems when conducting in-facepiece sampling on half-facepieces.

INTRODUCTION

EXTRACTIVE air sampling techniques are routinely used by the respirator community to evaluate quantitatively an aspect of a respirator's performance while it is being worn. This type of sampling is commonly referred to as in-facepiece sampling. The wide variety of in-facepiece sampling strategies and quantitative performance evaluations that have been developed and used during the last 25 years has recently been reviewed (MYERS, 1986). Since in-facepiece sampling is an extractive sampling technique, the overall accuracy and precision of the data generated by it are a function of: (1) the representativeness of collected samples for the environment within the facepiece cavity; and (2) random and systematic error in the sampling and analytical procedures.

The two most common quantitative evaluations of respirator performance utilizing in-facepiece sampling are fit testing and workplace protection factor testing. The quantitative character of these tests depends upon obtaining representative samples of airborne contaminants from the cavity between the body of the respirator and the wearer's face. Otherwise, the picture provided of that environment will be distorted regardless of the accuracy and precision of subsequent analytical procedures. Measurements of fit (fit factors) produced by quantitative fit testing are commonly used to determine whether the fit of a respirator meets certain minimum criteria or whether a particular brand or size of a facepiece from an array of candidate facepieces 'fits better' than any other. For these interpretations of fit data to lead to correct

*Mention of company names or products does not constitute endorsement by the National Institute for Occupational Safety and Health.

decisions, the sampling must include any inboard leakage occurring through the face-seal.

The published respirator literature contains no data documenting whether samples collected by in-facepiece sampling are representative of the environment inside a negative pressure respirator, an environment which is subject to dramatic changes in instantaneous airflow rate, minute volumes and inboard contaminant leakage. This research was undertaken to provide some of that information. The specific objectives were to:

(1) identify parameters of the person–respirator system which could affect sampling results; and

(2) determine whether varying these parameters within specific limits causes sampling bias.

This paper discusses the identification and selection of parameters and the experimental work completed on half-facepieces. It is an extension of previously reported results for one half-facepiece respirator (MYERS *et al.*, 1986).

Parameter selection

To identify parameters that could potentially affect sampling results, a fault-tree analysis was performed on a widely used in-facepiece sampling procedure (Fig. 1). This procedure locates a sampling probe on the wall of a respirator, if possible on the mid-line of the facepiece somewhere between the nose and mouth of the wearer. The probe is attached to the wall such that its mouth does not generally extend more than 1/8 in. (3 mm) into the cavity of the facepiece. The dimensions of the sampling probe and sampling rates are not standardized. Internal diameters of probes normally range from 1/8 to 1/4 in. Sampling rates most often range between 0.5 and 2 l. min^{-1}. Sampling is continuous during both inhalation and exhalation. Normally, no corrections are made for lung retention effects. Other in-facepiece sampling strategies involve sampling of exhaled air (BS 2091, 1969) and sampling only during inhalation (FÜRST and RIEDIGER, 1980). This work did not consider these sampling strategies.

Five of the parameters identified through the fault-tree analysis were selected for initial study. Priority of selection was based primarily upon professional judgement and experience. Those parameters selected for the screening study are summarized in Table 1. A detailed discussion of the levels of effect chosen for these parameters has been reported previously (MYERS, 1986). Additional studies were then conducted separately to evaluate effects of: (1) geometry of the leak pathway; (2) pairs of leakages occurring simultaneously; and (3) different volumetric leak flow rates.

A general linear model (GLM) analysis, or *t*-test, was used to evaluate the data. The response variable in the experiment was sampling bias (defined in Methods and Materials) and the alpha risk level was set at 0.05. A more detailed discussion of all the experimental designs has been given previously (MYERS, 1986).

METHODS AND MATERIALS

Screening experiment

The test apparatus used for this and the subsequent studies is outlined in Fig. 2. Acetone vapour was selected for the study because of good sensitivity with infrared (i.r.) detection. A syringe pump and evaporating column were used to generate the

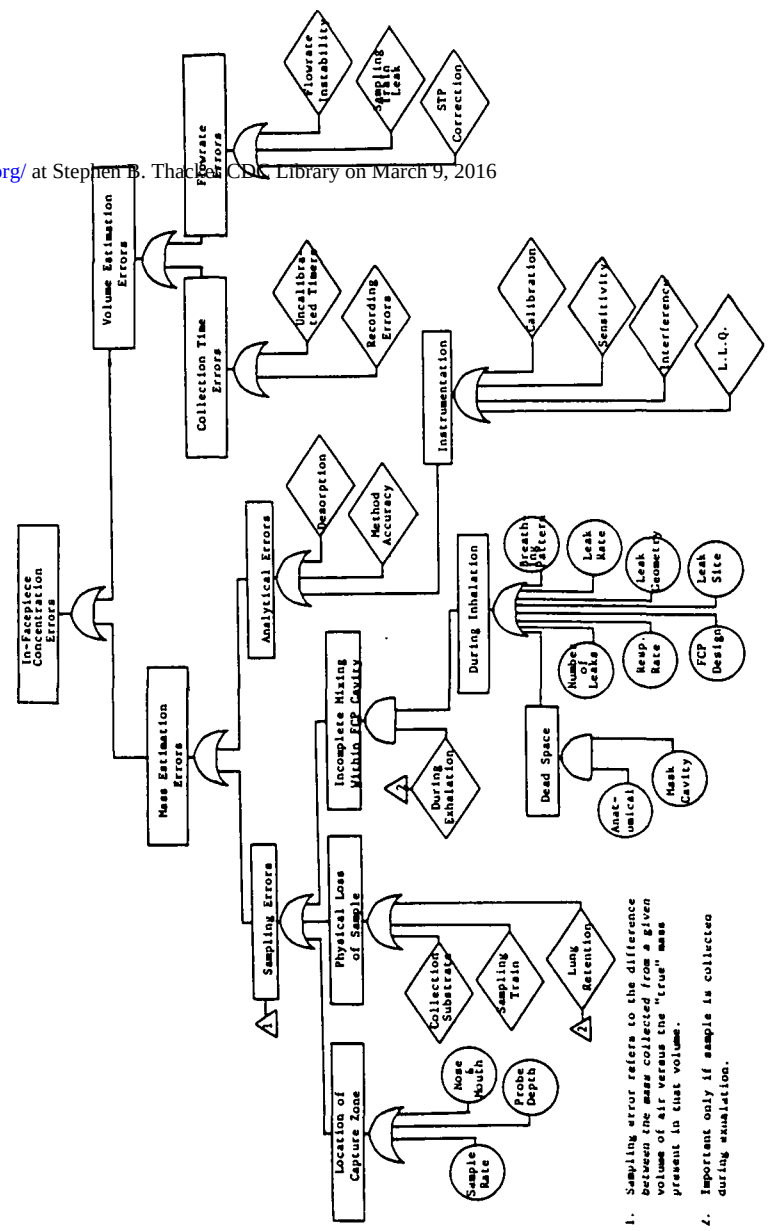

FIG. 1. Fault-tree analysis of in-facepiece sampling.

TABLE I. TEST PARAMETERS AND LEVELS OF EFFECT

Parameter	Levels of effect 1	2	3
Probe location on respirator mid-line	Nose	Between nose and mouth	Mouth
Depth of probe (in.)	0	0.25	0.5
Leak site	Nose	Cheek	Chin
Breathing pattern	Nose	Equal	Mouth
Sample rate (l. min^{-1})	1	2	3

acetone vapour. The syringe pump had a calibrated delivery rate of 0.191 ml min^{-1}. A flow controller provided a mean dilution flow rate of 4.9 l. min^{-1} to the evaporating column. Under normal temperature and pressure conditions the average concentration of acetone generated by the system, C_0, was 12 900 ppm. Daily corrections were made to C_0 for variations in temperature and pressure.

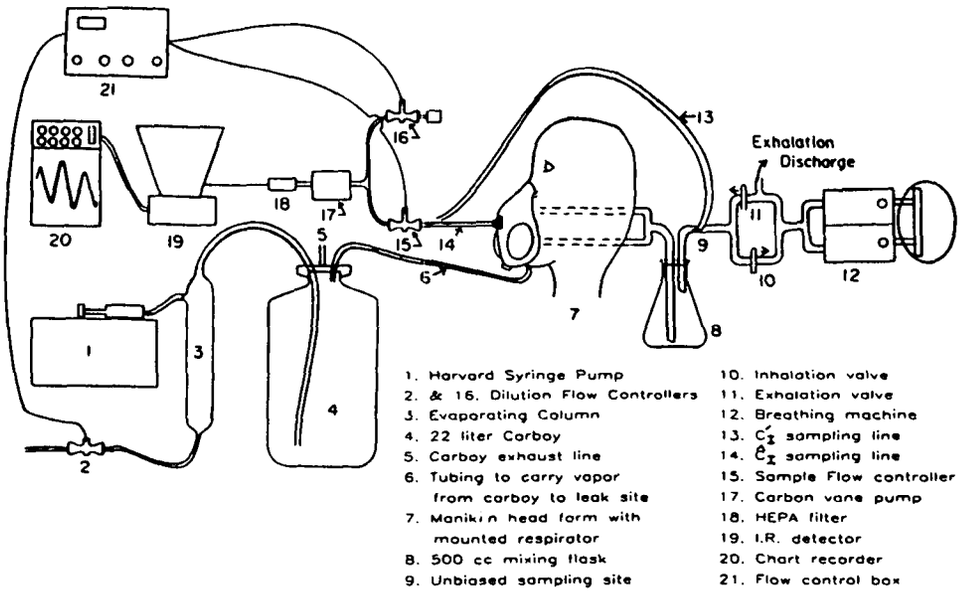

FIG. 2. Experimental test system.

The acetone–air mixture was plumbed into a 22-l. reservoir to help dampen fluctuations in concentration. The reservoir was allowed to exhaust to a hood. Vapour was transported via tubing from the reservoir to the respirator test setup. The tubing could be connected, as appropriate, to each leak site on the face-seal perimeter.

During testing the respirators were equipped with organic vapour cartridges and mounted on a headform with an airtight-seal of caulking. The leaks were created by 1/8 in. (3 mm) I.D. tubing inserted through the caulking seal between the headform and the sealing lip of the respirator. The tubing was inserted only to the inner edge of the face-seal lip. Leak flow resulted from the negative pressure within the facepiece

cavity during the inhalation phase of each breathing cycle. The rates of face-seal leakage were determined by bubble flowmeter. Visual observations of the bubble flowmeter clearly indicated that leak flow was responding to the pressure changes in the facepiece and that leakage inwards occurred only during inhalation.

The pressure within the facepieces ranged between 0 and approximately 1 in. (25 mm) negative water pressure during the inhalation of the breathing machine. The sampling probe used for the study has been previously described (Liu *et al.*, 1984). The headform was plumbed to accommodate air flow occurring simultaneously or separately through the nose and the mouth. It was attached to a breathing machine operated with a 622 kgm min^{-1} work rate cam. The tidal volume, V_T, produced by the cam was 1.6 l. During testing, the frequency of the breathing machine was adjusted for each sampling rate (1, 2 and 3 l. min^{-1}) to produce a total flow through the respirator of approximately 32 l. min^{-1}. The air exhaled was vented to the atmosphere and not returned to the respirator.

A calibrated infrared analyser was used to determine the quantity of acetone in the air samples. A flow controller was used to control and maintain the sampling rates of 1, 2 or 3 l. min^{-1}. After being withdrawn from the facepiece the sample was diluted with clean air to produce a final minute volume of approximately 10 l. which was fed to the i.r. detector. The volume of dilution air was maintained by flow controller. The absorbence response of the i.r. detector was recorded on a strip chart for data reduction and analysis.

Based upon the rates of leakage, the average concentration of acetone inside each half-facepiece respirator during inhalation, C_I, was calculated theoretically and measured experimentally from an unbiased sampling location in the test system plumbing (see Fig. 2, item 9). This unbiased sample is designated as C_I'. These results are summarized in Table 2. Samples were obtained from the unbiased sampling location and used as the 'true' concentration of acetone against which samples obtained by in-facepiece sample $\hat{C}_I$ could be compared.

Table 2. Calculated and experimentally measured concentrations of acetone

Respirator	n	C_I mean (ppm)	S.D.	C_I' mean (ppm)	S.D.	$\%\beta(C_I')$ mean	S.D.
MSA	81	151	1.7	150	8.1	−1.1	5.7
Scott	81	146	3.3	145	4.3	−0.74	4.4
U.S. Divers	81	158	1.4	154	5.6	−3.0	4.1

$$\beta(C_I') = (C_I' - C_I)/C_I \times 100\%$$

The representiveness of samples collected by in-facepiece sampling was evaluated by comparison with the experimentally measured 'true' concentration. The difference of concentration between the two samples was expressed in terms of bias (β) calculated from the expression

$$\beta(\hat{C}_I) = (\hat{C}_I - C_I')/C_I' \times 100.$$

The test sequence started by measuring C_I' over a period of approximately 4 min. The analytical system was then flushed with acetone-free air until absorbence readings

returned to zero and then reconnected to the sampling probe on the respirator to measure $\hat{C}_1$. This sample was collected over a period of approximately 6 min after which the analytical system was again flushed with acetone-free air until absorbence readings return to zero. A second C_1' measurement was made for approximately 4 min. To test five parameters in combination at three levels of effect for each would result in 243 (3^5) treatment combinations for each facepiece. Since this was a screening experiment, a one-third factorial reduction was used to partition the full factorial design of 242 treatment combinations to 81. The same 81 treatment combinations were then evaluated on each respirator. The order for testing the 81 treatments was randomized.

Leak geometry experiment

Definitive information on the cross-sectional geometry of leak pathways does not exist. In a recent report (COHEN, 1984) a fit test is described that utilized photographic film exposed to light penetrating leak pathways on the face-seal. From personal conversation with the author, he indicated that approximately 50% of the exposure patterns were suggestive of light passing through a circular aperture while the other 50% of the exposure patterns seemed to be suggestive of light passing through a slit. Although limited, these observations do suggest that leak pathways having circular- and slit-like cross-sectional geometries do occur.

Probably actual face-seal leaks will vary dynamically in their geometry under actual use conditions. In view of how leaks can be formed, their shape may vary from a circular- to a slit-like geometry, or any hybrid shape in between.

Based upon these considerations, circular- and slit-like tubes were both chosen as leak pathways. The internal diameter of the circular tubing was 3.18 mm (1/8 in.), producing a cross-sectional area of 7.9 mm^2 (0.012 $in.^2$). The slit geometry was created by flattening a piece of the circular tubing. The flattened tubing had a slit with a length of 6.35 mm (0.25 in.) and a height of 1.19 mm (0.047 in.).

To deal with the effect of leak site on sampling bias, these two tubes were bound together so that their positions on the face-seal perimeter were physically as close as possible to one another. This arrangement resulted in the centre-lines of the tubes being approximately 8 mm apart (Fig. 3). The tubes were positioned on the face-seal perimeter at locations identified as nose, cheek and chin.

The leaks produced by the circular or slit tubing were evaluated on 12 test setups which incorporated different combinations of leak sites, sampling rates and breathing patterns. Leaks were varied between all three sites. Sampling rate was varied between 1 and 2 l. min^{-1} and the breathing pattern was varied between all nose breathing and all mouth breathing. The sampling rates and breathing patterns selected represent conditions very likely to be found in fit testing. In all test setups the probe was located at the mid-nose–mouth position and kept flush on the wall of the facepiece. These factors were held constant because fit testing procedures often specify a mid-nose–mouth probe location flush on the wall of the respirator.

Multiple leak experiment

The presence of multiple leaks occurring simultaneously from the face-seal perimeter may promote improved mixing within the facepiece cavity, and thereby reduce sampling bias. This experiment was to investigate the magnitude of bias in air

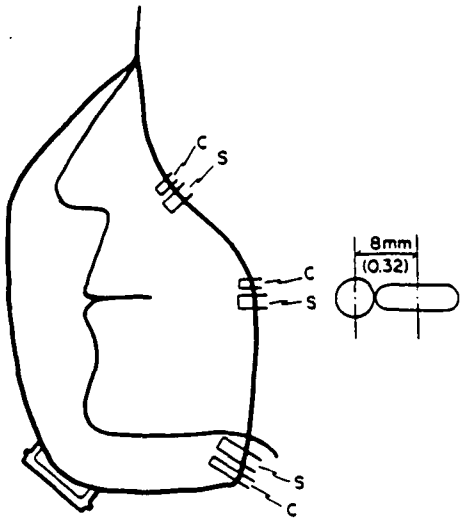

FIG. 3. Physical proximity of leak geometries and positions on the face-seal perimeter. C indicates circular-type geometry; S indicates slit-type geometry.

samples collected when multiple leaks were occurring simultaneously at two different areas on the face-seal.

Multiple leaks could occur either on the same or on opposite sides of the facepiece. For this experiment six areas of face-seal leakage were created on the face-seal perimeter. They were designated as: nose—right (N_R) and left (N_L); cheek—right (CK_R) and left (CK_L); and chin—right (CH_R) and left (CH_L). In pairing the leaks it was assumed that there would be no order effect (i.e. N_R:N_L equivalent to N_L:N_R) and that mirror images of particular leak combinations were the same (i.e. N_R:CK_L is equivalent to N_L:CK_R). Given these assumptions four pairs of leaks were randomly chosen for study. They were: nose right–chin right; nose right–cheek right; nose left–chin right; and cheek right and left. Single leak areas were kept at N_R, CK_R and CH_R.

The four leak pairs and three single leaks constituted the treatment groups. Testing conditions, replications, treatments and manufacturers were completely randomized. For analysis of the data a *t*-test for unequal population variances was conducted on the treatment means.

Volumetrically different flow rate experiment

This experiment was to evaluate sampling for three volumetrically dissimilar leak rates with the circular and slit leak tubes located at each leak site.

The amount of acetone vapour that could be drawn through the leak during each inhalation was controlled by inserting needle flow restrictors in the line connecting the leak to the acetone reservoir (Fig. 2, item 6). The leak volumes are designated as small, medium and large. The data presented in Table 3 expresses the leak volume as a percentage of the total volume drawn through the respirator and in ml min^{-1}. The difference in leak rates between respirators was due to the pressure drop associated with each manufacturer's organic vapour cartridges.

During testing probe location was at mid-nose–mouth, the sample rate was

TABLE 3. MEAN LEAK RATES AS A PERCENTAGE OF TOTAL MINUTE VOLUME

Leak size	*n*	MSA (%)	Scott (%)	U.S. Divers (%)
Small	18	0.66 (213)*	0.59 (189)	0.71 (228)
Medium	18	1.1 (365)	1.1 (360)	1.3 (416)
Large	18	1.7 (559)	1.4 (466)	1.6 (502)

*Numbers in parenthesis are ml min^{-1}.

2 l. min^{-1}, and the probe depth was flush on the wall of the respirator. Various combinations of leak sizes, leak geometries and breathing patterns were randomly chosen for study.

RESULTS AND DISCUSSION

Screening experiment

Summaries of the sampling data collected on the MSA, Scott and U.S. Divers half-facepiece respirators during the first experiment are given in Table 4. A significant difference was found to exist in the sampling bias observed between the different respirators. This would seem to indicate that certain design features of the facepiece are able to influence the magnitude of the bias associated with in-facepiece sampling. One such design feature may be the location of inhalation valves in relation to probe location. For example, the geometry between the inhalation valves and the sampling probe mouth may be such that air, cleaned by the respirator's air-purifying elements, could be 'washed' over the sampling probe during each inhalation. In such a case the resulting air sample collected by in-facepiece sampling would reflect concentrations more representative of the penetration through the air-purifying element even though the intent of the sampling is to measure penetration through the face-seal. Research is needed to identify the design features (e.g. shape, cavity, volume, etc.) of the facepiece which are important influences on in-facepiece sampling bias. Since facepieces can influence the accuracy of in-facepiece sampling results, comparisons of such data to select the 'best fitting' facepiece from among candidate brands of facepieces must be made with considerable caution.

TABLE 4. SAMPLING RESULTS ON HALF-FACEPIECE RESPIRATORS

Respirator	*n*	C_i' mean (ppm)	S.D.	$\hat{C}_i$ mean (ppm)	S.D.	$\hat{C}_i$ range (ppm)	$\%\beta(\hat{C}_i)$ mean	$\%\beta(\hat{C}_i)$ range
MSA	81	150	8.1	124	55.4	3–300	−17[a]	−98 to +98
Scott	81	145	4.3	77	45.5	8–207	−47[b]	−94 to +42
U.S. Divers	81	154	5.6	121	58.9	11–283	−21[a]	−92 to +84

Means with different superscripts are significantly different.

Results of the GLM analysis of variance are summarized in Table 5. Sampling rate was not found to be a significant factor in sampling from any of the half-facepieces evaluated.

TABLE 5. PARAMETERS AND INTERACTION WITH SIGNIFICANT EFFECTS ON SAMPLING IN HALF-FACEPIECE RESPIRATORS

Effect	MSA	Scott	U.S. Divers
Leak site	X	X	X
Breathing pattern	—	—	X
Probe location	X	—	—
Probe depth	—	—	X
Leak site–breathing pattern interaction	X	X	X

Mean sampling biases measured at different probe locations for each half-facepiece are shown graphically in Fig. 4.

For the MSA and U.S. Divers facepieces, the best sampling on average was observed with the probe located approximately opposite the mouth. The same location on the Scott facepiece exhibited the worst sampling bias. The general trend in the data for the Scott facepiece appears to be almost opposite that observed for the MSA and U.S. Divers facepieces. The reason for this is unkown but it is presumed to be due to the design features of the facepiece. With each facepiece the greatest change occurred between the mid-nose–mouth or nose probe location and the mouth probe location. On the MSA facepiece the mean sampling bias was significantly lower at the mouth location than at the nose or mid nose–mouth location. Little net change was observed between the nose and mid-nose–mouth locations for the facepieces.

The effect of probe depth on sampling bias is shown in Fig. 5. These data suggest that the magnitude of sampling bias can be reduced by locating the probe deeper into the facepiece cavity. With the U.S. Divers facepiece, the deeper probe depths significantly improved sampling. On the MSA and Scott facepieces the sampling was also improved at the deeper probe depths; however, the improvement was not significant. Additional research is needed to evaluate the sampling bias associated with probing depths greater than 0.5 in. (12.5 mm).

Owing to the significant interaction between leak site and breathing pattern, evaluations of sampling bias associated with these factors are considered and discussed together. To test for differences due to leak site the breathing pattern was held constant and a Duncan Multiple Range Test (DMRT) conducted on the leak site means associated with that pattern. Results for the MSA half-facepiece are shown in Fig. 6. The mean sampling biases for nose breathing ranged from −85% for leakage at the nose to 20% for leakage at the chin. With this breathing pattern, sampling for leakage at the nose was significantly more biased than sampling for leakage from the other two locations. With the mouth breathing pattern, the mean sampling bias values were considerably reduced, ranging only from −23% to −8%. These data seem to indicate that more consistent sampling is achieved with mouth breathing than with nose breathing.

The data for the Scott half-facepiece are presented in Fig. 7. For nose breathing, the sampling bias ranged from −76% for leakage at the nose to −8% for leakage at the chin. Sampling for nose or cheek leakage was significantly more biased than sampling for chin leakage. As observed with the MSA half-facepiece, the spread in the sampling bias falls markedly with mouth breathing, ranging only from −49% to −45%. Again mouth breathing seems to result in more consistent sampling.

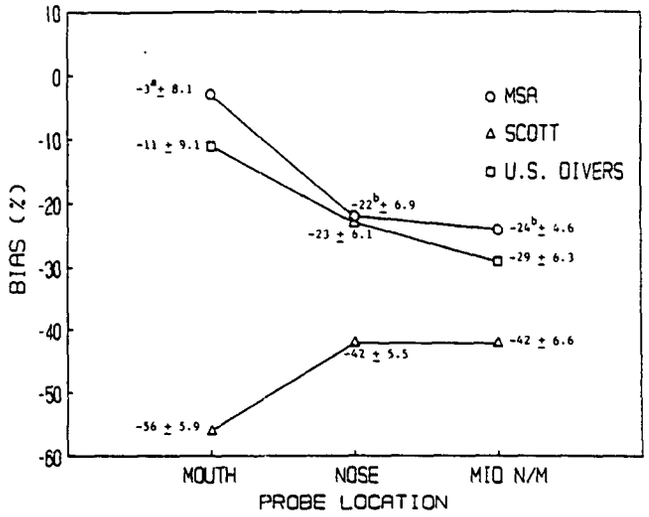

FIG. 4. Sampling bias for different mid-line probe locations on half-facepieces. Values are mean ± S.E. for $n = 27$ treatment combinations. Mean values were calculated without consideration of other significant parameters. Means within respirator type with different superscripts are significantly different at $P < 0.05$.

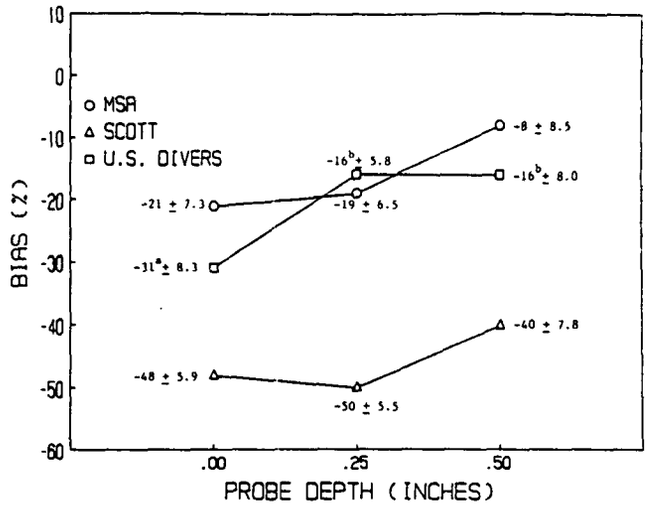

FIG. 5. Sampling bias for different probe inlet depths on half-facepieces. Values are mean ± S.E. Treatment combinations (n) for probe depths = 28 for flush, 30 for 0.25 in. and 23 for 0.5 in. The mean values were calculated without consideration of other significant parameters. Means within respirator type with different superscripts are significantly different at $P < 0.05$.

The data on the U.S. Divers half-facepiece are presented in Fig. 8. When nose breathing the sampling bias ranged from −57% for leakage at the nose to 45% for leakage at the chin. The mean bias for leakage in the area of the cheek was −19%. Sampling biases for the three leak areas were all significantly different. When breathing

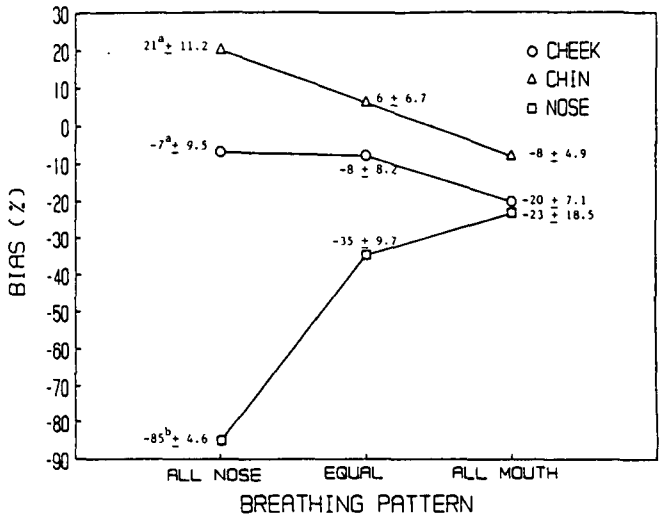

FIG. 6. Sampling bias on the MSA half-facepiece for breathing pattern and leak site. Values are mean ± S.E. Treatment combinations (n) for nose breathing = 8 for nose, 8 for cheek and 9 for chin; for equal breathing $n = 9$ for each leak; for mouth breathing $n = 8$ for nose, 9 for cheek and 12 for chin. Means within breathing pattern with different superscripts are significantly different at $P < 0.05$.

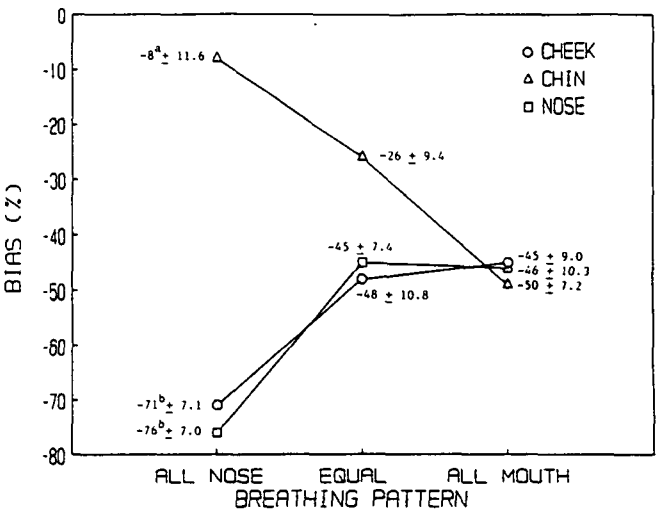

FIG. 7. Sampling bias on the Scott half-facepiece for breathing pattern and leak site. Values are mean ± S.E. Treatment combinations (n) for nose breathing = 7 for nose, 10 for cheek and 8 for chin; for equal breathing $n = 9$ for each leak; for mouth breathing $n = 9$ for nose, 7 for cheek and 13 for chin. Means within breathing pattern with different superscripts are significantly different at $P < 0.05$.

through the mouth, the range in the observed bias is again seen to decrease markedly, although a significant difference was still found to exist between the cheek and the other two leak sites.

In real life circumstances the area(s) where a respirator will develop face-seal

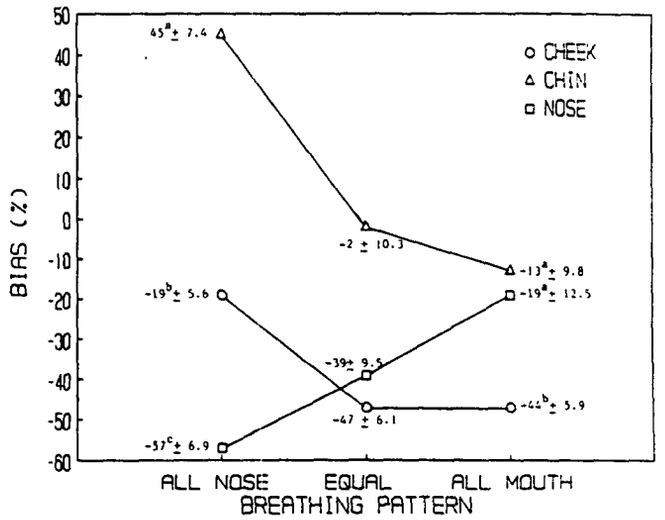

FIG. 8. Sampling bias on the U.S. Divers half-facepiece for breathing pattern and leak site. Values are mean ± S.E. Treatment combinations (n) for nose breathing = 8 for nose, 8 for cheek and 9 for chin; for equal breathing $n = 10$ for nose, 8 for cheek and 9 for chin; for mouth breathing $n = 8$ for nose, 9 for cheek and 12 for chin. Means within breathing pattern with different superscripts are significantly different at $P < 0.05$.

leakage cannot be fixed as they were in these experiments. It is possible that the locations would change somewhat randomly during a fit test as head–face movements change. Sampling inaccuracy and variability caused by such changes could be reduced by having the test subject breathe entirely through the mouth. On the other hand, the leak location may remain static. This may be true for particular wearer–respirator combinations. In these cases mouth breathing may not improve sampling accuracy.

Sampling rate was the last parameter considered in the experimental analysis. Rates of 1, 2 or 3 l. min^{-1} were not found to have any important effects on in-facepiece sampling in any of the half-facepieces. However, it was noted that the sampling rate itself caused a small amount of artificial (i.e. non-inhalation caused) face-seal leakage. The increase in leakage was small and probably would not be of major concern with tests on half-facepieces, where acceptable penetration commonly ranges from 1 to 2% or more. However, with full facepiece respirators, where acceptable penetration commonly ranges from 0.02 to 0.1%, this effect may be much more important and control measures may need to be taken. These findings should be considered when reviewing historical data, like that of HYATT (1976), where in-facepiece sampling rates as high as 8 l. min^{-1} were used.

The significant effect of sampling bias on results of quantitative facepiece fit testing can be demonstrated by expressing our concentration measurements in terms of fit factors (FF). The value of $\hat{C}_I$ measured for each of the 81 treatments was evaluated in the argument $FF = C_0/\hat{C}_I$, where C_0 is 12 900 ppm corrected for daily variation in temperature and pressure. On the MSA respirator the 'true' fit factor (breathing machine minute volume/leak minute volume) was 85. The mean of the 81 fit factors calculated from the in-facepiece sampling data was 213 (the geometric mean was not calculated because the data were not log-normal). The fit factor values ranged from a low of 44 to a high of 4727. On the Scott respirator the 'true' fit factor was 119. The

mean of the calculated fit factors was 367 with individual fit factors, ranging from a low value of 86 to a high value of 2082. For the U.S. Divers respirator the 'true' fit factor was 104. The mean of the calculated fit factors was 177, with individual fit factors ranging from a value of 56 to a value of 1384. These fit factor calculations serve to illustrate the very significant impact that unrepresentative in-facepiece sampling has on the integrity of fit test results.

Leak geometry experiment

The findings from the leak geometry experiment are summarized in Table 6. The mean values of C_i' are very similar between the different tube geometries for each brand of facepiece, indicating that the penetrations were very similar. The ANOVA analysis conducted on the data indicated that the cross-sectional geometry was not a significant factor for sampling with any of the three half-facepieces.

TABLE 6. SAMPLING RESULTS FOR CIRCULAR AND SLIT FACE-SEAL LEAK GEOMETRIES

Respirator	Parameter	n	C_i' mean (ppm)	S.D.	$\hat{C}_i$ mean (ppm)	S.D.	$\beta(\hat{C}_i)$ mean (%)	S.D.
MSA	Circular	12	179	12.8	108	59.4	−39	34.3
	Slit	12	177	10.7	95	59.6	−46	34.1
Scott	Circular	12	169	6.3	126	56.2	−26	32.2
	Slit	12	169	6.6	128	57.0	−24	34.9
U.S. Divers	Circular	12	168	3.7	164	43.2	−3	26.4
	Slit	12	169	7.1	162	46.3	−4	28.0

Since the circular- and slit-type geometries represent reasonable geometric extremes in the shape that an actual leak could potentially assume, these findings suggest that the cross-sectional geometry of a leak, regardless of the shape it assumes at any instant in time, would not be a major sampling problem for collecting gas or vapour air samples inside half-facepieces.

Multiple leak experiment

The findings of the paired leak experiment are summarized in Table 7. The difference in the magnitude of the 'true' concentration for the treatment groups results from the fact that more total inboard leakage was occurring when two areas of leakage were present. In both treatment groups the concentration measured by in-facepiece sampling underestimated the 'true' concentration. No significant differences were detected in the sampling bias associated with the two treatment groups.

Volumetrically different flow rate experiment

The data collected on volumetrically different leak rates is presented in Table 8. No significant difference in sampling was detected between leak rates. These data do suggest a slight trend which suggests that sampling bias decreases with increasing volume of leak rate. Further research, involving larger leak rates (for example 2, 5 and 10%) is needed to evaluate clearly this effect for half-facepieces. The analysis did indicate a significant effect due to leak site–breathing pattern interaction which was

TABLE 7. SAMPLING RESULTS FOR HALF-FACEPIECE RESPIRATORS WITH MULTIPLE AREAS OF LEAKAGE

Facepiece	Parameter	n	C_i' mean (ppm)	S.D.	$\hat{C}_i$ mean (ppm)	S.D.	$\beta(\hat{C}_i)$ mean (%)	S.D.
MSA	Single	9	141	7.50	127	69.6	−11	52.9
	Double	9	152	7.50	112	31.0	−28	24.8
Scott	Single	9	133	5.37	91	66.4	−37	44.8
	Double	9	137	7.36	95	48.7	−32	37.0
U.S. Divers	Single	9	134	3.92	88	48.0	−32	37.0
	Double	9	140	6.31	77	26.3	−43	20.7

similar to the finding of the screening experiment. The effect of leak geometry was not significant, which was consistent with the findings of the leak geometry experiment.

CONCLUSIONS

The additional results obtained on the Scott and U.S. Divers respirators are in good agreement with those previously reported for the MSA respirator (MYERS *et al.*, 1986) and fully support the hypothesis that face-seal leakage does not mix well within the cavity of the respirator during the inhalation phase of the respiratory cycle.

The large range in measured concentration values (all over 1 order of magnitude) is remarkable considering that:

(1) the different levels at which the study parameters were evaluated, except for probe depth, are well within the allowances normally considered acceptable for in-facepiece sampling; and

(2) the face-seal leak rate was relatively constant as indicated by the small standard deviation in C_i' values.

The variability associated with the estimates of $\hat{C}_i$ obtained with this widely used in-facepiece sampling technique illustrates the potential for a wide range of uncontrolled sampling errors that may occur during both quantitative facepiece fit testing and workplace protection factor testing on negative pressure half-facepiece respirators. The variability associated with quantitative facepiece fit test results has been recognized for some time and discussed at length. The general conclusion most often put forward is that respirator fit is a function of several varying factors (i.e. subject variability, tightening of straps, etc.) which sufficiently explains the observed measurement variability. However, the results of this study suggest that some of the observed variability in such test data may be actually due to varying magnitudes of sampling error. Different magnitudes of sampling error would be caused by changes in sampling probe locations and area of leakage and breathing pattern interactions. Such changes are inherent in intra- and inter-subject fit testing as it is now conducted.

Significantly different magnitudes of sampling bias between different probe locations, probe depths, leak sites, breathing patterns and facepiece designs suggest that the sampling bias associated with in-facepiece sampling may not be easily defined. Varying degrees of bias will exist for differing sets of parameters on different facepieces. This causes major complications in the interpretation and use of this type of quantitative data.

TABLE 8. MEAN SAMPLING BIAS ON HALF-FACEPIECES WITH VOLUMETRICALLY DIFFERENT LEAK RATES

Leak size	n	MSA (% bias)	S.D.	Scott (% bias)	S.D.	U.S. Divers (% bias)	S.D.
Small	18	−15	29	−45	41	−35	29
Medium	18	−8	36	−41	40	−24	27
Large	18	−4	35	−43	38	−22	30

Without unbiased sampling, data interpretations such as 'goodness-of-fit' selections, pass–fail criteria decisions on acceptable fit, etc., must be made with the recognition of the limitations imposed by unrepresentative sampling data. This recognition will require the respirator community to rethink carefully how it uses and interprets quantitative evaluations of respirator performance.

Within the constraints and design of the experiments, leak geometry, multiple leaks and volumetrically different leak rates were not found to be significant problems for conducting in-facepiece sampling.

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