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CAUSES OF IN-FACEPIECE SAMPLING BIAS—II. FULL-FACEPIECE RESPIRATORS*

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Abstract—A commonly used in-facepiece sampling procedure has been shown to provide unrepresentative sampling on full-facepieces. These experiments were conducted on a manikin test system using acetone vapour as a test agent. The sampling bias appears to be due to a number of parameters including: location and depth of sampling probe; area on the face-seal where inboard leakage occurs; breathing pattern (nose or mouth); and design of the facepiece. These results are consistent with those observed on half-facepieces. The results clearly show that the airflow pattern produced by the design of the full-facepieces had a very marked effect on sampling. Locating the sampling probe in the vicinity of an airstream cleaned by the air purifying elements caused large degrees of undersampling of face-seal penetration. In-facepiece sampling can be so influenced by airflow pattern that it renders it impossible to make a meaningful comparison between full-facepieces that incorporate different airflow patterns. The in-facepiece sampling procedure studied appears to be inadequate and unsuitable for providing reliable quantitative performance data on full-facepieces. The performance data are not strong enough to be used as a discriminating criterion to select a 'best fitting' facepiece from a group of candidate facepieces unless the fits would be grossly different. The same concern can be felt about using the data as a criterion to determine whether a fit exceeds a certain minimally aceptable level; or to raise maximum use concentrations. Conclusions from past research, which have been based upon sampling results obtained by this or a basically similar sampling procedure, must be viewed with considerable caution in the light of this new information.

INTRODUCTION

RESEARCH results from the National Institute for Occupational Safety and Health (NIOSH) (MYERS and ALLENDER, 1984; MYERS *et al.*, 1988), 3M (MULLINS, 1985) and the United Kingdom Health and Safety Executive (BENTLEY, 1985) have demonstrated, on manikin test systems using half-mask respirators, that results of samples collected by in-facepiece sampling can be very unrepresentative of the environment within the facepiece cavity. One of the causative factors for this sampling bias is the incomplete mixing of leakage inwards through the face-seal during the inspiratory phase of the respiratory cycle. We have suggested the underlying cause of the incomplete mixing to be the existence of relatively well-defined streams of leakage between a leak site and the nose or mouth during each inhalation. This hypothesis is consistent with the results and analysis of our half-facepiece sampling data and has been supported by visual observations of streamlines of face-seal leakage within the cavity of a full-facepiece respirator (MYERS *et al.*, 1986). The purpose of this research was to extend our studies to full-facepiece respirators and evaluate the representativeness of in-facepiece

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

sampling on these devices under experimental conditions similar to those we previously employed on half-facepiece respirators.

METHODS AND MATERIALS

Test respirators

Three brands of full-facepiece respirators were selected for study. They were the MSA Ultra-Twin Model, the Scott, Scott-O-Vista Model 65, and the U.S. Divers, Model 3200. All respirators were tested without an inner mask (i.e. nose cups).

The MSA ultra-twin facepiece is designed so that air entering the facepiece through the inhalation valves is routed through air ducts to the base of the visor where it is discharged up over the visor. The inspired air is handled this way to reduce fogging on the visor caused by high humidity in the exhaled air.

The Scott-O-Vista facepiece is designed so that the cartridge holder assembly, including the inhalation valve and air deflector, can be removed from the facepiece. Two types of air deflectors have been used with this assembly. One type of deflector directs the inspired air up over the facepiece to reduce fogging. The facepiece configured in this fashion is designated as Scott No. 1. A second type of deflector used with the cartridge holder assembly directs the inspired air down into the area of the chin. The facepiece configured in this fashion is designated as Scott No. 2. In all other respects the facepieces and cartridge holder assemblies were identical. This unique situation allowed us to examine how different patterns of airflow through the facepiece affected sampling.

The U.S. Divers respirator is designed with the inhalation valves located far back on the side of the facepiece, slightly below the level of the mouth. The valves have no flow deflectors and simply open into the cavity of the respirator.

Selection of parameters for study

The parameters studied on the full-facepiece respirators were basically identical to those evaluated previously on half-facepieces (MYERS *et al.*, 1986).

The levels of each parameter evaluated during testing are as follows:

(1) sampling rates were 1, 2 and 3 l. min^{-1};

(2) areas of face-seal leakage were positioned in the corner of the eye, the cheek and the chin (Fig. 1);

(3) breathing was entirely through the mouth, entirely through the nose or equally divided between the nose and mouth;

(4) probe inlet positions were flush on the visor or wall of the respirator, halfway between the visor or wall of the respirator and the manikin, and within 6.4 mm (1/4 in.) of the surface of the manikin (Fig. 1); and

(5) probe locations on the MSA and U.S. Divers full-facepieces were positioned on the mid-line approximately opposite the area of the mouth, in the area between the nose and mouth and in the area of the nose. Probing opposite the nose was analogous to the probe location recommended by these two manufacturers. On the Scott facepiece the location corresponding to the mouth was situated on the side of the respirator. This position is the standard recommendation made by Scott in its fit test literature. The probe location corresponding to the nose and mid-nose–mouth positions were on the mid-line of the facepiece.

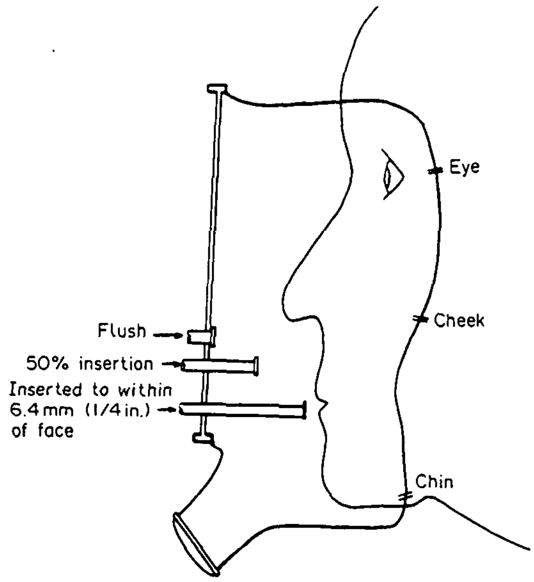

FIG. 1. Areas of face-seal penetration and probe depths evaluated on full-facepieces.

TEST SYSTEM AND EXPERIMENTAL DESIGN

The test system and experimental designs for this study were identical to those previously described for the half-facepiece studies (MYERS *et al.*, 1988). A summary is provided in Table 1 of the predicted concentrations C_1, the unbiased concentration measurement C_1', sampled from the test system plumbing, and the rates of face-seal penetration (P) and fit ratios obtained on the test system. All penetrations were kept below 0.1% so as to result in fit ratios of greater than 1000.

TABLE 1. CONCENTRATION AND PENETRATION DATA ON THE TEST SYSTEM USED TO EVALUATE FULL-FACEPIECE RESPIRATORS

Facepiece	n	Face-seal penetration (% P)	C_1 mean (ppm)	C_1' mean (ppm)	Fit ratio $\frac{1}{\% P}$
MSA	81	0.087	15.7	15.3	1150
Scott No. 1	81	0.071	12.6	13.5	1410
Scott No. 2	81	0.088	15.4	15.2	1140
U.S. Divers	81	0.091	15.9	15.9	1100

RESULTS AND DISCUSSION

A summary of the sampling results obtained for each full-facepiece is presented in Table 2. The in-facepiece measurement is noted as $\hat{C}$ and the unbiased measurement as C'. An observation worth noting is that the MSA and Scott No. 1 facepieces are both designed to direct the inspiratory airflow over the visor which also happens to be the area where the sampling probe is usually located. On the other hand, the Scott No. 2 and the U.S. Divers facepieces do not have the same airflow design. These data and those presented in subsequent figures clearly illustrate that in-facepiece sampling can be affected greatly by the inspiratory airflow characteristics of a facepiece.

TABLE 2. SAMPLING RESULTS ON THREE BRANDS OF FULL-FACEPIECES

Facepiece	n	C_i' mean (ppm)	$\hat{C}_i$ mean (ppm)	S.D.	$\hat{C}_i$ range	$\%\beta(\hat{C}_i)$ mean	$\%\beta(\hat{C}_i)$ range
MSA	81	15.3	7.3	5.9	0.8–27.7	−53	−94 to +74
Scott No. 1	81	13.5	6.2	3.8	1.3–17.8	−53	−91 to +30
Scott No. 2	81	15.2	14.3	9.1	1.4–37.5	−5	−89 to +140
U.S. Divers	81	15.9	17.2	2.1	11.9–22.4	8	−15 to +38

A General Linear Model (GLM) procedure identical to that previously described (MYERS *et al.*, 1988) was used to identify the parameters of the experiment that caused significant changes in sampling bias. The model used in the GLM procedure considered all five main parameters and all two-way interactions. The results are summarized in Table 3.

TABLE 3. PARAMETERS WITH SIGNIFICANT EFFECTS ON SAMPLING IN FULL-FACEPIECES

Effect	MSA	Scott No. 1	Scott No. 2	U.S. Divers
Probe location	X	X	X	—
Probe depth	X	X	—	X
Leak site	X	X	X	X
Breathing pattern	X	X	—	X

With the MSA and Scott No. 1 full-facepieces probe location, probe depth, area of face-seal leakage and breathing pattern (nose, mouth or equal) were identified as significant factors. On the Scott No. 2 facepiece only probe location and area of face-seal leakage were identified as significant factors. With the U.S. Divers facepiece probe depth, area of face-seal leakage and breathing pattern were the significant factors. In addition to these main effects, various interactions were also found to be present. Changing the rate of in-facepiece sampling from 1, 2 and 3 l. min^{-1} was not a significant factor for any of the full-facepieces. This observation was identical with that found with half-facepiece respirators (MYERS *et al.*, 1988).

The sampling biases associated with different probe locations on the full facepiece respirators are shown in Fig. 2. One thing to notice in this figure is that the sampling bias data obtained on the MSA and Scott No. 1 full-facepieces and the data from the Scott No. 2 and U.S. Divers full-facepieces tend to group. These groupings are consistent with the previously noted similarity in how the inspired air is discharged into the facepieces. The mean sampling bias associated with the mouth probe location on the MSA respirator was −37%. The magnitude of the bias increased to −46% for the mid-nose–mouth probe location and −75% for the nose probe location. The distance separating the mouth and nose probe locations was approximately 4 cm (1.6 in.). Sampling with the probe located at the nose (the approximate location recommended by the manufacturer) was significantly worse than the other two probe locations. Very similar observations were made on the Scott No. 1 facepiece. The mean sampling bias was −50% when the probe was positioned on the side of the facepiece (the approximate location recommended by the manufacturer), −49% when positioned mid-nose–mouth and −60% when positioned at the nose (Fig. 2). Like the MSA facepiece, sampling with the probe positioned at the nose was significantly worse than with the other two positions. With this facepiece, a significant probe location–leak site interaction was also identified. This interaction showed that significantly better sampling occurred when the face-seal leakage was in the area of the eye, as compared with the other two face-seal leak sites, regardless of probe location. This observation suggests that the patterns of airflow in the facepiece cavity during inhalation were such that leakage in the area of the eye was being more uniformly mixed than leakage from the other two leak positions.

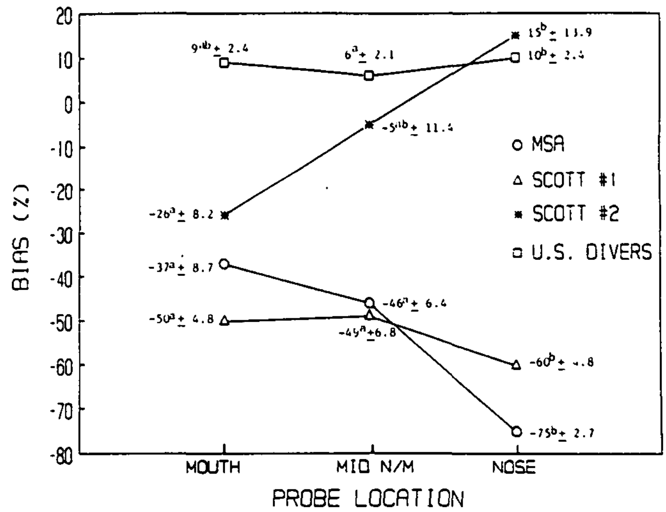

FIG. 2. Sampling bias for different probe locations on full-facepieces. Values are means ±S.E. for $n = 27$ treatment combinations. Mean values were calculated without consideration of other significant parameters. Means within respirator type with different superscripts are significantly different at $P < 0.05$.

One possible explanation of why the nose probe position was significantly worse than the other two probing locations for the MSA and Scott No. 1 facepieces is that 'clean' inspiratory air (drawn through the air-purifying elements) directed over the visor produces a 'clean' air wash over the probe during inhalation. During inhalation the sample is then comprised largely of clean air. When the probe is located at the bottom edge of the visor, it is not in the immediate area of the clean air wash.

The data collected on the Scott No. 2 facepiece, physically the same facepiece as the Scott No. 1 except for the change in airflow deflector, further supports this proposition. The sampling bias associated with the probe positioned at the mouth was −26% when the inspiratory airflow was not diverted over the visor as compared with −50% when it was. The bias improved similarly at the mid-nose–mouth and nose probe locations. The Scott No. 2 facepiece exhibited a significant probe location–breathing pattern interaction and a significant probe location–leak site interaction. These interactions also demonstrate that a severe sampling bias occurred when the sampling probe was positioned in an area flushed by 'clean' inspiratory airflow.

Based upon these findings the fit results obtained by using in-facepiece sampling techniques which employ on-the-visor mounting should be evaluated very carefully. A full-facepiece designed to divert inspiratory airflow over the visor may falsely appear to provide a superior fit as compared with a facepiece not having similar design features when the sampling probe is positioned flush on the visor. This situation makes it extremely difficult to interpret fit data obtained for different brands of full-facepieces on an individual: i.e. to select the 'best fitting' respirator. This difficulty can be illustrated by using the data collected on the MSA and Scott No. 2 facepieces to calculate some hypothetical fit factors. The fit factor would be the numerical result obtained by dividing the concentration of acetone in the leak, which is analogous to the concentration outside the respirator, by the concentration of acetone measured inside the facepiece cavity by in-facepiece sampling. It should be noted from Table 1 that the average face-seal leakages on the MSA and Scott No. 2 facepieces were essentially equal. The true fit factor is simply the inverse of the face-seal leakage or 1150 and 1140, respectively. However, the arithmetic mean value of the 81 fit factors calculated from samples obtained by in-facepiece sampling was 4800 for the MSA facepiece but only 2390 for the Scott No. 2 facepiece. The two facepieces had virtually equal face-seal leakages, but the larger sampling bias on the MSA facepiece will lead to the false conclusion that it fits 'better'.

The U.S. Divers full-facepiece demonstrated relatively small degrees of sampling bias for different probe locations, however the mid-nose–mouth probe position was significantly better than the nose position (Fig. 2). There is obviously better mixing with this particular full-facepiece, although the feature of its design responsible for enhancing the mixing is as yet unknown.

The mean effect of different probe sampling depths across all the other experimental parameters is illustrated in Fig. 3. Again the grouping of the data for facepieces having similar inspiratory airflow routing is evident. The probe depth indicated as 95% in the figure corresponds to extending the mouth of the probe to within approximately 6 mm of the face. The importance of probe depth on sampling is apparent with the MSA and Scott No. 1 facepieces. Increasing the depth of the sampling probe significantly improved the sampling. These findings are consistent with the idea that sampling inside the facepiece is sensitive to the location of the discharged inspiratory airflow. When the airflow is over the visor, extending the probe into the cavity of the respirator serves to move it through and away from the influence of the clean air discharge. As a result, significantly better sampling is obtained with the deep probe position. Increasing the depth of probing did not significantly improve the sampling on the Scott No. 2 facepiece.

With the U.S. Divers facepiece, locating the probe mid-way between the visor and face resulted in a small but significant change in sampling as compared with the other probe depths. The analysis of the U.S. Divers data indicated a significant probe depth–leak site interaction. The character of the interaction is illustrated in Fig. 4. When the probe is flush on the visor no differences are seen in the sampling for different sites of

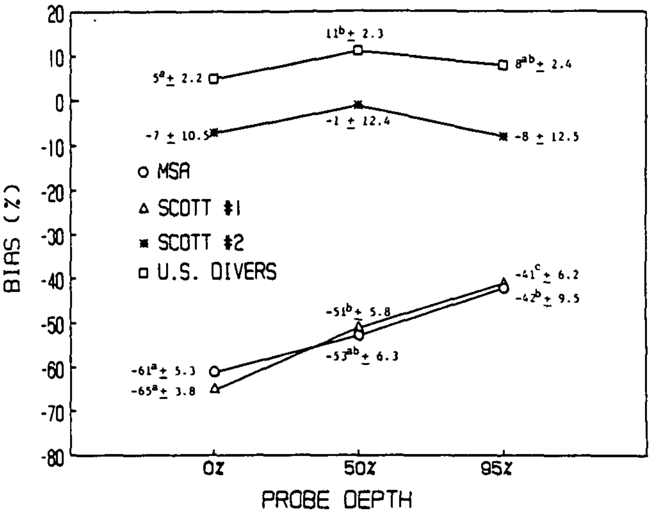

FIG. 3. Sampling bias at different probe depths on full-facepieces (0% = flush on facepiece, 100% = against headform). Values are means ± S.E. Treatment combinations $n = 28$ for flush, 30 for 50% and 23 for 95%. Mean values were calculated without consideration of other significant parameters. Means within respirator type with different superscripts are significantly different at $P < 0.05$.

face-seal leak. However, as the probe is extended deeper into the cavity some significant sampling differences do develop. At 50% insertion, sampling for a chin leak was significantly better than for a leak at the cheek or nose, whereas at 95% insertion the differences in sampling were only significant between leaks at the chin and at the nose. The implications of this interaction support the hypothesis that face-seal leakage is streamlining inside the cavity causing areas of concentration gradients.

The effect of the position of the face-seal leak on in-facepiece sampling is illustrated in Fig. 5. As noted with the other parameters already discussed, the trends in the MSA and Scott No. 2 sampling data were similar. The worst sampling occurred when the leak came through the area of the chin while the best sampling occurred when the leak came through the area of the eye. For the MSA and Scott No. 1 facepieces, sampling was significantly better for leakage penetrating the face-seal in the area of the eye than for penetration through the other positions.

The reason for the better sampling may be two-fold. First a leak near the eye or the temple has to travel a greater distance within the cavity to enter the respiratory tract (be it nose or mouth) than a leak in the area of the cheek or chin. Therefore there is more time for diffusional mixing or mechanical mixing due to airflow patterns. The second reason relates to how the inspiratory air is handled. By forcing the air to flow up over the visor it is kept from effectively flushing the cheek and chin areas of the cavity, thereby reducing the potential for mixing. On the other hand, this pattern brings the airflow into the top of the facepiece cavity at the eye–temple area. Here a change in direction of flow must occur as the air flows down the face to one of the entries to the respiratory tract. The improved flushing and changes in flow direction result in better mixing of the leak contaminant which produces better sampling results.

With the Scott No. 2 and U.S. Divers facepieces, a somewhat opposite trend is seen.

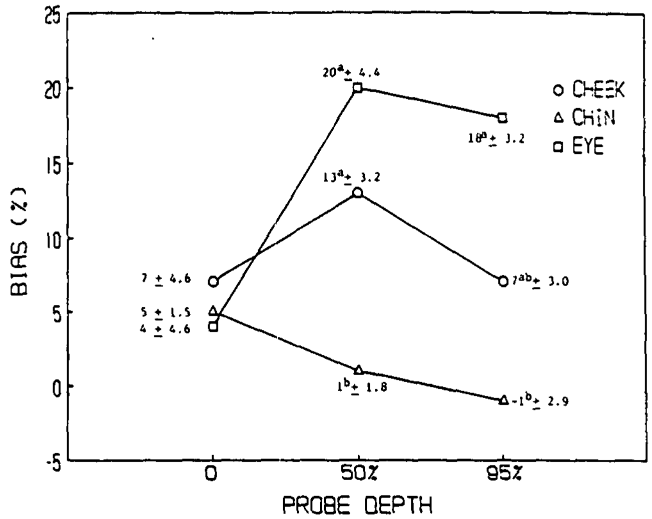

Fig. 4. Sampling bias on the U.S. Divers full-facepiece for probe depth (0% = flush on facepiece, 100% = against headform) and leak site. Values are mean ±S.E. Treatment combinations: probe depth = 0% $n = 9$ for chin and cheek and 10 for nose; probe depth = 50% $n = 11$ for chin, 10 for cheek and 9 for nose; for probe depth = 95% $n = 8$ for chin and cheek and 7 for nose. Means within probe depth with different superscripts are significantly different at $P < 0.05$.

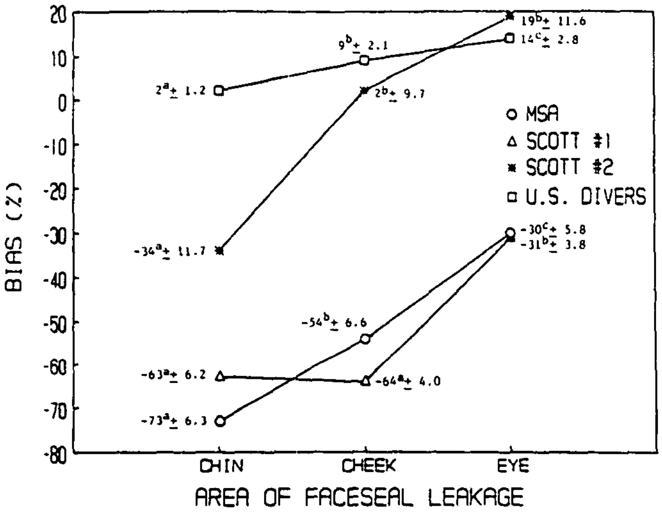

Fig. 5. Sampling bias for different areas of leakage on the face-seal perimeter of full-facepieces. Values are means ±S.E. Test combinations $n = 28$ for chin, 27 for cheek and 26 for eye. Mean values were calculated without consideration of other significant parameters. Means within respirator type with different superscripts are significantly different $P < 0.05$.

With these facepieces, sampling for leakage coming through the area of the chin was significantly better than for leakage elsewhere. This somewhat opposite trend can be explained by the fact that these facepieces dump the inhalation air into the area of the chin. The improved flushing and mixing in this area results in improved sampling just as it did for the area round the eye on the MSA and Scott No. 1 facepieces.

The position at which leakage occurs on the face-seal perimeter is usually unknown. Therefore changing leak positions due to head or face movements or different fits will create an unquantified amount of sampling bias in most existing in-facepiece sampling procedures. There is a very real possibility that this bias will be introduced during multiple intra- or inter-subject donning of respirators and may be quite substantial in magnitude.

The sampling bias observed with different breathing patterns is shown in Fig. 6. Significantly worse sampling resulted with mouth breathing on both the MSA and Scott No. 2 facepieces. There was a breathing pattern–leak site interaction identified by the analysis for both facepieces. The character of the interactions was consistent with what would be expected to occur with streamlines developing between individual leak sites and entries (nose or mouth) into the respiratory tract.

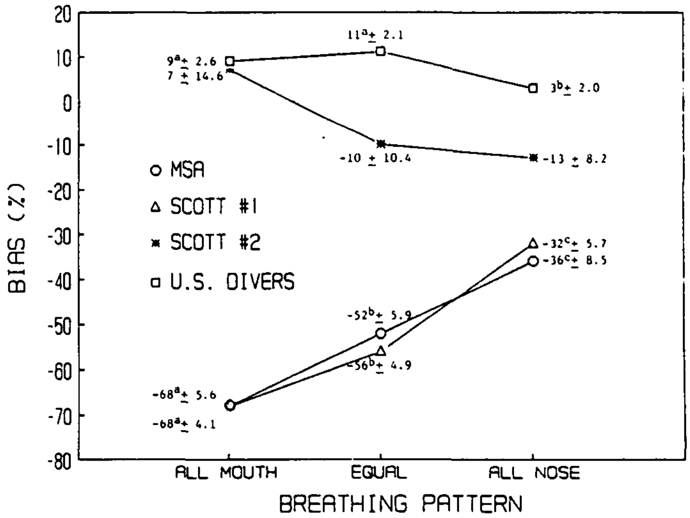

FIG. 6. Sampling bias for different breathing patterns on full-facepieces. Values are means ±S.E. Treatment combinations $n=29$ for mouth, 27 for equal and 25 for nose. Mean values were calculated without consideration of other significant parameters. Means within respirator type with different superscripts are significantly different at $P<0.05$.

With nose breathing, sampling on the U.S. Divers facepiece was significantly better than with mouth breathing, but the improvement was small. With the Scott No. 2 facepiece sampling was not found to be influenced by breathing pattern.

Sampling was not affected by sampling at rates of 1, 2 or 3 l. min^{-1} with any of the facepieces.

A second experiment was conducted with the full-facepieces to evaluate effects of volumetrically different leak rates. The concern is that small leaks possibly may not mix as homogeneously within the facepiece cavity as large leaks and therefore may be either harder to detect or harder to measure accurately. The leak rates we examined, expressed as minute volume and percentage of breathing machine volume, are given in Table 4.

The sampling data are presented in Fig. 7. For the MSA respirator, sampling was significantly worse with a large leak in comparison with a small leak. The same general trend appears with the Scott No. 1 facepiece, although no differences were found to be significant. Leak volume did not appear to affect sampling in the Scott No. 2 facepiece. In the U.S. Divers facepiece, the sampling was again significantly different for the large leak when compared with the other two leak sizes. The causes for these observations are not clear. Additional research is needed to study this relationship further.

It is important to emphasize again that these experiments were conducted on full-facepieces not equipped with an inner mask. The bias associated with in-facepiece sampling on these facepieces may not reflect what would occur with full-facepieces equipped with an inner mask if the sampling probe were located in the inner mask. The bias associated with such sampling still must be evaluated experimentally. Furthermore, the use of a gas or vapour which is not absorbed by the lungs may attenuate the magnitude of the sampling bias observed. However that possibility still awaits confirmation from experimental results.

Conclusion

It has been demonstrated that in-facepiece sampling from full facepiece respirators is affected by a number of parameters, leading to the collection of unrepresentative samples. The parameters identified in this research were:

(1) location and depth of the sampling probe;
(2) area on the face-seal where penetration occurs;
(3) breathing pattern (nose or mouth); and
(4) design of the facepiece.

Numerous important interactions were identified between all the parameters excluding design of the facepiece and leak rate. The nature of the interactions was consistent with what would be expected if streamlining of face-seal penetration inwards was occurring.

The results were consistent with those observed on half-facepiece respirators. From the significantly different levels of sampling bias observed among the half-facepieces it was speculated that certain features in the design of a facepiece could affect sampling. The full-facepiece research has not only confirmed that conclusion but has provided considerably more insight into it. The sampling results clearly show that inspiratory airflow patterns in the full-facepieces had a very marked effect. Locating the sampling probe in or near the clean inspiratory airstream caused large degrees of undersampling. The sampling bias is so influenced by inspiratory airflow patterns that it makes it impossible to achieve an objective comparison between full-facepieces with different internal airflow patterns.

The in-facepiece sampling procedure studied is inadequate and unsuitable for providing reliable quantitative performance data on full-facepieces. The performance data are not strong enough to be used as a discriminating criterion for selecting a 'best fitting' facepiece from a group of candidate facepieces unless the fits would be grossly different, for example $\pm 50\%$. In such cases, qualitative fit tests with adequate protocols may be a less expensive alternative. The same concern can be raised about

TABLE 4. LEAK VOLUMES AS A PERCENTAGE OF TOTAL MINUTE VOLUME

Leak size	Full-facepiece MSA	Scott No. 1	Scott No. 2	U.S. Divers
Small	0.05% (15.9)	0.051% (16.2)	0.051% (16.2)	0.047% (15.1)
Medium	0.124% (39.8)	0.125% (39.9)	0.125% (39.9)	0.120% (38.5)
Large	0.216% (69.1)	0.212% (67.7)	0.212% (67.7)	0.208% (66.6)

Number in parenthesis in ml min^{-1}.

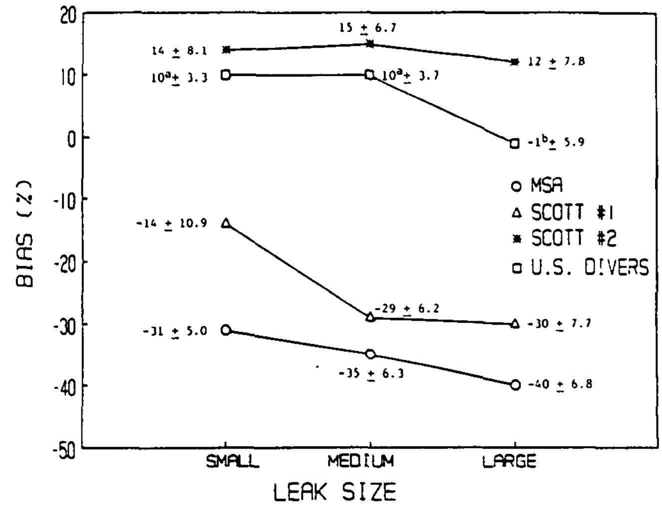

FIG. 7. Sampling bias for different leak rates on full-facepieces. Values are means ±S.E. Treatment combinations $n = 27$ for all leak sizes. Mean values are calculated without consideration of other significant parameters. Means within respirator type with different superscripts are significantly different at $P < 0.05$.

using the data as a criterion to determine if a fit exceeds a certain minimally acceptable level. Maximum use concentrations (MUC), protection factor classifications, etc., based upon quantitative fit research results obtained by this or a basically similar in-facepiece sampling procedure, must be viewed with considerable caution in the light of this new information.

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