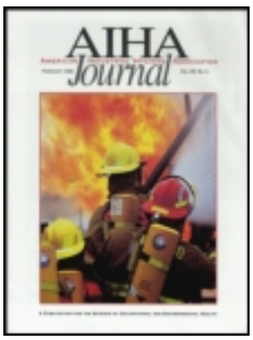

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SIMPLIFIED PRESSURE METHOD FOR RESPIRATOR FIT TESTING*

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A simplified pressure method has been developed for fit testing air-purifying respirators. In this method, the air-purifying cartridges are replaced by a pressure-sensing attachment and a valve. While wearers hold their breath, a small pump extracts air from the respirator cavity until a steady-state pressure is reached in 1 to 2 sec. The flow rate through the face seal leak is a unique function of this pressure, which is determined once for all respirators, regardless of the respirator's cavity volume or deformation because of pliability. The contaminant concentration inside the respirator depends on the degree of dilution by the flow through the cartridges. The cartridge flow varies among different brands and is measured once for each brand. The ratio of cartridge to leak flow is a measure of fit. This flow ratio has been measured on human subjects and has been compared to fit factors determined on the same subjects by means of photometric and particle count tests. The aerosol tests gave higher values of fit.

In a quantitative fit test, a fit factor is determined by measuring the ratio of aerosol concentration outside the respirator to that inside the respirator.[1] Aerosol measurements, however, require complex and expensive equipment. The test results not only depend on the particle size of the aerosol used and on the testing method,[2,3] but also on the mixing conditions inside the respirator cavity, the sampling probe location, and the leak site position.[2,4,5]

Recently, a pressure decay method has been studied as a simple and inexpensive means to conduct a quantitative fit test.[6–8] In this method, the mask's air-purifying cartridges are temporarily removed, a pressure sensor is attached, and a pressure decay slope is determined during breath-holding. The slope is then used as a measure of air leakage into the respirator cavity.[6] However, the pressure decay slope has been found to be dependent on the respirator cavity volume and affected by the degree of pliability of the respirator.[7,9] The main goal of this study was, therefore, to develop a simplified pressure method that is not affected by the respirator cavity volume and the pliability of the respirator body.

PRINCIPLES

When a person wears an air-purifying respirator, two kinds of airflow enter the respirator cavity. As shown in Figure 1, the primary airflow, Q_c, enters through the cartridges and the secondary airflow, Q_l, enters through leak sites, which are usually small gaps between the wearer's face and the respirator body, but may also be small pathways in a defective exhalation valve. Both types of leak flow will be referred to as Q_l.

The protection provided by a respirator is defined by the protection factor, PF, which is the ratio of the concentration of contaminants outside the respirator (C_o) to the concentration inside the respirator cavity (C_i).[10]

$$PF = \frac{C_o}{C_i} \quad (1)$$

The amount of contaminant present inside the respirator, N_i, depends on the flow rate through the cartridges and their efficiency of contaminant removal, η_c, as well as the flow rate through the leak sites and their efficiency of contaminant removal, η_l.

$$N_i = C_o Q_c t(1 - \eta_c) + C_o Q_l t(1 - \eta_l) \quad (2)$$

where t is a time unit.

$$C_i = \frac{N_i}{Q_c t + Q_l t} = \frac{C_o Q_c (1 - \eta_c) + C_o Q_l (1 - \eta_l)}{Q_c + Q_l} \quad (3)$$

Thus, the protection factor

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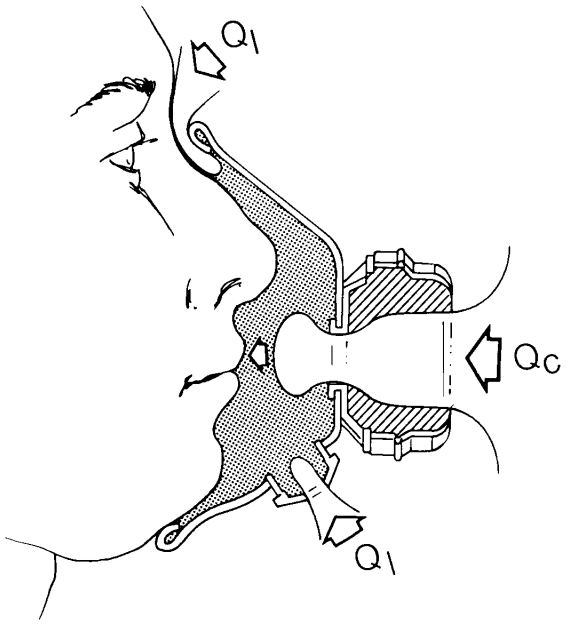

FIGURE 1. Schematic representation of the airflows entering the respirator cavity volume. Q_l = leak flow, Q_c = cartridge flow.

$$PF = \frac{1 + Q_c/Q_l}{(Q_c/Q_l)(1-\eta_c) + (1-\eta_l)} \quad (4)$$

In conventional quantitative fit testing with aerosols, high-efficiency particulate air-purifying (HEPA) filters remove at least 99.97% of the outside aerosols ($\eta_c \cong 1$) so that the fit factor obtained from such a test reflects only leakage, Q_l. For a fit test, the protection factor is referred to be a fit factor (FF), Equation 4 becomes

$$FF = \frac{1 + Q_c/Q_l}{1-\eta_l} \quad (5)$$

The ratio of Q_c to Q_l, flow ratio (FR), is a measure of the fit of the respirator to the wearer's face. FR is independent of particle size.

$$FR = \frac{Q_c}{Q_l} \quad (6)$$

Previous investigations have shown that the flow through a cartridge is laminar and, therefore, depends linearly on the pressure difference (ΔP) between the inside and the outside of the respirator.[7]

$$Q_c = f_c \Delta P \quad (7)$$

where f_c = coefficient for a specific cartridge, determined experimentally.

The setup for the new pressure test is shown schematically in Figure 2. A small air pump creates a negative pressure inside the respirator cavity that is comparable to the pressure during actual wear. The total pump flow, Q_t, is the sum of the leak flow, Q_l, and the bypass flow, Q_b. The system was set up so that the largest leak flow, Q_l (with which the fit test would be considered a failure for most quantitative fit tests), was only 2% of the total flow, Q_t, and so that the changes of leak flow from 0 to the largest Q_l would have no significant effect on the total flow. Therefore, Q_t can be considered constant. A steady-state pressure is reached within 1 or 2 sec while the wearer's breath is held. This pressure, measured by the pressure sensor and displayed on a computer screen, is highest for a small leak, Trace A in Figure 2, and lowest for a large leak, Trace C. The relationship between the steady-state pressure difference, ΔP, and leak flow, Q_l, depends on the size of the leak only and is therefore independent of the respirator used, including its volume and pliability.

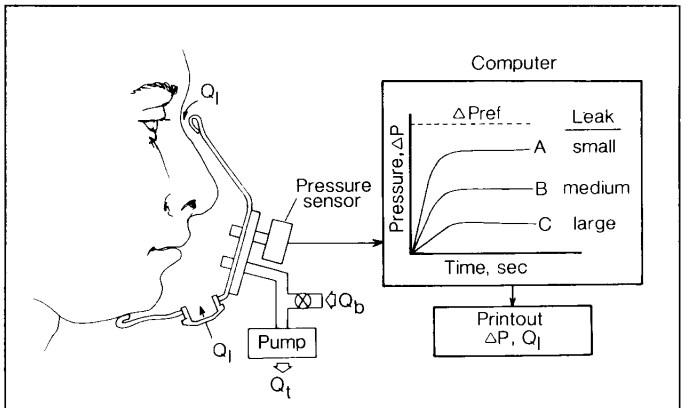

FIGURE 2. Determination of leak flow, Q_l. Q_b = pump bypass flow, Q_t = total pump flow. ΔP_{ref} = pressure difference when there is no leak.

The relationship between leak flow, Q_l, and ΔP can be expressed as follows.

$$Q_l = f_l(\Delta P_{ref} - \Delta P) \quad (8)$$

where f_l and ΔP_{ref} are constants that depend on the experimental setup.

The pressure difference across the cartridges equals that across the face seal leak. From Equations 7 and 8, the flow ratio can, thus, be written

$$FR = \frac{Q_c}{Q_l} = \frac{f_c \Delta P}{f_l(\Delta P_{ref} - \Delta P)} = \frac{a\Delta P}{\Delta P_{ref} - \Delta P} \quad (9)$$

where $a = f_c/f_l$ is a constant. The dependence of flow ratio, FR, on test pressure, ΔP, reflects the leak flow and, therefore, face seal fit.

EXPERIMENTAL MATERIALS AND METHODS

The following materials were used in the experimental setup for the pressure method: pressure test attachment (pressure sensor and air inlet valve); pressure sensor with an operational range of 0 to 25 cm w.g. and a response time of 1 msec (Model PX-160, Omega Engineering, Stamford, Conn.); computer-based data acquisition system; air pump with a flow rate of 10 L/min (Model No. 1531-107-0288, Robbins and Myers, Springfield, Ohio). For calibration tests, eight artificial holes (diameters ranging from 0.27 to 1.5 mm) were used on a mannequin. Human subjects were used in the comparison studies.

Two aerosol testing systems were used in the comparison studies: a photometric system (Model 264, Dynatech Frontier Corp., Albuquerque, N.Mex.) and a particle count system (Model Porta-Count, TSI, St. Paul, Minn.).

The pressure tests on human subjects were conducted as follows.

1. The respirator cartridges were replaced with the pressure test attachments. The subject was instructed to breathe normally.
2. The pump was turned on. The subject's breath was held for a few seconds while the air inlet in the attachment was closed.
3. Steady-state pressure difference, ΔP, was recorded.
4. The air inlet was reopened and the subject was instructed to breathe normally again.
5. Flow ratio, FR, was calculated as a measure of respirator fit by using Equation 9.

Because the focus of this study was on the development of a new technique, comparison tests were performed only to determine whether the new method can be related to currently used fit tests. Therefore, only three human subjects participated in the comparison studies. Two brands of respirators with three different sizes were used. The sequence of comparison testing was randomized. The subject, however, did not remove the respirator until all three tests were finished and was instructed not to adjust the respirator while the three tests were performed. Each test was repeated three times.

RESULTS AND DISCUSSION

Figure 3 shows the relationship between ΔP and leak flow, Q_l, determined with eight artificial holes. The measured steady-state pressure differences, ΔP, are less than 1 cm w.g., which corresponds to inspiratory pressures during typical respirator wear as found from the authors' observations. Each point in the figure represents the average of three replicate tests. The standard deviations of the leak flow varied from 0.7% to 3% of the mean. The relationship between Q_l and ΔP is a straight line with a regression equation of $Q_l = 276\ (0.76 - \Delta P)$ and a correlation coefficient of 0.97.

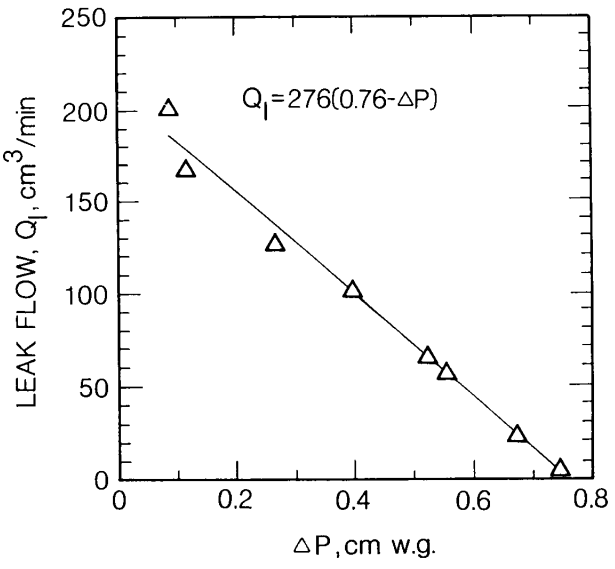

FIGURE 3. Calibration curve for leak flow as a function of steady-state pressure difference, ΔP

In Figure 4, flow ratio (FR) is plotted directly versus ΔP for a given half-mask respirator. From this plot, for a measured ΔP, a flow ratio can be obtained that reflects the leak flow and thus face seal fit. Flow ratio and fit factor are also dependent on the type and brand of cartridges used because different cartridges have different flow resistances, and therefore, different cartridge flows. An individual plot for each brand of cartridge can be obtained experimentally and stored in the computer.

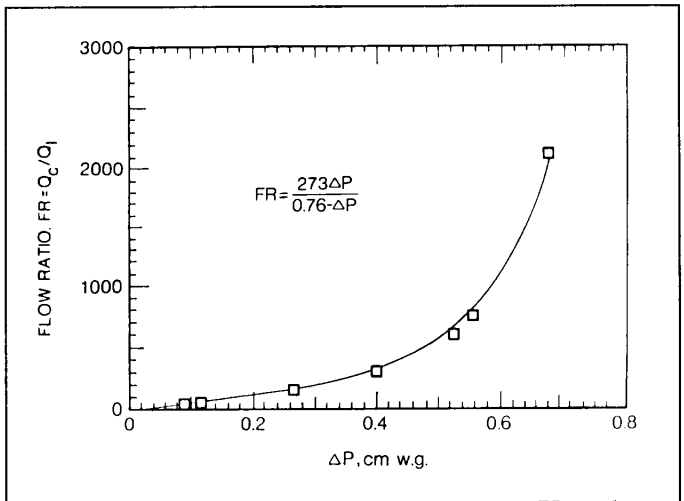

FIGURE 4. Relationship between flow ratio, FR, and steady-state pressure difference, ΔP, for a given half-mask respirator

The flow ratios obtained by the pressure method on human subjects were compared to fit factors determined by photometric and particle count tests. The results are shown in Figure 5. The arithmetic average fit factors are plotted against the flow ratios, measured by the pressure method. Based on the limited data, the standard deviations for the pressure tests varied from 2% to about 51% of the mean. The standard deviations for the aerosol tests were as low as 3% of the mean when the fit factor was small but reached up to about 90% of the mean when the average fit factor exceeded 10 000. The two lines in Figure 5 represent the best fit. From these data, it can be seen that the flow ratios measured by the pressure method are smaller than the fit factors measured by the aerosol methods. The difference between flow ratio and fit factor increased with better fitted respirators. Similar observations have been made by use of a system that measures the leak flow directly.[11]

The above observations were expected. In quantitative respirator fit testing with aerosols, HEPA filters are used to purify the cartridge flows. Therefore, it is assumed that the aerosols recorded by the aerosol detector represent only the aerosols that have entered the respirator cavity through face seal leaks. However, the contaminated leak flow could not thoroughly mix with

the clean cartridge flow during the short inhalation/exhalation period. Therefore, the sampled aerosol does not, in general, represent the average aerosol concentration in the respirator.[3–5]

Because pressure adjusts almost instantaneously in the small respirator volume, a pressure test truly represents the face seal leakage wherever the pressure sensor is located. Because air is the carrier for particulate and gaseous contaminants entering the respirator, measurement of the leak flow is, in the authors' opinion, the parameter of interest. The amount of contaminant aerosol or gas entering the respirator is given by the efficiency of transmission in the leak site, as shown in Equation 5. The traditional fit factor determination focuses on the transmission of a specific aerosol size range. Because some of the external aerosols are deposited before reaching the detector, one expects the fit factor (derived from aerosol measurements) to be higher than the flow ratio (derived from pressure measurements). Furthermore, one expects the correlation between fit factor and flow ratio to have greater variability for high fit factors where the aerosol instrument detects statistically fewer particles and the aerosol concentration signal is close to the instrument's noise level.

Comparison of the two aerosol methods in Figure 5 indicates that the particle count method usually gives somewhat higher fit

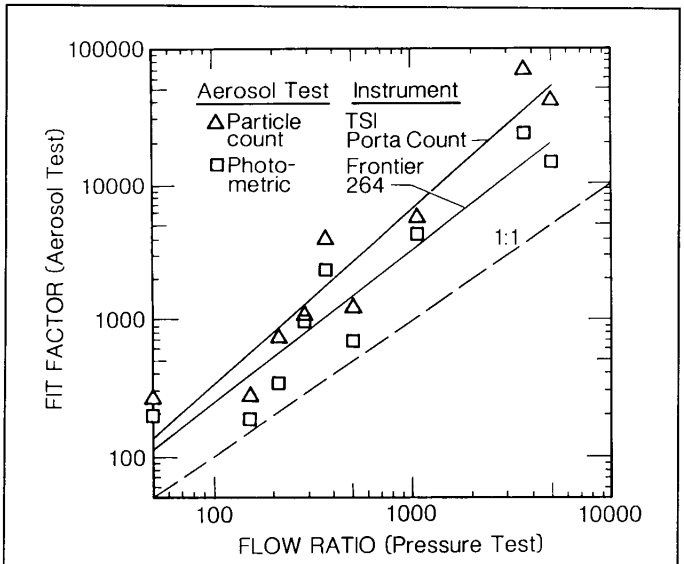

FIGURE 5. Comparison of pressure test with two aerosol tests on human subjects

factors than the photometric method. This may be explained by the difference in particle size measured by the two aerosol methods.[3,12] The particle count method uses ambient aerosols with the majority of particles in the size range of 0.1 μm or less, and the photometric method uses aerosols of about 0.5 μm in size. The 0.5-μm particles pass through the leak sites somewhat more effectively than the smaller particles because loss by diffusion to the surface of the leak hole increases with decreasing particle size.

CONCLUSIONS

The simplified pressure test is conducted by measuring the steady-state pressure difference inside and outside the respirator while air is withdrawn simultaneously from the respirator and a flow-resisting bypass branch. The cartridge-to-leak flow ratio, determined from this pressure test and measurements of flow through the air-purifying cartridges, represents the respirator fit, independent of respirator size and pliability. Each test takes a few seconds and may be conducted on the respirator that is actually worn in the workplace. Comparison studies between the pressure method and the two aerosol methods have shown that fit factors obtained from aerosol tests are higher than the flow ratios obtained with the pressure method.

Further studies with more human subjects and an optimized test system setup are needed to further evaluate the method. Future studies will also evaluate the effect of head motion and resulting facial deformation on fit testing results.

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REFERENCES

1. **Myers, W.R., S.W. Lenhart, D. Campbell, and G. Provost:** The Forum. *Am. Ind. Hyg. Assoc. J. 44(3)*:B25–B26 (1983).
2. **Holton, P.M., L. Tackett, and K. Willeke:** Particle Size-Dependent Leakage and Losses of Aerosols in Respirators. *Am. Ind. Hyg. Assoc. J. 48(10)*:848–854 (1987).
3. **Holton, P.M. and K. Willeke:** The Effect of Aerosol Size Distribution and Measurement Method on Respirator Fit. *Am. Ind. Hyg. Assoc. J. 48(10)*:855–860 (1987).
4. **Myers, W.R., J. Allender, R. Plummer, and T. Stobbe:** Parameters that Bias the Measurement of Airborne Concentrations within a Respirator. *Am. Ind. Hyg. Assoc. J. 47(2)*:106–114 (1986).
5. **Myers, W.R., J. Allender, W. Iskander, and C. Stanley:** Causes of In-Facepiece Sampling Bias—I. Half-Facepiece Respirators. *Ann. Occup. Hyg. 32*:345–359 (1988).
6. **Willeke, K.:** U.S. Patent No. 4,846,166 (1989).
7. **Carpenter, D.R. and K. Willeke:** Noninvasive, Quantitative Respirator Fit Testing through Dynamic Pressure Measurement. *Am. Ind. Hyg. Assoc. J. 49(10)*:485–491 (1988).
8. **Carpenter, D.R. and K. Willeke:** Quantitative Respirator Fit Testing: Dynamic Pressure versus Aerosol Measurement. *Am. Ind. Hyg. Assoc. J. 49(10)*:492–496 (1988).
9. **Han, D.:** "Simplified Pressure Method for Respirator Fit Testing." M.S. thesis, University of Cincinnati, 1989.
10. **Bollinger, N.J. and R.H. Schutz:** *NIOSH Guide to Industrial Respiratory Protection.* Washington, D.C.: U.S. Government Printing Office, 1987.
11. **Crutchfield, C.D., R.W. Murphy, and M.D. Van Ert:** "A Comparative Study of Quantitative Respirator Fit Test by Negative Pressure and Aerosol Technology." Paper No. 180 presented at the American Industrial Hygiene Conference, St. Louis, Mo., May 1989.
12. **Willeke, K., H.E. Ayer, and J.D. Blanchard:** New Methods for Quantitative Respirator Fit Testing with Aerosols. *Am. Ind. Hyg. Assoc. J. 42(2)*:121–125 (1981).