

The Effect of Moisture on the Face Seal Fit of Half-Mask Respirators

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ABSTRACT

A study was conducted to investigate the effect moisture has on the face seal fit of half-mask particulate respirators using a “simulated” sweat procedure intended to assess fit under more realistic wear conditions. Respirator fit factor data were obtained while 48 subjects completed two different quantitative fit testing (QNFT) methods under ambient environmental conditions. The two QNFT methods compared were an 8-exercise ambient aerosol protocol, conducted using a commercial condensation nuclei counter (CNC) fit testing device (Portacount®, TSI, Inc.), and a 10-exercise corn oil aerosol protocol that was performed in an exposure chamber using a forward light-scattering photometer. Four commercial P-100 particulate half-mask respirators were evaluated. To simulate face sweating, the inside of the respirator facepiece was wetted with water administered from a spray bottle. Fit test trials were performed using dry and wet respirators. Statistical analysis of the dry and wet fit factor results for both QNFT methods showed that respirator fit was not significantly ($p < 0.05$) degraded due to wetting of the facepiece. However, there was a trend for lower fit factors for each of the respirator models tested wet using the photometer/corn oil aerosol QNFT method. Post-hoc analysis of the CNC exercise data revealed significantly lower mean fit factors for the talking, grimace, and bending over exercises ($p < 0.02$). The grimace exercise was observed in both QNFT methods to cause the greatest degradation in fit. Although the study failed to demonstrate the value of wetting the respirator facepiece prior to fit testing, the findings do support the use of dynamic exercises to provide a more discerning measure of fit.

Keywords: Fit factors, quantitative fit testing, half-mask respirators, sweat

INTRODUCTION

Air-purifying half-mask respirators are widely used in the workplace to provide protection against a variety of gas, vapor, and particulate contaminants. The resistance to breathing inherent to these respirators generates negative pressure inside the respirator's facepiece that may permit outside contaminant-laden air to enter the face seal. The face seal design, facepiece material, weight of the respirator, and filter resistance are factors that can influence the degree of facepiece leakage experienced by a respirator wearer. In addition, certain workplace activities in conjunction with perspiration may also induce leakage by causing the respirator to slip on the face.

Quantitative fit factors are often used to quantify the degree of face seal leakage. Fit factors represent a measure of the quality of the face seal of a specific respirator facepiece to a particular individual. Fit factors are determined by dividing the concentration of the test atmosphere outside the respirator by the concentration measured inside the facepiece. Quantitative fit test procedures accepted by The Occupational Safety and Health Administration (OSHA) to fit respirators in the workplace are described in Appendix A of 29 CFR Parts 1910 and 1926 (January, 1998). These fit test protocols take

less than 10 minutes to complete and involve a regimen of low intensity exercises intended mainly to stress the facepiece seal. They are not rigorous enough to induce significant sweating, and thus do not take into account a key factor that can contribute to facepiece leakage in the workplace. The purpose of this study was to determine the effectiveness of using a "simulated" sweat procedure in the fit testing of respirators to provide a more demanding real-world assessment of face seal fit.

Although data is lacking that shows a definitive causal relationship between perspiration and respirator leakage, several studies have reported a tendency towards increased leakage due to facial sweating. Caretti and Gardner (1999) measured facial and whole body sweat production on subjects exercising at room temperature for 30 minutes on a treadmill while wearing a military, air-purifying, full-facepiece respirator. Fit factors were found to significantly decrease to a moderate degree over time, however, no significant correlation between sweat production and measured fit factors was observed. The authors concluded that certain mask design factors along with head and facial sweating may act together to alter the fit and thus degrade respirator performance.

A follow-on study by Caretti and Gardner (1999) investigated the effect of exercise on respirator face seal fit under high temperature and humidity conditions. Overall fit factors were measured before, during, and after a 60-minute treadmill walk with subjects wearing three different military full-facepiece air-purifying respirators. Fit factors measured after the treadmill walk on two of the respirators were significantly lower than those measured before the start of the exercise period. No significant differences in fit factors were observed between the three respirators at the three fit test periods. Other investigators have found air-purifying half-mask and full-facepiece respirators to degrade due to simulated work activities performed while subjects wore respirators under hot conditions. Skaggs *et al.* (1988) found fit factors obtained at room temperatures to be higher than those obtained under simulated work conditions in a controlled hot and humid environment. The findings were attributed to facepiece slippage caused by sweating.

In this study the effect of moisture on face seal leakage of half-mask respirators was assessed by comparing fit factors measured using dry masks to those measured using masks wetted with water to simulate sweat. The foremost objective was to determine the value of using a simulated sweat procedure as a means to evaluate respirator performance under more realistic wear conditions. A secondary objective was to compare the overall fit factors determined using two different QNFT methods, an ambient aerosol and generated aerosol protocol, to determine how well the methods agreed with each other. The ambient aerosol QNFT protocol was performed using a commercial condensation nuclei counter (CNC) fit testing device (Portacount®, TSI, Inc.). A photometer fit test system developed by TSI, Inc., St. Paul, MN was used to conduct the generated aerosol (corn oil) protocol. Individual exercise fit factors from each method were also compared to determine which exercises had the most impact on fit factors.

MATERIALS AND METHODS

Test Participants

Forty-eight, clean-shaven, male volunteers between 18 and 25 years of age participated in this study. The volunteers were recruited from a predominately male source of military personnel stationed at Aberdeen Proving Ground, MD. At the time of the study, no female volunteers were available for testing. All subjects completed a medical questionnaire to determine their health status and were screened for any condition(s) that would preclude safe participation in the study. Subjects were given a detailed briefing on the nature of the test protocol and objectives of the study. Written informed consent was obtained from each volunteer prior to testing.

Respirators

Four brands of half-mask respirators from four different manufacturers, designated Masks A, B, C, and D, were used in this study. Each of the respirator brands came in three sizes: small, medium, and large. All

of the respirator facepieces were made of silicone rubber with the exception of Mask A's facepiece which consisted of a thermoplastic polymer. Masks A and B were equipped with light-weight "pancake" type high efficiency particulate air (HEPA) filters that were very similar in size and weight. Masks C and D had traditional low-profile HEPA cartridge filters that were also similar in size and weight to each other. All filters were certified by the National Institute for Occupational Safety and Health as P-100 particulate filters in accordance with 42 CFR Part 84 (June, 1995).

Subject Training

Subjects were sized and fitted by trained test personnel using the manufacturer's procedures provided with each respirator model. Subjects were instructed on how to don the respirator according to the manufacturer's instructions before the start of testing. The training included a donning practice session whereby the subjects self-donned the respirator until they became proficient with the technique. A typical training session lasted approximately 30 minutes.

Test Conditions

Subjects were tested in six groups, each consisting of eight volunteers. Each group of volunteers was randomly assigned two of the four respirator brands. Each subject was tested once in each assigned respirator brand by each QNFT method under each wear condition (wet and dry). The two fit test protocols were conducted sequentially without having the subjects remove or adjust their masks. Due to logistic and time constraints, the CNC fit test was always performed first. This minimized the waiting time between the two tests, which was less than 5 minutes for each test group, and thus reduced the total test time. Due to subject availability and time constraints, only four sequential CNC/Photometer fit test trials were conducted. For the photometer test, subjects completed a duplicate trial in two randomly assigned respirator wear combinations for a total of six trials. The respirators were removed, cleaned, and dried at the end of each test sequence. Respirators tested in the wet condition were wetted immediately prior to donning by spraying water onto the facepiece to simulate sweat. Water was administered using a spray bottle filled with filtered tap water that was adjusted to deliver a fine mist. Approximately 5 ml of water (6 full pump strokes) was applied to the inside of the respirator to sufficiently wet the sealing surface. For the dry test condition, the subject's face and mask were dried using a clean cotton towel. After the respirator was donned, a visual inspection of the subject's fit was performed to ensure that the respirator had been properly donned. Subjects wore the respirator for a minimum of 5 minutes prior to the initial fit test trial to allow sufficient time for the mask to conform to the face.

CNC/Ambient Aerosol QNFT Method

Before entering the corn oil aerosol chamber, the subjects performed a quantitative fit test using the TSI Portacount® 8020M (TSI Inc., St. Paul, MN). The Portacount is a portable microprocessor-controlled quantitative fit testing (QNFT) device that uses a miniature condensation nuclei counter (CNC) to measure ambient aerosols inside and outside of the respirator to determine the fit factor. The instrument is capable of detecting fit factors of 10,000 or higher depending on the background aerosol concentration. The OSHA-accepted quantitative fit test protocol for the CNC (Portacount) was followed (29 CFR Parts 1910 & 1926 [Appendix A], 1998) with the exception that the grimace exercise was performed for one minute, as opposed to 15 seconds, and the fit factor data recorded for subsequent analysis. This was done to obtain data to permit direct comparison of the grimace exercise to the remaining exercises. In-mask samples were collected using a 1/8" I.D. stainless steel probe mounted in the center of the facepiece such that the inlet was located approximately 5/8" from the inside surface at a position mid-point between the wearer's upper lip and nose. The fit factor data obtained was used to compare the CNC/ambient aerosol protocol to a standard photometer/corn oil aerosol protocol used by the U.S. joint services to assess the performance of military respirators.

The CNC QNFT exercises consisted of the following eight activities: Normal breathing, deep breathing, turning head side to side, moving head up and down, talking (counting down from 100), grimacing, bending over (reaching up and down), and normal breathing. Each test exercise was performed for one minute. The CNC QNFT method calculates overall fit factors using the following equation:

$$\text{Overall fit factor} = n / (1/ff_1 + 1/ff_2 + 1/ff_3 + \dots + 1/ff_{n-1} + 1/ff_n)$$

where ff = fit factor for each test cycle (exercise) and n = number of exercises. Individual exercise and overall fit factor data was manually recorded for subsequent analysis.

Photometer/Corn Oil Aerosol QNFT Method

A large test chamber (30 m² by 3 m high) containing a uniform concentration of corn oil aerosol was used to conduct this study. The test aerosol was generated by the nebulization of corn oil at room temperature using an array of Laskin nozzle aerosol generators. The corn oil challenge aerosol was polydispersed and had a mass median aerodynamic diameter of approximately 0.6 μm and mass concentration of $30 \pm 2 \text{ mg/m}^3$. In-mask leakage of the corn oil aerosol was measured using an automated laser photometer-based quantitative fit test (QNFT) system (TSI, model 8597, St. Paul, MN). The QNFT system consists of a data acquisition system (TSI, model 8588, St. Paul, MN) and four laser photometers (TSI model 8587, St. Paul, MN). The test system is capable of measuring fit factors up to 100,000 and testing up to 8 subjects simultaneously (TSI, 1991). In-mask sampling was accomplished using the same sample probe described above for the CNC QNFT method. The flow rate for in-mask sampling was approximately 2.2 L/min. The photometer QNFT system presented the fit factor data graphically in real time on a computer display. Overall fit factors were computed using the same procedure as the CNC QNFT method (see above equation). Upon completion of a fit test, fit factors for each exercise and the overall fit factors were saved to computer disk for future analysis. A thorough description of the corn oil chamber fit test system and sampling procedures used are described in a previous paper (Caretti and Gardner, 1999).

Without adjusting their masks, the subjects entered the corn oil chamber and performed a standard 10-exercise fit test routine used by the U.S. military services to evaluate their respirators. The exercise routine consisted of normal breathing, deep breathing, turning head side to side, moving head up and down, talking (reciting "Rainbow Passage"), sighting a rifle stock, crouching on hands and knees and turning head side to side, bending over, grimacing, and normal breathing. Each fit test exercise was performed for one minute.

Statistical Analysis

Fit factor data were analyzed using two-way analysis of variance (ANOVA), paired t-test, and correlation analysis. All fit factor data were transformed using the natural logarithm ($\ln$) prior to statistical analysis. Statistical tests involving mean differences (i.e., the ANOVA and t-test) assume that the distribution of the data within each group follow the normal distribution. The second assumption is that the variation is the same within each comparison group. To test the assumption of normality, the Kolmogorov-Smirnov and Shapiro-Wilk tests were performed on the transformed fit factor data for the various individual and combined data sets analyzed in this study. The majority of the comparison groups analyzed failed one or both of these normality tests. A more thorough examination of the data was performed using detrended normal probability plots to show the extent and location of the deviation from normality. The deviations from the normal were relatively moderate and occurred at the extremes of the distributions as expected. In all cases, the normality plots showed that the distributions within each comparison group were very similar to each other (skewed in the same direction). The skewness and kurtosis values calculated as part of the normality analysis also confirmed this observation. The Kolmogorov-Smirnov and Shapiro-Wilk tests are robust tests when the sample sizes are moderate to large (e.g., > 25) and the dependent measure has the same distribution within each group as for the case in this study. Under these

circumstances, moderate departures from normality do not appreciably affect the outcome of parametric statistical tests (Kirk, 1968).

The Levene's homogeneity-of-variance test was performed to check for equality of variance within each comparison group. In every case, the test failed to reject the hypothesis indicating that the variance of the transformed fit factors was the same across the various group means. Based on the detailed normality analyses performed and results of the Levene's test, the data was judged acceptable for parametric statistical analysis. The Scheffe *post-hoc* test was used to detect any significant differences found between group means. For all analyses, statistical significance was accepted at the $p < 0.05$ level.

RESULTS

Effect of Mask and Wear Condition

The overall fit factor results for the CNC and photometer QNFT methods are summarized in Tables I and II, respectively. The two-way ANOVA significance tests performed on both fit test methods revealed no significant differences in overall respirator fit factors between the respirators and wet/dry wear conditions. Although differences between the two wear conditions were not significant, fit factors tended to be lower for the wet wear condition. Figures 1 and 2 show the group log means and 95% confidence intervals for each respirator and wear condition for the CNC and photometer QNFT methods, respectively. As illustrated by Figure 2, wetting the facepiece resulted in a notable decrease in the fit factors for all respirator models except Mask D. This tendency was not as prominent for the CNC QNFT method, where the geometric mean wet fit factors were lower for only two of the four respirators, Masks B and C (Figure 1).

Table I. CNC Overall Fit Factor Results

Respirator	Wear Condition	N	GM	Median	GSD
Mask A	Dry	24	3,958	5,346	4.51
	Wet	24	3,980	7,004	6.26
Mask B	Dry	24	2,226	3,301	4.38
	Wet	24	1,421	2,377	5.20
Mask C	Dry	24	3,202	5,970	5.81
	Wet	24	2,263	5,379	6.92
Mask D	Dry	24	2,832	6,496	7.93
	Wet	24	4,823	7,082	3.74

N = number of trials, GM = geometric mean, GSD = geometric standard deviation

For Mask D, the mean wet fit factor was approximately 70% greater than the dry condition. The reason for this apparent anomaly is not known. The only notable design feature found in Mask D and lacking in the other mask models was the presence of a drain slot in the chin cup used to remove excess sweat. It is unlikely, however, that this could account for the observed trend due to the nominal volume of water applied to the inside surface of the half-mask, and the fact that the dry and wet mean fit factors were essentially the same for Mask D when measured by the photometer QNFT method.

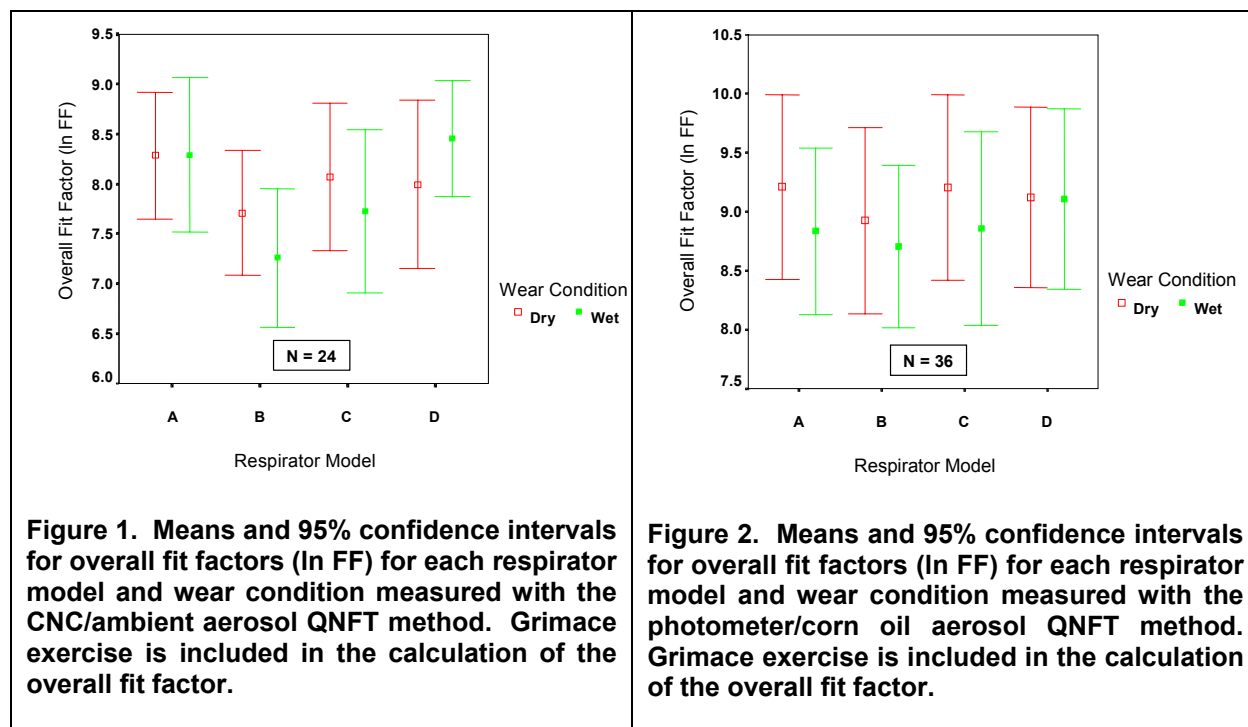
Since the ANOVA showed no significant difference among the overall fit factors for the four respirator models, the data were combined and compared by wear condition. The overall fit factors measured using the CNC QNFT method for the dry condition were found to range from 16 to 34,200 with

a geometric mean of 2,990 and a geometric standard deviation of 1.706. The fit factors for the wet condition ranged from 19 to 28,567 with a geometric mean of 2,803 and a geometric standard deviation of 1.742. For the photometer QNFT method, the overall fit factors for the dry condition ranged from 32 to 99,708 with a geometric mean of 9,094 and a geometric standard deviation of 2.285. The wet fit factors ranged from 20 to 99,708 with a geometric mean and geometric standard deviation of 7,151 and 2.189, respectively. Paired t-tests performed for the two QNFT methods found no significant difference between the dry and wet wear conditions.

Table II. Photometer Overall Fit Factor Results

Respirator	Wear Condition	N	GM	Median	GSD
Mask A	Dry	36	9,986	24,676	10.12
	Wet	36	6,863	8,382	8.05
Mask B	Dry	36	7,512	15,468	10.28
	Wet	36	6,016	5,367	7.64
Mask C	Dry	36	9,951	18,949	10.14
	Wet	36	7,007	7,488	11.35
Mask D	Dry	36	9,163	10,592	9.64
	Wet	36	9,040	18,208	9.59

N= number of trials, GM = geometric mean, GSD = geometric standard deviation



OSHA requires a minimum fit factor of 100 for half-mask respirators. Of the 192 total fit tests performed using the CNC QNFT method (wet and dry), only 11 fit tests failed to meet the OSHA acceptance criterion. The photometer QNFT method yielded 11 failures out of a total of 298 fit tests. This corresponds to pass rates of 94.3% and 96.3%, respectively. In both cases, the number of individuals that failed a fit test in a given respirator model was greater for the dry condition. The Dry/Wet failure ratios were 11/3 (3.7) and 11/4 (2.75) for the CNC and photometer QNFT methods, respectively.

Exercise Effects

The exercise data obtained from both QNFT methods were analyzed using ANOVA to determine the effect of the exercise on the performance of the four respirators evaluated. No significant differences in exercise fit factors were found between the respirator models for the two wear conditions. Likewise, no significant differences in exercise fit factors were observed between the dry and wet wear conditions when the data from all respirators were combined. The data was then pooled for all respirators and wear conditions to determine statistical differences between the exercises performed during each QNFT method. Descriptive statistics for the pooled data are presented in Tables III and IV. The ANOVA results showed highly significant differences between the log mean exercise fit factors for both the CNC ($F=37.5$, $df=7$, $p<0.0001$) and photometer ($F=21.4$, $df=9$, $p<0.0001$) QNFT methods. Scheffe post-hoc analysis performed on the photometer data showed that the grimace exercise fit factor was significantly lower than the remaining nine exercises ($p<0.0001$); no other significant differences between the exercises were found. Post-hoc analysis of the CNC data revealed significantly lower mean fit factors for the talking, grimace, and bending over exercises ($p\leq 0.022$).

Table III. CNC Exercise Fit Factor Results (Pooled Data)

Exercise	N	GM	Median	GSD
Normal Breathing (NB ₁)	192	12,523 ^B	14,350	3.79
Deep Breathing (DB)	192	13,964 ^B	15,596	3.82
Head Side to Side (SS)	192	13,116 ^B	15,500	4.39
Head Up and Down (UD)	192	13,754 ^B	16,900	4.66
Talking (T)	192	2,931 ^A	2,935	3.77
Grimace (G)	192	2,656 ^A	7,885	12.29
Bending Over (BO)	192	6,138 ^A	7,690	4.83
Normal Breathing (NB ₂)	192	14,462 ^B	21,099	5.49
Overall FF (FF ₁) (Includes Grimace)	192	2,895 ^A	5,495	5.58
Overall FF (FF ₂) (Excludes Grimace)	192	4,864 ^A	6,545	4.00

N= number of trials; GM = geometric mean; GSD = geometric standard deviation (ln FF)
Values with different superscripts are significantly different at $p<0.05$

The OSHA-accepted fit test protocol for the CNC/ambient aerosol method does not factor in leakage during the grimace exercise. However, the grimace exercise is usually the most rigorous exercise in terms of facepiece leakage as demonstrated in this study. Overall fit factors measured using the CNC method were calculated with and without the grimace exercise. The mean overall fit factors for the two calculations are presented in Table III. A paired t-test performed on the log-transformed overall fit factor data (obtained from the 192 CNC fit test trials) yielded a significant difference between the two overall fit factor calculations ($p<0.0001$), providing further evidence of the rigorous nature of the grimace exercise on half-mask fit.

Table IV. Photometer Exercise Fit Factor Results (Pooled Data)

Exercise	N	GM	Median	GSD
Normal Breathing (NB ₁)	288	37,045 ^B	99,997	6.02
Deep Breathing (DB)	288	39,704 ^B	99,997	5.54
Head Side to Side (SS)	288	35,235 ^B	99,997	6.38
Head Up and Down (UD)	288	38,511 ^B	99,997	6.06
Talking (T)	288	24,850 ^B	54,704	6.76
Sight Rifle Stock (SR)	288	28,811 ^B	96,868	7.02
Crouching (C)	288	32,186 ^B	97,032	6.92
Bending Over (BO)	288	24,736 ^B	99,419	9.31
Grimace (G)	288	5,861 ^A	14,663	19.40
Normal Breathing (NB ₂)	288	23,384 ^B	86,604	8.59
Overall Fit Factor (FF)	288	8,064 ^A	11,406	9.36

N= number of trials; GM = geometric mean; GSD = geometric standard deviation (ln FF)
 Values with different superscripts are significantly different at $p < 0.05$

Comparison of Fit Test Methods

A secondary interest of this study was to compare the fit factors measured using the CNC and photometer QNFT methods. Statistical analysis was performed on the 192 paired observations obtained from sequential testing of 24 subjects completing one set of test trials in each mask and wear combination. Comparisons between the two methods were made using the CNC overall fit factor results calculated with and without the grimace exercise. Geometric mean overall fit factors calculated for the photometer method and the CNC method including and excluding the grimace exercise were 8,064, 2,895, and 4,864, respectively. Results of the paired t-tests using the grimace and non-grimace data showed significant differences between the two QNFT methods ($p < 0.001$).

A simple linear regression analysis was performed using the photometer fit factors as the independent variable and the CNC fit factors as the dependent variable. The CNC fit factors calculated with and without the grimace exercise showed little correlation with the photometer fit factors with R^2 values of 0.25 and 0.09, respectively. Regression plots for the data are shown in Figures 3 and 4.

DISCUSSION

Sweating during respirator wear is a common occurrence in most workplace environments. Moisture inside the facepiece from sweat may cause the facepiece to shift on the face, thereby potentially altering the fit. This in turn may induce leakage and increase the respirator wearer's risk of exposure to contaminants in the workplace. The volume of sweat produced within the facepiece of a respirator can often be substantial. Johnson *et al.* (1997) measured sweat accumulation in subjects wearing a full-facepiece respirator while sitting in a warm, humid environment (35°C and 90% humidity) for 90 minutes and found that sweat rates from the face, head, and neck averaged 0.203 g/min. The authors estimated that up to 60 cm³ of sweat could accumulate inside a respirator facepiece in an 8-hour workday. Caretti and Gardner (1999) found facial sweat rates almost five times greater (1.05 g/min) than those reported by Johnson *et al.* (1997) for subjects exercising moderately at room temperature on a treadmill wearing a

full-facepiece respirator. Although facepiece slippage was observed to slightly degrade respirator fit, no significant correlation of facial sweat production and measured fit factor was found.

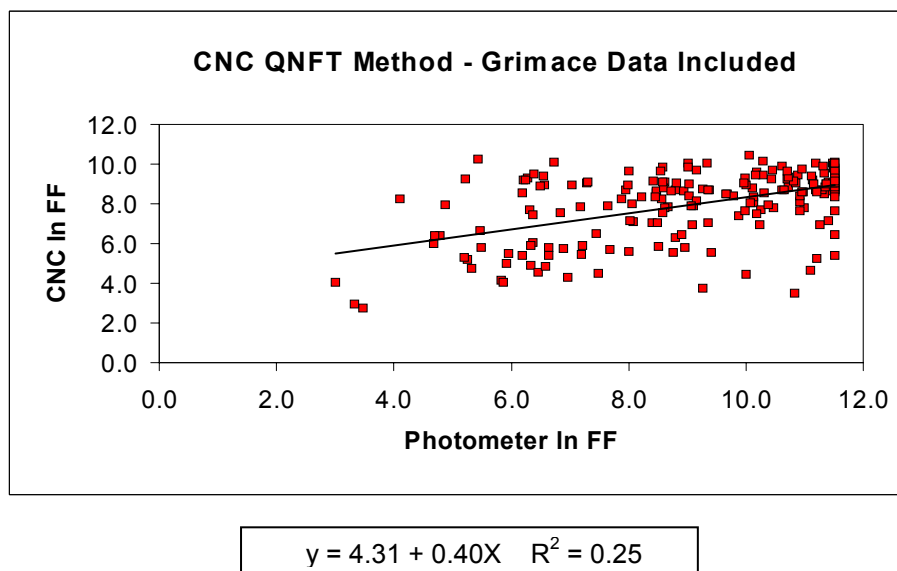


Figure 3. Regression of natural log (ln) photometer fit factors (FF) and ln CNC fit factors calculated with the grimace exercise.

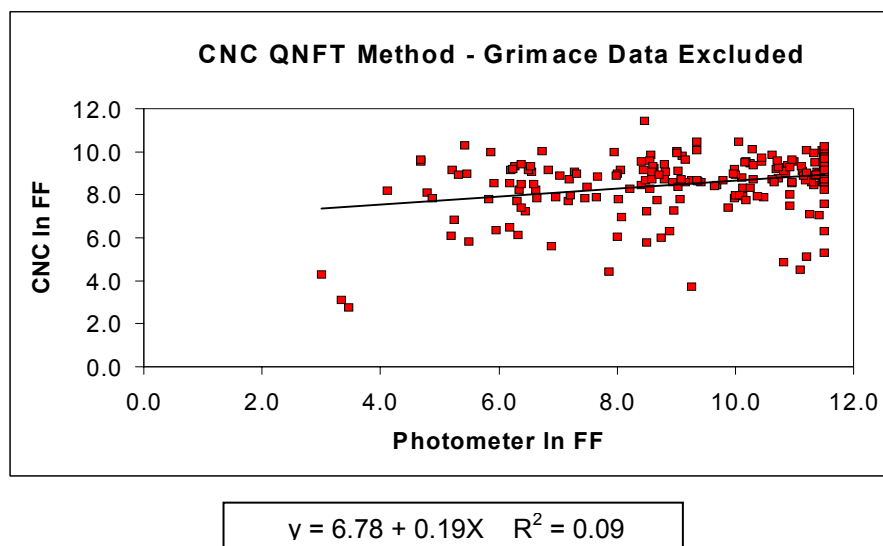


Figure 4. Regression of natural log (ln) photometer fit factors (FF) and ln CNC fit factors calculated without the grimace exercise.

In this study the effect moisture has on the face seal fit of half-mask respirators during fit testing was investigated. A notable trend towards lower fit factors was demonstrated for the CNC and photometer methods for respirators that received the wet treatment. This trend was much less

pronounced for the CNC QNFT method. The different exercise protocols used could account for some of the discrepancy between the two QNFT methods. Another possible explanation is that because the CNC method was always performed first, the effect (i.e., lower FFs caused by a wet facepiece) did not fully manifest itself until the photometer fit test. In addition, the procedures used in this study represent ideal conditions. Great attention was given to ensure that the test participants were properly sized, fitted, and trained in their assigned respirators just prior to being tested. In actual practice, the wetting procedure may produce more conservative estimates of fit since QNFT practices in the workplace rarely approach the ideal conditions used in this study.

The findings suggest that some change in fit occurred as a result of the simulated sweat treatment. The cause of the degradation in fit observed is not readily apparent. No obvious signs of facepiece slippage were observed in this study. Furthermore, subjects were monitored closely and instructed not to touch or adjust the respirator once donned. The wetting procedure, however, did not increase the percentage of fit failures (i.e., $FF < 100$). On the contrary, those few individuals that failed a CNC or photometer fit test were on average approximately three times more likely to fail in the dry than in the wet wear condition. Consequently, the results do not support the usefulness of wetting the facepiece in the context of workplace fit testing. The procedure, however, may have merit in research and development applications where the purpose is to assess the overall fit performance of different respirator models and facepiece designs.

Filtered tap water was used as a surrogate for sweat and thus did not contain the dissolved salts (electrolytes) and other metabolic compounds found in sweat. What impact these substances may have on facepiece slippage is unknown, but it is reasonable to assume that water is the principal component of perspiration that induces mask slippage. Since filtered water is readily available, the procedure could be easily administered in the workplace.

A relatively small amount of water (5 cm³) was used to simulate light sweating. In most workplace settings, total sweat accumulation inside the facepiece would be much higher as suggested by studies referenced above. However, facepiece slippage can occur at any time once sweating has begun and is therefore not solely dependent on the rate or total volume of sweat produced. Other factors such as the initial quality of fit, facial anthropometrics, donning techniques, and type and duration of activities performed most likely play a more important role in the performance of the respirator in the workplace.

Results of this study provide evidence to support the use of dynamic exercises in assessing respirator fit. The exercise protocols used in QNFT are designed to represent activities and movements experienced by the respirator wearer in the workplace. Certain exercises tend to place more stress on the facepiece seal than others, which can result in a lower overall fit factor. Some investigators have downplayed the importance of head and facial movements during fit testing. Oestenstad and Graffeo (1993) cited a 1979 study conducted by Revoir that found no significant differences between individual exercise penetrations measured during a six-exercise QNFT protocol and the overall average penetration values. The mean penetration during the talking exercise, however, was found to be significantly higher (lower fit factors) than that for the initial normal breathing exercise. Crutchfield and Van Ert (1993) compared exercise fit factors to the first normal breathing fit factor from select fit-test data sets reported in literature. A total of 98 individual exercise fit factor measurements obtained from six different fit-test data sets were analyzed. Of these, 26 cases were found to be significantly different from their corresponding initial normal breathing fit factor. Six of the 26 cases had mean exercise fit factors lower than the initial corresponding normal breathing exercise, five of which involved the talking exercise. Based on their analysis, the authors concluded that dynamic exercises add limited value to the fit test in determining the adequacy of the respirator fit.

In the present study, three of five dynamic exercises included in the CNC/ambient aerosol protocol (talking, grimacing, and bending over) yielded mean fit factors that were significantly lower than the initial normal breathing fit factor ($p < 0.0001$, 0.0001 , and 0.022 , respectively). In the corn oil aerosol protocol, only the mean fit factor for the grimace exercise was found to be significantly lower than the remaining exercises ($p < 0.0001$), including the initial normal breathing exercise.

Leakage as a result of dynamic exercises can have a dramatic impact on the determination of the overall fit factor value. Since the overall fit factor is calculated as a harmonic mean, its value can be no greater than the value of the lowest fit factor multiplied by the number of exercises performed. Therefore,

the overall fit factor tends to approach the value of the worst performing exercise of the fit test routine. This effect is evident when comparing the means of the individual exercise fit factors with the overall fit factor for the pooled data (Tables III and IV). For the CNC method, the mean overall fit factor (FF_1) was not found to be significantly different from the two lowest mean fit factors obtained for the talking and grimace exercises ($p < 0.05$). Likewise, in the photometer data the overall fit factor was not significantly different from the grimace exercise ($p < 0.05$). The data, therefore, suggests that dynamic exercises can play a major part in determining the acceptability of respirator fit.

Results of this study indicate that the fit factors determined by the CNC and photometer QNFT methods are not directly comparable as evidenced by the poor correlation found. As expected, the correlation coefficient was higher (0.50 versus 0.29) for the data set that included the grimace exercise since leakage during this activity contributed significantly to the overall fit factor result for both QNFT methods. Other investigators have reported much better agreement between the two methods. Rose *et al.* (1990) compared fit factors determined by an ambient aerosol/CNC method (Portacount[®], TSI Inc.) and an oil aerosol/photometer method (Dynatech-Frontier Corp). Twenty-four subjects wearing a half-mask respirator were sequentially fit tested with the two methods using the same exercise routine. A correlation coefficient of 0.86 was obtained ($R^2 = 74$) and the two methods were in very good agreement when the results were compared using critical pass/fail fit factor criteria of 100 and 1000. In a similar study conducted by daRosa *et al.* (1991), a correlation coefficient of 0.67 ($R^2 = 45$) was obtained from the regression analysis of exercise fit factor data collected on 10 subjects performing sequential fit tests with the two QNFT methods. The authors concluded that overall there was good agreement between the two methods with the CNC method showing a bias towards lower fit factors as observed in the present study.

The poor correlation found between the two QNFT methods in this study was most likely the result of the different exercise routines used and/or due to the effects of sequential testing and the nonreproducible nature of face seal leakage (daRosa *et al.*, 1983). Since the original intent of the study was not to compare the CNC and photometer QNFT methods, the order of the fit tests were not randomized. The special attention given to training the subjects may have contributed to higher fit factors than what would be expected under less ideal fit testing practices in the workplace. Biases introduced by such factors could very well account for the poor agreement found between the two QNFT methods.

CONCLUSIONS

The focus of this study was to evaluate the effect moisture has on respirator facepiece fit. Two different QNFT protocols, a CNC/ambient aerosol and a photometer/corn oil aerosol method, were used to measure fit factors. Overall fit factors obtained for subjects wearing half-mask respirators that had been wetted with water (to simulate sweat accumulation in the facepiece) were in general lower than those obtained with the respirator worn dry. Although no significant differences were found, all but one of the four respirator models tested (Mask D) showed reduced fit factors with the facepiece worn wet. The mean fit factors determined for both QNFT methods and wear conditions were notably lower for one of the respirator models (Mask B). All of the respirators, however, provided excellent fit and were resistant to facepiece slippage as demonstrated by the relatively high mean fit factors observed for the wet wear condition.

The results indicate that certain dynamic exercises have a significant effect on the integrity of the face seal. The grimace exercise was observed in both QNFT methods to cause the most degradation in fit. In the CNC fit tests, the talking and bending over exercises were also shown to significantly stress the face seal. Collectively, these findings emphasize the important role dynamic exercises serve in respirator fit testing.

In the workplace the amount of sweat accumulated inside the facepiece in most circumstances would be greater than that simulated in this study. Furthermore, under actual use conditions, head sweating could play a major role by causing the head harness to loosen and slip which in turn could alter the fit and degrade face seal performance. The intent of this study, however, was not to duplicate all workplace conditions of respirator wear but to evaluate a simple procedure designed to provide a more

rigorous and realistic assessment of respirator fit. The goal of fit testing is to assist in the selection of a respirator that provides the best protection to an individual wearer. The results of this study suggest that the current practice of fit testing half-mask respirators dry adequately accomplishes this goal, since the wetting procedure did not significantly affect individual mask fit. Although the study failed to demonstrate the practical value of wetting the facepiece prior to fit testing, the findings do support the use of dynamic exercises to provide a more discerning measure of fit.

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