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EVALUATION OF NEW IN-FACEPIECE SAMPLING PROCEDURES FOR FULL AND HALF FACEPIECES

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Abstract—Precision and bias were determined on five different methods of conducting in-facepiece sampling. In-board penetration occurred through fixed, circular, leak geometries positioned at different areas on the face-seal of full and half facepiece negative-pressure respirators. The sampling procedures evaluated in the study were: (1) a continuous, low sampling rate, flush on the respirator, mid nose–mouth probing (CLF) procedure; (2) a continuous, high sampling rate, deep front-of-mouth probing (CHD) procedure; (3) a pulsed exhalation, deep front-of-mouth probing (PED) procedure; (4) an exhalation value discharge (EVD) procedure; and (5) a pulsed inhalation, deep front-of-mouth, probing (PID) procedure. The CLF procedure represents a recommended in-facepiece sampling procedure in the United States. Evaluations were done on populations of nine full facepiece respirators and five half facepieces. The full facepieces were not equipped with nose cups. The average sampling biases on the full facepieces were: (1) CLF procedure, −21%; (2) CHD procedure, −3%; (3) PED procedure, 0.7%; (4) EVD procedure, −14%; and (5) PID procedure, −12.3%. On the five half facepiece respirators the average sampling biases were: (1) CLF procedure, −26%; (2) CHD procedure, −13%; (3) PED procedure, −4%; (4) EVD procedure, −2%; and (5) PID procedure, −24%. The bias observed with each method was found to be affected, to some extent, by the location of the face-seal penetration.

INTRODUCTION

LABORATORY research has demonstrated that in-facepiece sampling on half and full facepiece, negative-pressure respirators is subject to large sampling biases. The underlying cause of the sampling bias is incomplete mixing, within the facepiece cavity, of the face-seal leak with the remainder of the tidal volume drawn through the air-purifying elements (MYERS *et al.*, 1986b; OESTENSTAD *et al.*, 1990). A number of factors contribute significantly to this sampling bias. These include the location and depth of the sampling probe (MYERS *et al.*, 1988; MYERS and ALLENDERS, 1988; BENTLEY, 1988), the location of the face-seal leak (MYERS *et al.*, 1988; MYERS and ALLENDER, 1988; BENTLEY, 1988; MULLINS, 1988; HOLTON *et al.*, 1987; OESTENSTAD *et al.*, 1990), whether the wearer is nose or mouth breathing (MYERS *et al.*, 1988; MYERS and ALLENDER, 1988), the aerosol size-selective features of different leak sizes (HOLTON *et al.*, 1987; HINDS and KRASKE, 1987; MYERS *et al.*, 1991) and the inspired air flow patterns in different designs of facepieces (MYERS and ALLENDER, 1988). A model by CAMPBELL and MYERS (1989) evaluated the effect of cavity flushing and mixing on observed in-facepiece penetration measurements made on full facepiece respirators. By iteratively selecting coefficients for these parameters the model was able to predict the observed in-facepiece concentration measurements made in the laboratory on the full facepiece respirators.

The objective of this research was to quantitate the bias and precision of the recommended in-facepiece sampling procedures in the United States and Europe, and

some other modified in-facepiece sampling procedures. The goal of the evaluation process was to identify if possible, an in-facepiece sampling procedure that had the lowest bias and greatest precision.

METHODS AND MATERIALS

Test-system

A laboratory test system employing a vapour challenge agent was used to evaluate the bias in the sampling methods (Fig. 1). An acetone vapour was generated using a syringe pump and evaporating column. The liquid delivery rate of the syringe pump was calibrated. Dilution air to the evaporating column was maintained by a calibrated flow-controller. The acetone-in-air mixture was plumbed into a 22 l. reservoir to help dampen fluctuations in concentration. Acetone concentration in the reservoir was calculated from the liquid delivery rate of the syringe pump and the dilution air flowrate. In addition it was monitored with a calibrated infra red (i.r.) analyser. The reservoir was maintained at approximately ambient pressure and allowed to exhaust to a hood. Acetone vapour was transported via Teflon tubing from the reservoir to the respirator test set-up where it could be connected, as appropriate, to each leak site on the face-seal perimeter.

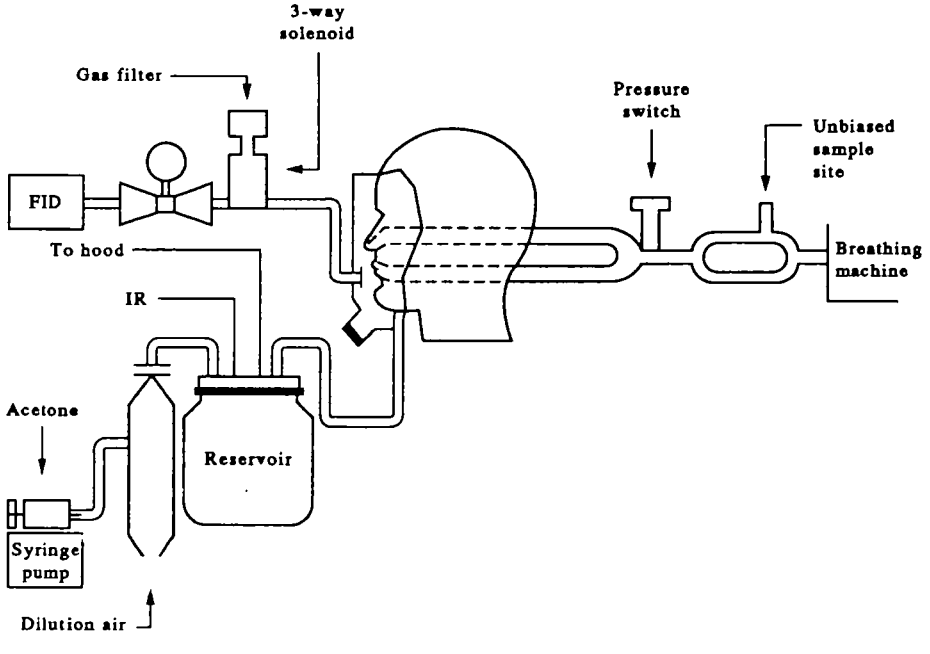

FIG. 1. Experimental test system used to evaluate the bias in different methods of sampling for inboard, face-seal, penetration on half and full facepieces.

The full or half facepieces were equipped with organic-vapour cartridges. The assembled respirator was mounted on a headform with an airtight face-seal for testing. The headform was designed to accommodate nose or mouth breathing. Leaks through the face-seal perimeter were positioned in the area of the chin, cheek and eye on the full

facepieces, and in the area of the chin, cheek and nose on the full facepieces. Inboard flow of acetone vapour through the leak resulted solely from the negative pressure created within the facepiece cavity during each inhalation cycle of the breathing machine.

The experimental design considered both a 'large' and a 'small' inboard leak. Both leak flows were introduced into the full facepiece cavity through 18-gauge needles. The volume and velocity of the 'large' leak was a function of the pressure differential inside the facepiece and the diameter and length of the 18-gauge needle. Given the pressure differentials experienced with the full facepieces, this size needle produced an inboard penetration of approximately 0.1% (fit factor of 1000). The 'smaller' leak was produced by simply restricting the flow of acetone in the tubing which connected the 18-gauge needle to the acetone vapour reservoir.

Before data collection started on half facepieces, the full facepiece test data were examined. The sampling biases measured with the 'small' leak on the full facepieces were found to be routinely lower than those associated with the 'large' leak. While considering possible explanations for these observations with the full facepieces a suspicion was raised that the methodological approach taken to simulate the 'small' leak may not have been the appropriate. In retrospect, the small leak should have been simulated with a smaller gauge needle actually penetrating the face-seal perimeter rather than simply restricting the flow through the 18-gauge needle. Corrections were made to the experimental set-up before testing began on the half facepieces.

Evaluations conducted on the half facepieces with the 'large' and 'small' leak flows were done utilizing two different size needles each of which penetrated the face-seal perimeter. The larger leak resulted in a penetration of approximately 1% (fit factor of approximately 100) and the smaller leak a penetration of approximately 0.2% (fit factor of 500).

Breathing was simulated by breathing machine operated with a 622 kp-m min^{-1} (kp is the gravitational weight of 1 kg) workrate cam. The tidal volume produced with the cam was 1.58 l. The breathing frequency was maintained between 18 and 19 cycles min^{-1} resulting in minute volumes of between 29 and 31 l. The inspired air was exhaled back through the facepiece without removal of the acetone.

Pulsed sample collection of the unbiased sample location and the in-facepiece sample location was accomplished using a pressure-sensitive switch that activated a three-way solenoid valve. One port of the solenoid was attached to the in-facepiece sampling line while the other was connected to an organic vapour gas filter open to room (acetone-free) air. Sample collection alternated between the respirator test set-up and acetone-free air.

A calibrated flame-ionization detector was used for real-time measurement of acetone concentration in collected samples. The analogue signal of the detector was monitored with a computer-based data acquisition system.

Experimental design and data analysis

Full facepieces. The original experimental design was a fixed-effects factorial model that considered three leak sites, two leak sizes and five sampling methods on nine models of full facepieces. There were three replications made for each of the 30 design cells for each of the nine facepieces. A total of 90 tests was run on each full facepiece. The nine facepieces were certified by NIOSH and represent the majority of different brands

of full facepieces which are not equipped with nose cups. In the text these nine brands are denoted as types A, C, G, M, N, P, S, U and W.

The accuracy of samples collected by the various sampling methods is expressed in terms of bias where the estimated bias is some function of the difference between the measured in-facepiece concentration and the 'true' concentration.

The sample representing the 'true' acetone concentration (C') was taken from the plumbing which connected the respirator and headform to the breathing machine (Fig. 1) and analysed by the flame ionization detector. Previous evaluations had indicated that samples taken from a similar site were not subject to sampling errors caused by location of face-seal leaks, breathing pattern and facepiece design (MYERS *et al.*, 1986a). This 'true' sample was assumed to be measured without error since the range in these measurements was negligible.

Four different measures of bias based on C' the 'true' concentration measurement and or $\hat{C}$ the in-facepiece concentration measurements were examined for use as the dependent or response variable in this analysis. The four were:

$$\beta_1 = (\hat{C} - C')/C' \tag{1}$$

$$\beta_2 = \ln[(\hat{C} - C')/C'] \tag{2}$$

$$\beta_3 = |(\hat{C} - C')|/C' \tag{3}$$

$$\beta_4 = \ln[\beta_3/(1 - \beta_3)]. \tag{4}$$

After preliminary testing of residuals in the original factorial model, β_2 was selected as the best measure of bias for use as the response variable. Residuals appeared to follow a normal distribution and β_1 is the most direct measure of accuracy among the four measures considered.

The experimental design was then set up as an analysis of variance with β_1 as the dependent variable measured at the designated levels of the four factors listed above. All two-, three- and four-way interactions of these factors were included in the initial phase of analysis. The purpose of the analysis was two-fold: to compare the average bias with respect to the levels of the designated factors and to estimate the precision (variability) associated with the five sampling methods. Since analysis of variance presumes that the residual variance is homogeneous across all factor combinations, the latter objective amounted to testing for departures from the homogeneity of variance assumption.

Half facepieces. The experimental design was a fixed-effects factorial model that considered three leak sites, two leak sizes and five sampling methods on five models of elastomeric, half facepieces. Five models were chosen from a total population of over 16 NIOSH certified elastomeric, half facepieces. All had a twin filter–cartridge configuration. Two replications were made for each of the 30 design cells for each of the five facepieces. A total of 60 tests was run on each half facepiece. The 'true' acetone concentration and measure of bias were the same as for the full facepiece design.

SAMPLING PROCEDURES

Method 1—CLF sampling procedure

The CLF sampling procedure is a continuous, low sampling rate, procedure utilizing a probing location virtually flush on the body of the respirator [Fig. 2(A)]. In the context of the CLF procedure, flush implies that the sampling probe is mounted directly on the body of the facepiece, in the general area located between the nose and mouth.

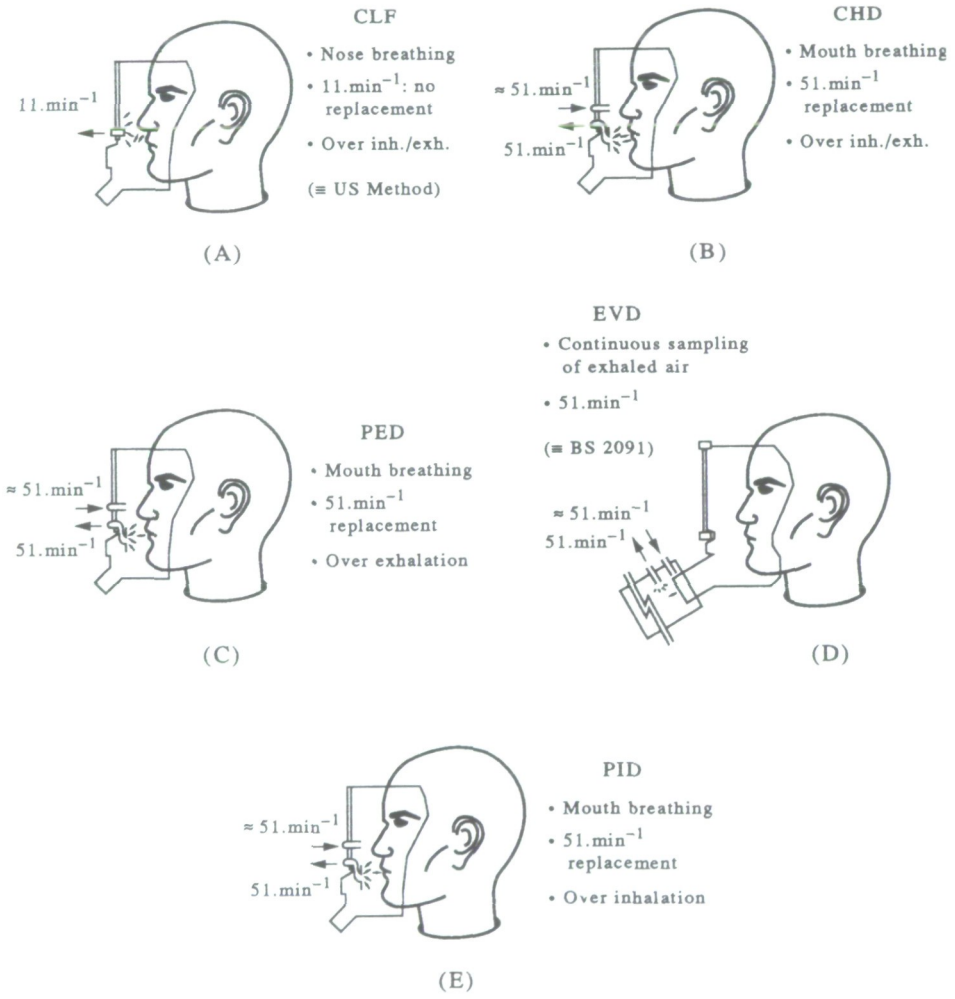

FIG. 2. Sampling and test parameter associated with different procedures of sampling for inboard, face-seal, penetration: (A) CLF procedure; (B) CHD procedure; (C) PED procedure; (D) EVD procedure; and (E) PID procedure.

Normally the probe is situated on or near the midline of the facepiece, but on occasion a manufacturers' instructions for quantitative fit testing will specify differently. The CLF procedure is characteristic of the in-facepiece sampling procedure currently used in the United States for quantitative evaluations of respirator fit involving both

the oil mist and some CNC QNFT procedures and research on workplace protection. The sampling probe used in our evaluations has been reported on by LIU *et al.* (1984), it is designed to be attached directly to the wall or visor of the facepiece. Unless specified differently by the respirator's manufacturer, the sampling probe was located on the midline of the facepiece in the general area between the nose and mouth. The probe was always mounted flush on the visor or wall of the respirator.

The sampling flowrate was 1 l. min^{-1} and was collected continuously over both inhalation and exhalation. No replacement air was provided to the facepiece to compensate for the 1 l. min^{-1} sample. The manikin was set-up to simulate nose breathing. This simulation was chosen because response from quantitative fit test subjects utilized in our laboratory indicated that nose breathing was more prominent than mouth breathing during quantitative fit testing.

Method 2—CHD sampling procedure

The CHD sampling procedure is a continuous, high sampling rate procedure utilizing a deep probing location [Fig. 2(B)]. The CHD procedure reflects an approach to quantitative in-facepiece sampling that is different than what is utilized with the CLF procedure. The CHD procedure incorporates information and insight gained from previous research that studied the effect of different man–respirator parameters on the accuracy of in-facepiece sampling (MYERS *et al.*, 1986b, 1988; MYERS and ALLENDER, 1988). Briefly that research suggested that sampling accuracy could be significantly improved by: (1) extending the throat of the sampling probe deeper into the facepiece cavity; (2) locating the probe in front of the mouth while mouth breathing; and (3) increasing sampling rates to above 3 l. min^{-1} but in a manner that will not artificially increase face-seal penetration.

With the CHD procedure the throat of the sampling probe was positioned deep in the facepiece cavity in the general area in front of the mouth. After a facepiece was mounted on the manikin a probe was made from mouldable plastic tubing. The body of the probe was passed through the facepiece visor and positioned so that its throat was located $\frac{1}{2}$–$\frac{3}{4}$ in. (12–19 mm) in front of the manikin's mouth (Fig. 3). The throat of the probe was 6 mm in diameter and it had an 8 mm circular flange.

Sampling flowrate was 5 l. min^{-1} during both inhalation and exhalation. Approximately 50 ml min^{-1} of the 5 l. min^{-1} sample was consumed by the flame-ionization detector during sample analysis. The remainder of the sample (approximately 4.95 l. min^{-1}) was returned to the facepiece cavity. No attempt was made to use the jet of the discharged air to facilitate mixing within the cavity. This sampling arrangement proved to be suitable for high sampling rates with very little risk of artificially increasing the face-seal penetration. A 5 l. min^{-1} sampling rate was chosen because it can be achieved with personal sampling pumps over long periods of use. Such consideration was felt to be important because the CHD procedure should be compatible with obtaining workplace protection factor measurements.

The manikin simulated mouth breathing. Having an individual mouth breathe during a quantitative fit test could easily be achieved simply by asking the subject to mouth breathe for the duration of the test. With the short duration of a quantitative fit test (< 20 min) this is an innocuous requirement which has not been a problem for any of our fit test subjects. With the longer test times often required in workplace protection factor studies a request to mouth breathe would be impracticable. However, from the

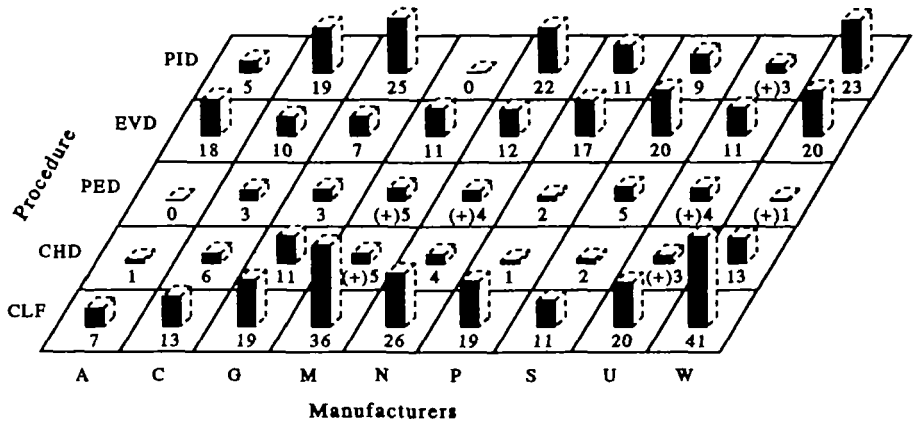

FIG. 3. Absolute value of the mean sampling bias observed with five sampling methods on nine different brands of full facepieces having an approximate face-seal penetration of 0.1%. Mean values are given beneath each column. A plus in parentheses indicates that the mean evaluated in the absolute value function was positive, otherwise the mean was negative. Mean values include effects of leak location.

personal experience of our laboratory personnel and discussions with workers engaged with our respirator field studies there seems to be a natural tendency to mouth breathe. This is caused by restriction of the nose when a half facepiece or full facepieces with nose cups is used. Furthermore there is the natural tendency to begin some mouth breathing with light levels of activity as would be very typical of industrial workplace use of respirators. This suggests the strong likelihood that workers would already be experiencing some degree, if not total, mouth breathing during field performance testing.

Method 3—PED sampling procedure

The PED sampling procedure employs a deep probing location to collect a sample or 'pulse' of air from the facepiece only during exhalation [Fig. 2(C)]. The PED procedure collects an air sample from within the facepiece cavity only during the exhalation phase of the respiratory cycle. It should not be mistakenly viewed as being equivalent to sampling air discharged from the exhalation valve. Some of the reasons for the difference are discussed in the results and discussion.

The PED procedure utilized the same probing position, sampling rate and mouth breathing pattern that was used for the CHD procedure.

Method 4—EVD sampling procedure

The EVD sampling procedure continuously samples the air discharged through the exhalation valve of the facepiece [Fig. 2(D)]. The procedure is similar in principle to that used in British Standard 2091 covering quantitative fit testing with a salt aerosol (BS 2091, 1969). The EVD procedure utilized an exhalation trunk which was attached to the exhalation valve. The volume of the exhalation trunk was approximately 750 ml. It was made of flexible corrugated tubing. The end of the trunk was fitted with a second exhalation valve to minimize potential back flow of room air into the trunk. A 5 l. min^{-1} airflow was sampled from the trunk and then continuously replaced to the trunk as described with the CHD procedure. Airflow occurs through the trunk only

during exhalation. The manikin simulated mouth breathing with this sampling procedure.

Method 5—PID sampling procedure

The PID sampling procedure collects a sample or 'pulse' of air from the facepiece on inhalation utilizing a deep probing location [Fig. 2(E)]. The PID procedure takes a pulsed air sample from within the facepiece cavity only during the inhalation phase of the respiratory cycle. It is quite similar in principle to the procedure reported by FUERST *et al.* (1985). The probe location, breathing pattern and sampling rate used were the same as those used with the CHD and PED procedures. The only difference between the PID and PED procedures is that the sample is collected over inhalation rather than exhalation.

RESULTS AND DISCUSSION

Full facepiece respirators

Due to the methodological problems with the small leak size discussed previously, data analysis was confined to the large leak size. Table 1 shows the results of the full analysis of variance (ANOVA) involving manufacturer, leak site, sampling method and all their interaction terms. The high degree of statistical significance for all factors and their interactions was largely due to the use of three replicates per cell which provided a great deal of statistical power. Because of uncertainties regarding the amount of variability in replicate runs of the system, the initial experiment was designed to be large for precautionary purposes. The most important interaction was between sampling method and manufacturer. This implies that the pattern of differences in average sampling bias among the five methods was not the same for all manufacturers. This is illustrated in Figs 3 and 4.

After examining the residual variance for each of the three factors, it was not only apparent that sampling method was a highly significant factor ($P < 0.0001$), but that estimates of the variance for the five methods were significantly different. Therefore, subsequent analyses were computed separately for each of the five methods.

Two other important considerations distinguish the data. First, the test system did not simulate any lung retention. Lung retention of contaminant would add magnitude to the average sampling bias values reported for each procedure except PID. Second, the test system utilized a vapour challenge agent. The particulate aerosols used with conventional QNFT equipment or that exist in workplace environments may mix differently within the facepiece cavity. This condition may increase the magnitude of the bias values reported here.

Mean results for the conventional CLF method are presented graphically in Fig. 3 and summarized in Table 2. The height of the column in each cell of Fig. 3 is representative of the absolute value of the mean bias for each sampling-procedure–facepiece cell. The number under the column is the mean value. The plus sign in parentheses indicates that the argument in the absolute value function was positive. In all other cases, the argument was negative. For example, the average sampling bias was −19% for the CLF method on the type P facepiece while it was 4% for the PED method on the type N facepiece. Figure 3 clearly shows that the CLF sampling

TABLE 1. ANALYSIS OF VARIANCE TABLES

Source	Degrees of freedom (df)	Mean square	*F* statistic value	Probability of exceeding *F*
(a) Full facepieces				
Manufacturer (MFG)	8	0.0816	20.25	<0.0001
Leak site (LS)	2	0.8486	208.14	<0.0001
Method (MTD)	4	0.6245	153.16	<0.0001
MFG LS	16	0.1582	38.79	<0.0001
MFG MTD	32	0.0484	11.86	<0.0001
LS MTD	8	0.0980	24.05	<0.0001
MFG LS MTD	64	0.0254	6.23	<0.0001
Error	269*	0.0041		
(b) Half facepieces				
Manufacturer (MFG)	4	2.073	657.95	<0.0001
Leak site (LS)	2	0.1199	76.10	<0.0001
Leak size (LK_SZ)	1	0.0037	4.78	<0.0303
Method (MTD)	4	2.932	930.24	<0.0001
MFG LS	8	0.6578	104.35	<0.0001
MFG LK_SZ	4	0.2462	78.11	<0.0001
MFG MTD	16	2.945	233.63	<0.0001
LS LK_SZ	2	0.0423	26.85	<0.0001
LS MTD	8	0.3746	59.44	<0.0001
LK_SZ MTD	4	0.0858	27.23	<0.0001
MFG LS LK_SZ	8	0.2727	43.26	<0.0001
MFG LS MTD	32	1.067	42.35	<0.0001
LS LK_SZ MTD	8	0.1249	19.83	<0.0001
MFG LS LK_SZ MTD	48	0.5930	15.68	<0.0001
Error	150	0.00079		

*One value missing.

procedure in general had the largest (most negative) sampling biases of all the sampling methods. The mean sampling biases went from a low of −7% (rounded to the nearest unit) with the type A facepiece to −41% with the type W facepiece.

The sampling bias associated with different leak locations is dependent upon the location of the face-seal leak for each individual facepiece. Similar findings have been reported previously (MYERS *et al.*, 1988; MYERS and ALLENDER, 1988; BENTLEY, 1988; MULLINS, 1988; HOLTON *et al.*, 1987; OESTENSTAD *et al.*, 1990). The significant interaction between leak location and manufacturer ($P < 0.001$) in the ANOVA for the CLF procedure suggests that the bias associated with different leak locations is influenced by the design of the facepiece. The facepieces of types M, N, P and W handle inspired airflow in a similar manner. These facepieces are designed to sweep the inspired airflow up over the visor. Such an airflow pattern causes the CLF method to under-sample leaks from areas of the chin and cheek. In contrast, leaks in the area of the temple are sampled with much less bias. This observation has been reported and discussed in more detail elsewhere (MYERS and ALLENDER, 1988).

The average sampling biases experienced with the CHD sampling procedure were in all cases smaller than those experienced with the conventional CLF sampling procedure. Over the nine brands of facepieces the bias ranged from −13% to 5%. A

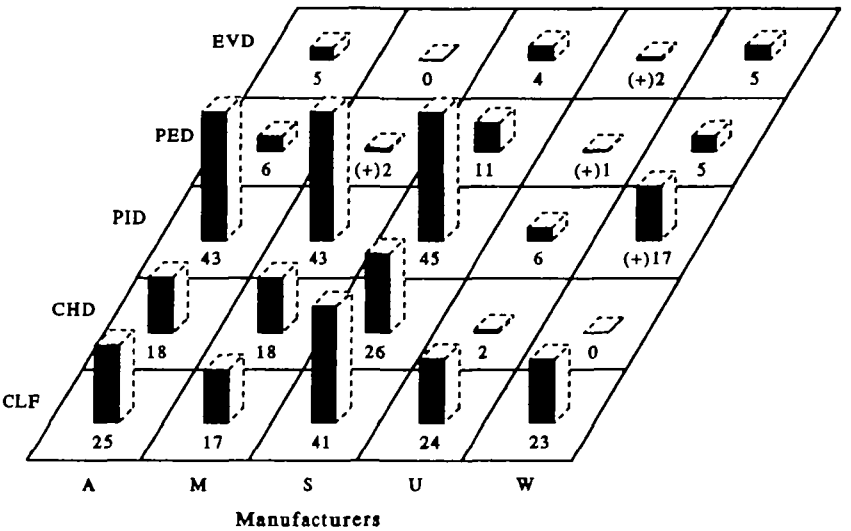

FIG. 4. Absolute value of the mean sampling error observed with five sampling methods on five different brands of half facepieces having an approximate face-seal penetration of 1 and 0.25%. Mean values are given beneath each column. A plus in parentheses indicates that the mean evaluated in the absolute value function was positive, otherwise the mean was negative. Mean values include effects of leak location and leak size.

comparison of the results in Fig. 3 between the CHD and conventional CLF sampling procedures shows that major improvements in sampling accuracy were achieved using the CHD procedure. The CHD sampling procedure was also sensitive to leak location. Within the CHD procedure the magnitude of sampling bias for some leak locations are reduced by as much as 50% or more as compared to the CLF procedure.

The PED sampling procedure consistently provided the lowest sampling bias of all five methods. The average biases measured on the nine facepieces ranged from −5 to +5% (Fig. 3). Only with the facepiece of type S did the PED sampling procedure have a noticeably higher sampling bias than the CHD sampling procedure. Yet the PED sampling procedure bias was only −5%. On the facepieces of types W and G the PED sampling procedure was considerably more accurate than the CHD sampling procedure. The sampling bias associated with the PED sampling procedure is much less sensitive to the location of the face-seal leak than the CHD sampling procedure. It may seem on initial consideration that the PED sampling procedure should not be dependent on leak location. This influence can be explained however by the flushing and mixing characteristics of the facepiece (CAMPBELL and MYERS, 1989).

The EVD sampling procedure provided better sampling than the CLF sampling procedure but not as good as the CHD or PED sampling procedures (Fig. 3). The mean sampling biases ranged from −7% on the type G facepiece to −20% on the type S facepiece.

Measuring the concentration of contaminant coming out of the facepiece should provide an accurate indication of what is coming into the facepiece (in this case only face-seal leakage) assuming no system loss. One reason why exhalation trunk sampling may not meet the criteria of providing a mass balance sample is that not all of the expired air exits through the exhalation valve. The effect of back flush past the

TABLE 2. MEAN SAMPLING BIAS AND RANGE OF OBSERVED BIAS FOR FIVE SAMPLING PROCEDURES

Facepiece type	CLF		CHD		PED		EVD		PID	
	$\beta \pm$SE*	Range	$\beta \pm$SE*	Range	$\beta \pm$SE*	Range	$\beta \pm$SE*	Range	$\beta \pm$SE*	Range
(a) Full facepieces										
A	-7 ± 4.9	-25 to 14	-1 ± 8	-3 to 4	0 ± 0.3	-0.6 to 2	-18 ± 1.7	-27 to -11	-5 ± 1.6	-10 to 4
C	-13 ± 1	-15.4 to -7	-6 ± 2.8	-20 to 4	-3 ± 1.9	-13 to 9	-10 ± 2.5	-24 to -2	-19 ± 4.5	-36 to 0
G	-19 ± 4.9	-41 to -4	-11 ± 3.1	-23 to 8	-3 ± 1.2	-4 to 8	-7 ± 2.3	-21 to 4	-25 ± 5.6	-39 to 16
M†	-36 ± 9.0	-59 to 1	5 ± 5.7	-15 to 27	5 ± 2	0 to 13	-11 ± 8.4	-53 to 34	0 ± 11.1	-30 to 55
N†	-26 ± 4.1	-42 to -10	-4 ± 5.8	-28 to 14	4 ± 1.9	-4 to 12	-13 ± 1.8	-18 to -4	-22 ± 9.5	-54 to 9
P†	-19 ± 3.2	-31 to -7	-1 ± 2.7	-10 to 9	-2 ± 1.5	-8 to 8	-17 ± 1.8	-24 to -10	-11 ± 4.3	-30 to 4
S	-11 ± 2.5	-21 to 1	-2 ± 1.4	-8 to 4	-5 ± 0.4	-7 to -4	-20 ± 1.2	-25 to -16	-9 ± 1.9	-20 to -4
U	-20 ± 3.3	-29 to -5	3 ± 4.9	-18 to -16	4 ± 1.4	-4 to 9	-11 ± 4	-26 to to	3 ± 7.6	-31 to 23
W†	-41 ± 10.9	-65 to 4	-13 ± 6.3	-33 to 15	1 ± 2.2	-6 to 11	-20 ± 5.1	-33 to 3	-23 ± 10.9	-58 to 20
(b) Half facepieces										
A	-25 ± 5.1	-42 to 9	-18 ± 3.7	-29 to 8	-6 ± 0.8	-10 to -2	-5 ± 0.5	-8 to -1	-43 ± 8.6	-72 to 25
M	-17 ± 3.2	-32 to 0.9	-18 ± 2.3	-29 to -7	2 ± 0.5	-0.3 to 5	-0.3 ± 0.5	-2 to 3	-43 ± 5.7	-72 to -13
S	-41 ± 3.4	-52 to -20	-26 ± 2.2	-36 to -11	-11 ± 1.6	-18 to 0.9	-4 ± 0.6	-6 to 0.5	-45 ± 4.4	-67 to -22
U	-24 ± 1.9	-36 to -10	-2 ± 0.9	-5 to 6	1 ± 0.9	-3 to 8	2 ± 0.5	-6 to 6	-6 ± 3.3	-22 to 13
W	-23 ± 2.6	-41 to -14	$0.4 + 2.6$	-11 to 14	-5 ± 0.6	-7 to 0.6	-5 ± 0.6	-8 to -2	-17 ± 6.9	-19 to 53

*β = means bias; SE = standard error of the mean ($s/\sqrt{N}$).
†Inspired air swept over visor.

inhalation valve on observed in-facepiece concentrations has been discussed by CAMPBELL *et al.* (1990).

The PID sampling procedure was also better than the conventional CLF sampling procedure (Fig. 3). However, it was not as good as the CHD and PED methods but quite similar to the EVD method. The mean sampling biases ranged from 0% on the type M facepiece to −25% on the type G facepiece. The sampling error associated with the method for different leak locations exhibited somewhat similar trends to those observed with the CLF sampling procedure.

A comparison of the sampling procedures based upon accuracy and precision is provided in Table 3. The PED sampling procedure had both the best precision and lowest sampling bias of the five procedures. An overall combined measure of precision and bias that gives equal weight to precision and bias, is expressed in Equation (5)

$$R = (\sigma^2 + \bar{\beta}^2)^{1/2}, \tag{5}$$

where R = combined measure of precision and bias; σ = precision; $\bar{\beta}$ = mean bias.

TABLE 3. PRECISION AND MEAN SAMPLING BIAS ACHIEVED WITH DIFFERENT IN-FACEPIECE SAMPLING PROCEDURES

Procedure	N	Precision (SD σ) %	Mean bias (β)	Combined measure* (R)
(a) Full facepieces				
CLF	81	14.0	−21.3	25.5
CHD	81	11.8	−3.4	12.3
PED	81	5.0	0.7	5.0
EVD	80	11.9	−14.2	18.5
PID	81	21.0	−12.3	24.3
(b) Half facepieces				
CLF	60	14.0	−25.9	29.4
CHD	60	11.7	−12.5	17.1
PED	60	5.8	−3.7	6.9
EVD	60	3.0	−2.3	3.8
PID	60	29.2	−24.1	37.9

*Combined measure of precision and bias = $(\sigma^2 + \beta^2)^{1/2}$.

The CLF sampling procedure, which represents the in-facepiece sampling procedure used in the United States for QNFT assessments was the worst of the five sampling procedures evaluated.

Half facepieces

The results of the full ANOVA are presented in Table 1. All interactions were found to be significant. As with the full facepiece data analysis, the most important interaction was between sampling method and manufacturer. This suggests that the differences in average bias among the five methods was not the same for all manufacturers. This is illustrated in Fig. 4. Three-way interactions of manufacturer, leak size and leak site were statistically significant for all methods with the exception of the EVD procedure. Examination of means for combinations of these three factors revealed no consistent pattern of biases which would explain a three-way interaction. The most likely

explanation for these significant effects is the high degree of precision in replicate runs of this experiment which makes detection of relatively small effects possible. Although these three-way interactions were statistically significant, the magnitude of these effects is considerably smaller than the total variation among manufacturers. This can be verified by examination of the sums of squares and *F*-values for 'manufacturers' compared to those for the three-way interactions. For this reason no interpretation of the three-way interactions appear to be justified. The significant three-way interaction between leak site, method and manufacturer was consistent with that observed with full-facepieces and results previously reported (MYERS *et al.*, 1988). The average bias as a function of manufacturer type are summarized in Table 3. The range in the measured bias for each method on each facepiece is noteworthy.

Figure 4 plots the mean sampling bias associated with the CLF procedure on the five half facepiece respirators. All values represent a negative bias unless otherwise indicated (+). The mean sampling biases ranged from a low of −17% with the type M respirator to −41% with that of type S. The overall average bias was −26%. The precision of the method was calculated to be 14%.

On a previous study using the CLF procedure, MYERS *et al.* (1986) reported measuring mean biases of −17, −47 and −21%, respectively, on the half facepieces of types M, S and U. The results in the present study on these same three half facepieces are in excellent agreement with those previously reported values.

The mean sampling biases measured with the CHD procedure on each half facepiece was equal to or better than that associated with the CLF procedure. The mean sampling biases ranged from a low of <1% on the type W facepiece to a high of −26% on the type S facepiece. The mean over the five facepieces was −13%.

The mean sampling biases obtained with the PED procedure were in four of five cases better than that obtained with either the CLF or CHD sampling procedure. The means ranged from 1% on the type U facepiece to −11% on the type S with an average bias of −4% over all five facepieces. The −11% bias on the Scott facepiece is quite unusual. The experiment on this respirator was repeated, yielding the same result. Apparently this degree of sampling bias does occur; however, it is approximately twice the magnitude of sampling bias observed with any of the half or full facepieces studied to date. From examination of Fig. 4 it is apparent that the highest observed bias with the CLF, CHD, PED and PID sampling methods occurred with this facepiece. The cause of the elevated sampling bias with this facepiece is not known.

The results with the EVD sampling procedure were the most surprising of all. This method demonstrated considerable bias on full facepieces but not with the half facepieces. The biases ranged from <1% on the type M facepiece to −5% on the type W facepiece, averaging −2% overall. As mentioned in the discussion with the full facepiece results, the flushing and mixing of volumes drawn simultaneously through the air-purifying element and the face-seal leak inside the facepiece cavity could lead to biases with an EVD sampling method when inhalation value back flow occurs during exhalation. It is possible that with the much smaller cavity volumes (dead space) of the half facepieces, better flushing of the cavity occurs, therefore minimizing the problems of inhalation valve back flow observed on the full facepieces.

The results obtained with the PED and EVD procedures on half facepieces are significantly better than the other three methods and appear to be very comparable on a practical performance basis even though they are statistically different. Intuitively it

makes sense for them to give comparable results given no major facepiece cavity flushing problems exist.

The PID procedure resulted in the largest magnitude of sampling bias in three of the five facepieces. The biases ranged from −6% on the type U facepiece to −45% on the type S, averaging −24% overall.

The effect of leak size on sampling bias on these five half facepieces is significant, however, in terms of practical importance it appears to be minimal. Examination of the F values in Table 2 indicates that it is the least dominant of the four factors. Examining the three-way interaction of method, manufacturer and leak size on the sampling bias associated with a procedure indicates it is generally not significantly affected by the leak sizes employed in the study (Table 4).

TABLE 4. MEAN* SAMPLING BIAS ASSOCIATED WITH SAMPLING METHOD, MANUFACTURER AND LEAK SIZE

	Type A		Type M		Type S		Type U		Type W	
	Leak size		Leak size		Leak size		Leak size		Leak size	
Method	L	S	L	S	L	S	L	S	L	S
CLF	−15†	−35†	−15	−20	−39	−42	−22	−25	−20	−26
CHD	−13	−22	−17	−18	−24	−28	−1	−2	5†	−5†
PED	−6	−7	−2	−2	−8†	−14†	2	1	−5	−6
EVD	−5	−5	1	<1	−3	−4	3†	<1†	−4	−6
PID	−35	−51	−37	−50	−36†	−54†	1	−14	24	11

*$N=6$ for all means.
†Mean estimates of bias between large (L) and small (S) leaks are significantly different.

Table 3 summarizes the precision and mean sampling bias achieved with the sampling procedures on the five half facepieces. Both the EVD and PED procedures have good precision and low sampling bias. Considering these data the two methods are very comparable on the half facepieces. The other three procedures had poorer precision and higher sampling bias. The CLF procedure had the highest sampling bias and the PID procedure clearly had the lowest precision.

Lung retention may be a source of additional bias for all the sampling procedures, except possibly the PID sampling procedure. With the PED sampling procedure, corrections for lung retention would not be needed if it is used for quantitative fit testing of different facepiece sizes and/or designs. In these tests, correction for lung retention is not critical because the wearer serves as his own control and the data is used as a relative measure of 'goodness-of-fit'.

CONCLUSIONS

The bias and precision of the in-facepiece sampling procedure currently used in the United States and four other sampling procedures had been evaluated.

Based upon the experimental results with full facepieces used in the study, the PED procedure had the best precision ($\sigma=5\%$) and lowest avarage bias ($\beta=0.7\%$). The CHD procedure was second best with a precision of 11.8% and average bias of −3.4%. The conventional CLF procedure (current U.S.) was the worst of the five sampling methods with a precision of 14% (second lowest of all methods) and average bias of −21.3% (highest of all methods).

On the half facepiece respirators the EVD sampling procedure had the best precision ($\sigma = 3.0\%$) and lowest average bias ($\beta = -2.3\%$). The PED sampling method had the second best precision ($\sigma = 5.8\%$) and second lowest average bias ($\beta = -3.7\%$). Because of the small differences between the precision and average bias of these two methods they are considered, for practical purposes, to have equal capabilities.

The conventional CLF (current U.S.) procedure and the PID procedure had the lowest precision and highest average bias of the five procedures studied. This finding was similar to that made on the full facepiece respirators.

Based upon these data from the half and full facepiece respirators, the PED sampling procedure was found to be substantially more precise and less biased than the conventional CLF sampling procedure. Furthermore, it appears to have similar accuracy and precision on both facepiece types, thus allowing the adoption of one sampling procedure for fit testing. It is feasible and practical to develop the PED method as a replacement for the conventional CLF in-facepiece sampling procedure in the United States. The instrumentation must be suitably packaged for this particular application and the method evaluated in actual fit test applications. The concept of doing pulsed sampling during the inhalation is already used in the U.K. and some other European countries for total inward leakage testing of filtering-facepiece (single-use, disposable, etc.) respirators. This work was carried out on full facepieces without nosecups. It is easy to speculate that in-facepiece sampling on full facepieces with nose cups may behave more like half facepieces than full facepieces without nose cups. However given the complexity of airflows and mixing within these devices research workers must be cautioned against such speculation. The issue of sampling bias in full facepieces with nose cups is worthy of further research effort.

Until the PED method can be completely evaluated, it is recommended that the CHD sampling method be used for conducting in-facepiece sampling. While not as good as the PED method, it provides a marked improvement in sampling accuracy and precision over the CLF method. Furthermore, it can be implemented immediately with the adoption of longer sampling probes which would allow the probe mouth to be extended $\frac{1}{2}$–1 in. into the cavity of the facepiece. The sampling train equipment now used with the conventional CLF sampling method, in most cases, is adequate to provide the flowrates used with the CHD sampling procedure.

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