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VARIATION IN QUANTITATIVE RESPIRATOR FIT FACTORS DUE TO FLUCTUATIONS IN LEAK SIZE DURING FIT TESTING

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Variation in fit factors during quantitative respirator fit testing was studied for a high degree of fit (aerosol fit factors > 1000) and a low degree of fit (aerosol fit factors < 1000). In a controlled human study, fit factors were determined sequentially for three different exercises by (1) an aerosol fit test (using a portable condensation nuclei counter and room aerosol as the test agent) and (2) the newly developed dichotomous-flow fit test (Dichot). For the higher level of respirator fit, the aerosol fit factors were 30 to 60 times the corresponding flow fit factors, and for the lower level of respirator fit they were 2 to 4 times the flow fit factors. A coefficient of variation (CV) of 84% (GSD 1.6) for the higher respirator fit and 178% (GSD 2.2) for the lower respirator fit data was observed in the human study when aerosol fit factors for the three exercises were pooled. In a similar mannequin study, the center sampling probe gave aerosol fit factors with a CV of 5.4% (GSD 1.05). The flow fit factors for all three exercises pooled had a CV of 36% (GSD 1.3) for the higher respirator fit and 40% (GSD 1.5) for the lower respirator fit data, while the mannequin study gave flow fit factors with a CV of 2.2% (GSD 1.02). Thus, the variation in fit factors obtained in the human study was much higher than that obtained in a mannequin study. However, the variation in the aerosol method relative to the flow method, in the human study, is of the same order of magnitude as in the mannequin study. This suggests that the higher variation in the human tests is mainly due to variations in faceseal leak size and not to increased systematic errors. It was estimated that the fluctuations in faceseal leak size for the subject with the high fit factor varied between 0.5 mm and 0.7 mm, and between 1.0 mm to 1.3 mm for the subject with the low fit factor. Thus, the fit factor determined for a human cannot be expected to be constant even for the most perfect test system.

Respirator fit generally is expressed quantitatively by the fit factor, which is defined as the ratio of the concentration of the test agent outside the respirator to the concentration of the test agent inside the respirator cavity.(1) Large variations in aerosol fit factors (AFFs) have been observed both for individual respirator wearers and for a population of respirator wearers.(2) Since aerosol penetration is known to be strongly dependent on particle size,(3–5) variations in AFFs for the same respirator fit have been attributed to changes in the external aerosol size distribution. High variability in AFFs also has been attributed to the lack of complete mixing in the respirator cavity, which results in the dependence of the fit factor on leak and probe locations as well as the breathing rate.(4,6,7)

The flow fit factor (FFF) obtained by the newly developed dichotomous-flow respirator fit test system, "Dichot,"(8) is independent of leak and sampling probe locations. Results of a mannequin study with fixed leaks indicate that the coefficient of variation in the FFFs is lower

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(2.2%) than the variation in the corresponding AFFs (5.4%). The Dichot therefore potentially can be used to study the variability in fit factors due to natural changes in leak size during fit testing of human subjects.

This article describes a controlled experiment to study the variability in quantitative respirator fit factors for a high level of respirator fit (AFFs > 1000) and for a lower level of respirator fit (AFFs < 1000). The AFFs and FFFs are determined sequentially on each respirator wearer and the coefficient of variation in the two fit factors is compared with that obtained in a mannequin study with a fixed leak.(8)

A separate mannequin study is described in which fixed leaks are introduced and the corresponding flow fit factors determined. A relationship is established between the leak flow rate and the diameter of the leak. This relationship is used to estimate the variation in faceseal leak size during respirator fit testing.

The results of this study show that a large degree of variability exists in the faceseal leak size during normal breathing. Thus, the fit factor determined on a human cannot be expected to be constant, even for the most perfect test system.

EXPERIMENTAL METHODS AND MATERIALS

Sequential Aerosol Fit Test and Flow Fit Test

A two-part controlled study was carried out to determine the variation in fit factors during quantitative respirator fit testing. Part one focussed on a high level of respirator fit (AFFs > 1000) and part two focussed on a lower level of fit (AFFs < 1000). Silicone and natural rubber half-masks in three different sizes were obtained from a single manufacturer and tried on two human subjects—a Caucasian male and an Oriental male—to obtain a high respirator fit and a low respirator fit. A high respirator fit was obtained with a large-size silicone half-mask on the first subject and a low fit was obtained with a medium-size natural rubber half-mask on the second subject. The masks were equipped with a pair of high efficiency particulate air-purifying (HEPA) cartridges and a sampling probe in the center of the mask. Fit factors were determined sequentially by two fit testing methods on each respirator wearer for three different exercises. AFFs were determined with the portable version of a condensation nuclei counter(9) (model 8010 PortaCount®, TSI, Inc., St. Paul, Minn.) with ambient room aerosol as the test agent, and FFFs were determined with the "Dichot."

The subjects were informed of the purpose of the study and given a verbal description of the test protocol. Each subject was seated upright on a chair and breathed normally. He then donned the respirator to fit his face comfortably. The center probe was connected to the PortaCount and a set of six AFFs was determined while the subject looked straight ahead. The test was repeated to obtain two more sets of fit data for the same head position.

Next, the HEPA cartridges were removed very carefully to avoid altering the fit of the mask and were replaced with modified cartridges. The two HEPA cartridges were mounted on a reference mask and a flow of 32 L/min was drawn through them. This flow rate was selected because it is one of the two flow rates at which air-purifying respirator cartridges are tested.(10)

The sampling probe at the center of the mask was connected to the Dichot and the probe on one modified cartridge was connected to a pressure differential sensor. The second modified cartridge had a breathing port that was connected to a two-way solenoid valve. This allowed the wearer to breathe normally until he was ready for the test.

The subject held his breath while looking straight ahead and shut off the breathing port by activating a solenoid valve. The Dichot measured the inward leakage into the mask during breath-holding and the flow fit factor was calculated as the ratio of the total flow (cartridge flow + leak flow) to the leak flow. To ensure that no air from the lungs "washed" back into the respirator cavity, "nose-plugs" were used. Soft-cotton buds wrapped in a polyethylene cover (available as ear-plugs) were used in this experiment as "nose-plugs."

As in the case of the aerosol fit test, three sets of six flow fit factors were determined. The subject did not take off the mask between the aerosol and flow fit tests and great care was taken to ensure that the fit of the mask remained unchanged throughout the study.

AFFs and FFFs were determined sequentially for two other exercises. AFFs were determined while the subject moved his head up and down about 45 degrees. Corresponding FFFs were determined while the subject held his head turned at an angle of 45 degrees upward.(11) In the next segment of the study, AFFs were determined while the subject moved his head side to side about 45 degrees and corresponding FFFs were determined while the subject held his head turned 45 degrees to the right.

Relationship Between Leak Flow Rate and Leak Size

A mannequin study was conducted in which a half-mask was fitted with a center probe and three artificial leaks of 0.84 mm internal diameter and approximately 5 cm length were introduced at the faceseal. The pair of HEPA cartridges used in the above human study was mounted on a reference respirator and air was drawn through the cartridges at a flow rate of 43.5 L/min. An inhalation flow rate of 43.5 L/min represents moderate to light work activity.(12) Flow fit factors were determined for one, two, and three faceseal leaks.

RESULTS

Sequential Aerosol Fit Test and Flow Fit Test

Figure 1 shows the frequency distribution of AFFs and the corresponding FFFs obtained for the subject wearing a half-mask with the high level of respirator fit. The graph also shows the arithmetic mean (AM), and the percent coefficient of variation, the geometric mean (GM), and the geometric standard deviation (GSD) of the 18 fit factors determined for

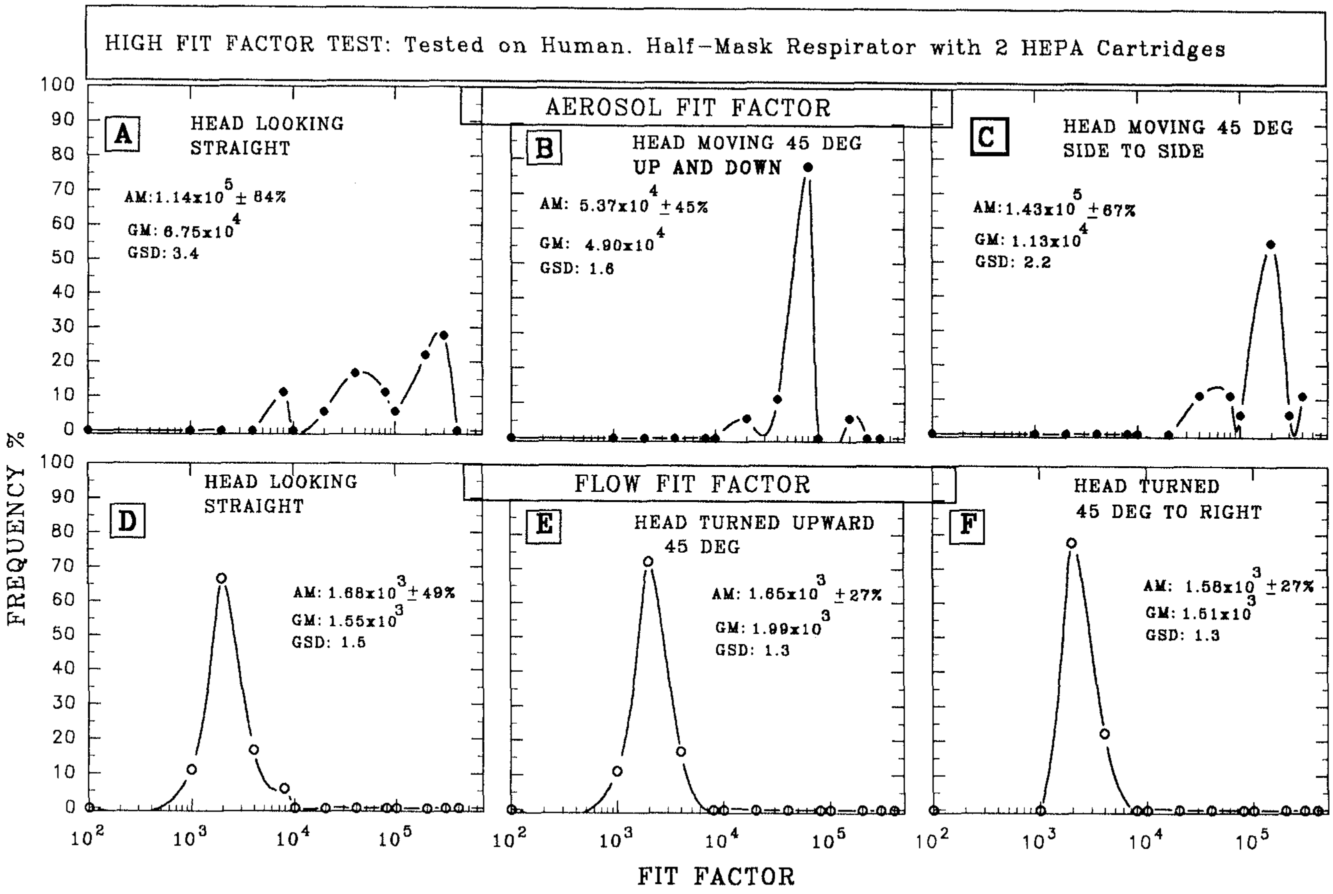

FIGURE 1. Frequency distribution of aerosol and flow fit factors obtained with a half-mask respirator on a human subject for a high respirator fit

each of the 3 exercises. Figures 1A and 1D show fit data when the subject was looking straight ahead. Figure 1B shows AFFs obtained while the subject moved his head up and down and Figure 1E shows the corresponding FFFs, determined while the subject held his head turned upward. Similarly, Figure 1C shows AFFs for a side-to-side head movement and Figure 1F shows the corresponding FFFs when the head was turned to the right.

The AFFs were in general higher than the FFFs, and had a higher variation. The coefficients of variation for the AFFs for the three exercises ranged from 45% to 84%, and those for the FFFs ranged from 27% to 49%. When the fit factors obtained for the three exercises were pooled, the aerosol fit factor had an AM of 1.04 10^5 with an 84% coefficient of variation, and a GM of 4.90 10^4 with a GSD 1.6. The pooled flow fit data had an AM of 1.64 10^3 with a 36% coefficient of variation, and a GM of 1.60 10^3 with a GSD of 1.3.

Figure 2 shows the frequency distributions for the subject wearing the half-mask that gave a lower level of fit. Figure 2B shows the AFFs for the side-to-side movement of the head. One of the fit-factor values obtained during this test was 23 300. This value was discarded as an outlier because it was about 80 times larger than 290, which was the median fit factor for all the other data of this exercise. As in the previous case, the AFFs were higher than the corresponding FFFs. The coefficients of variation for the AFFs for the three exercises ranged from 22% to 173%, and those for the FFFs ranged from 5% to 27%. When the fit factors obtained for the three exercises were pooled, the aerosol fit factor had an AM of 394 with a 180% coefficient of variation, and a GM of 250 with a GSD 2.2. The pooled flow fit data had an AM of 148 with a 40% coefficient of variation, and a GM of 135 with a GSD of 1.5.

The correlation plot between AFFs and FFFs obtained on human subjects is shown in Figure 3. This plot is very similar to the correlation plot between the two fit factors obtained on a mannequin,(8) except that the human fit factors show a higher degree of variation. It can be seen in Figure 3 that the variation in flow fit factor (horizontal lines) is less than that in aerosol fit factor (vertical lines). The higher variation in AFFs at the higher level of respirator fit may be due to the fact that at a higher fit (lower aerosol penetration) the particle losses are highly leak-size dependent.

Relationship Between Leak Flow Rate and Leak Size

Figure 4 shows the dependence of leak flow rate, Q_{leak}, on leak size. Since leak flow rate is a function of pressure

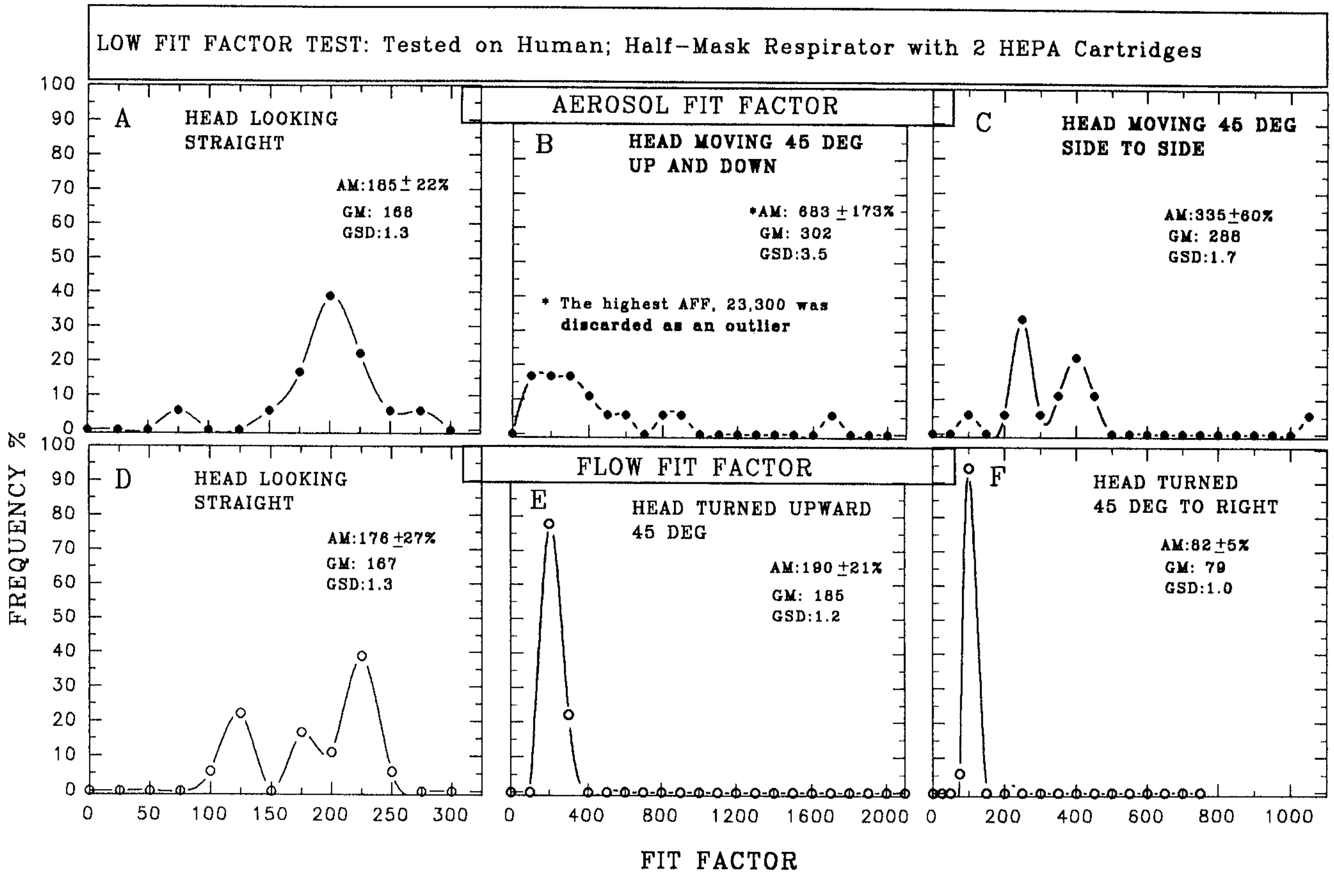

FIGURE 2. Frequency distribution of aerosol and flow fit factors obtained with a half-mask respirator on a human subject for a low respirator fit

drop across the leak, this relationship holds good only for that pair of HEPA cartridges used in the experiment. The cartridges used in this mannequin study were the same as those used in the human study. The relationship between leak flow rate and leak diameter, d_{leak}, is given by the equation:

$$Q_{leak}(\mathrm{mL/min}) = 152 d_{leak}^{4}, (\mathrm{mm})^{4} \qquad (1)$$

Q_{leak} was found to be proportional to the fourth power of diameter as explained further below. The correlation coefficient for the above relationship, R^2, was 0.99. This relationship is used to estimate the variation in faceseal leak size during fit testing.

DISCUSSION

Comparison of the coefficients of variation obtained in the human study with those obtained in the mannequin study$^{(8)}$ shows that the ratio of the coefficients of variation in the two fit testing methods is about the same. For the higher level of respirator fit in the human study, the coefficient of variation in the AFFs was 2.3 times the coefficient of variation in FFFs (84%:36%) when the data was pooled for the three exercises. In the mannequin study (with a fixed leak) the coefficient of variation in AFFs was 2.5 times that in the FFFs. As the test conditions in the human study were similar to those in the mannequin study, the higher variability in the human fit factors may be attributed to variations in the faceseal leak size during fit testing.

The Dichot was used to study the variability in fit factors due to natural changes in leak size during fit testing of human subjects because the FFF is independent of leak and sampling probe locations and has a very low degree of variability.

An estimate of the variation in faceseal leak size can be made based on the variation in flow fit factors. The flow fit factor is the ratio of the cartridge flow rate to the leak flow rate. When the cartridge flow rate is held constant, changes in leak flow rate can cause changes in FFF. The leak flow rate is a function of the pressure drop across the leak, and the diameter and the length of the leak. During quantitative respirator fit testing the HEPA cartridges create moderate pressure drops. At a given breathing rate, the average pressure drop during each inhalation cycle may be considered to be constant, so that changes in leak flow rate can be attributed to changes in leak size. If the length of the faceseal leak is assumed to be constant during fit testing, then changes in leak flow rate must be related to changes in leak diameter alone.

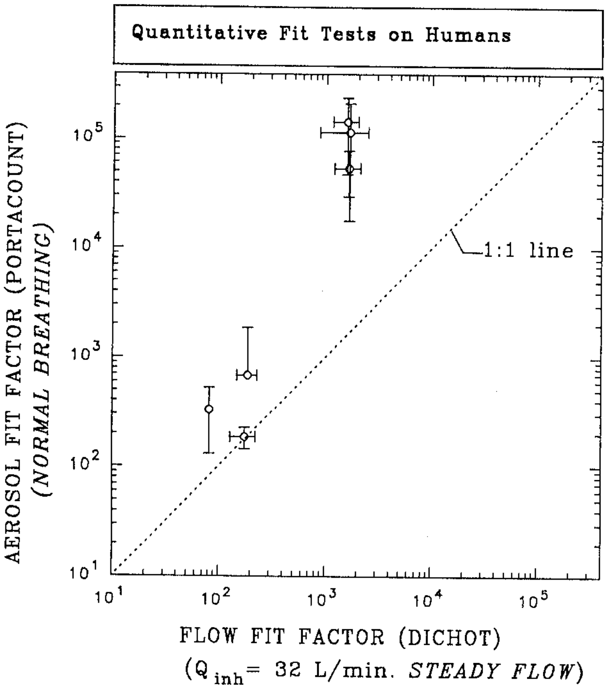

FIGURE 3. Correlation between aerosol fit factors and flow fit factors obtained sequentially on human subjects

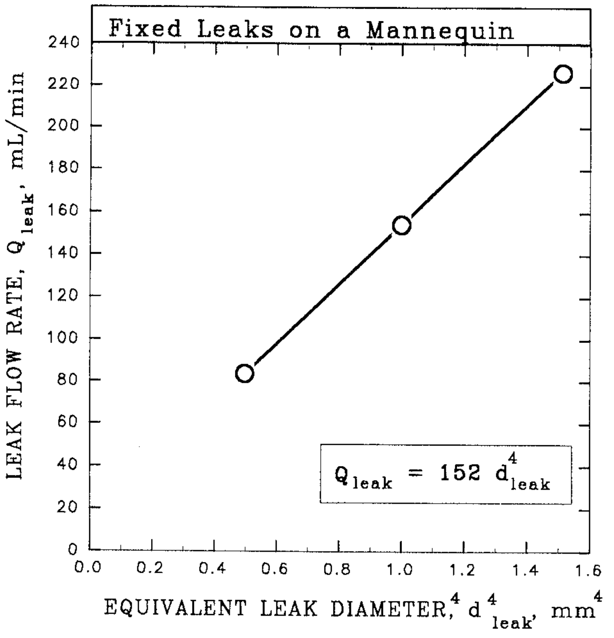

FIGURE 4. Relationship between leak flow rate and equivalent leak size for a mannequin fitted with a half-mask with two HEPA cartridges and three faceseal leaks of 0.84 mm I.D.

The Hagen-Poiseuille equation for pressure drop due to a steady laminar flow through a circular tube is given by:(13)

$$\Delta p = \frac{128\mu \ell Q}{\pi d^4} \tag{2}$$

If the pressure drop across the faceseal leak, Δp, the viscosity of air, μ, and the length of the faceseal leak, l, are assumed constant, then,

$$Q_{leak}\ \alpha\ d^4_{leak} \tag{3}$$

where d_{leak} is the diameter of the leak.

In Figure 4, the equivalent diameters for two and three leaks were calculated as follows. Let $d_{leak(1)}$ represent the leak size when only one leak is present, and $d_{leak(2)}$ the diameter of the leak equivalent to two leaks of the same size. $Q_{leak(1)}$ and $Q_{leak(2)}$ are the leak flow rates through one leak and through two leaks, respectively.

$$\left[\frac{d_{leak(2)}}{d_{leak(1)}}\right]^4 = \frac{Q_{leak(2)}}{Q_{leak(1)}} \tag{4}$$

But, when two leaks are in place, the leak flow rate is twice that due to a single leak.

$$Q_{leak(2)} = 2Q_{leak(1)} \tag{5}$$

Therefore,

$$d_{leak(2)} = (2)^{1/4} d_{leak(1)} \tag{6}$$

Similarly, for three leaks, the equivalent diameter is

$$d_{leak(3)} = (3)^{1/4} d_{leak(1)}. \tag{7}$$

Rewriting the regression equation for the relationship between leak flow rate and leak diameter gives

$$d_{leak} = \left[\frac{Q_{leak}}{152}\right]^{1/4} \tag{8}$$

This relationship is valid only for the particular pair of HEPA cartridges used in this mannequin study. However, this equation can be used to estimate the leak size variation during fit testing on humans since the same pair of HEPA cartridges was used in the human test. In the case of the high respirator fit (Subject 1), the range of FFFs was 820 to 4350, which corresponds to leak flow rates ranging from 39 mL/min down to 7 mL/min for the cartridge flow rate of 32 L/min used during the fit testing. This range of leak flow rates corresponds to an equivalent faceseal leak size diameter of 0.7 mm to 0.5 mm. The flow fit factor range for Subject 2 was 80 to 220, which corresponds to an equivalent faceseal leak diameter range of 1.3 mm to 1.0 mm.

CONCLUSIONS

Quantitative respirator fit factors are determined before field use for a particular respirator fit. In the present study application of two methods of fit testing—an aerosol fit test and the dichotomous-flow fit test—have shown that even for the same respirator fit there is a high degree of variation in the fit data collected due to fluctuations in the faceseal leak size.

Thus fit factors determined on a human cannot be expected to be constant even when the most perfect test system is used.

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REFERENCES

1. **Meyers, W.R., S.W. Lenhart, D. Campbell, G. Provost:** The Forum. *Am. Ind. Hyg. Assoc. J. 44*:B25–B26 (1983).
2. **da Roza, R.A., C.A. Cadena-Fix, G.J. Carlson, K.E. Hardis, and B.J. Held:** Reproducibility of respirator fit as measured by quantitative fitting tests. *Am. Ind. Hyg. Assoc. J. 44*:788–794 (1983).
3. **Hinds, W.C. and G. Kraske:** Performance of dust respirators with facial seal leaks: I. Experiment. *Am. Ind. Hyg. Assoc. J. 48*:836–841 (1987).
4. **Holton, R.M., D.L. Tackett, and K. Willeke:** Particle size-dependent leakage and losses of aerosols in respirators. *Am. Ind. Hyg. Assoc. J. 48*:848–854 (1987).
5. **Holton, R.M. and K. Willeke:** The effect of aerosol size distribution and measurement method on respirator fit. *Am. Ind. Hyg. Assoc. J. 48*:855–860 (1987).
6. **Myers, W.R., J. Allender, R. Plummer, and T. Stobbe:** Parameters that bias the measurement of airborne concentration within a respirator. *Am. Ind. Hyg. Assoc. J. 47*:106–114 (1986).
7. **Myers, W.R., J.R. Allender, W. Iskander, and C. Stanley:** Causes of in-facepiece sampling bias: i. Half-facepiece respirators. *Ann. Occ. Hyg. 32*:345–359 (1988).
8. **Krishnan, U., K. Willeke, A. Juozaitis, M. Lehtimäki, and K. Szewczyk:** Development of a dichotomous flow quantitative fit test for half-mask and full-facepiece respirators. *Am. Ind. Hyg. Assoc. J. 55(3)*:223–229 (1994).
9. **Willeke, K., H.E. Ayer, and J.D. Blanchard:** New methods for quantitative respirator fit testing with aerosols. *Am. Ind. Hyg. Assoc. J.42*:121–125 (1981).
10. "Respiratory protective devices; tests for permissibility; fees" *Code of Federal Regulations* Title 30, Part 11, 1984. p. 58.
11. **Willeke, K. and U. Krishnan:** Present procedures in quantitative respirator fit testing: problems and potential solutions. *Appl. Occup. Environ. Hyg. 5(11)*:762–765 (1990).
12. **Phalen, R.F.:** Airway anatomy and physiology. In *Particle Size-Selective Sampling in the Workplace, Report of the ACGIH Technical Committee on Air Sampling Procedures.* Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists, 1985.
13. **Streeter, V.L. and E.B. Wiley:** *Fluid Mechanics.* New York: McGraw-Hill, 1981. pp. 192–193.