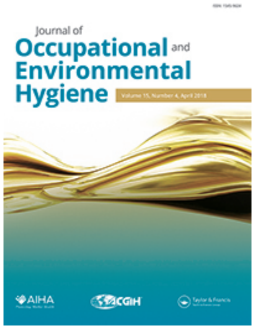

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Influence of facial hair length, coarseness, and areal density on seal leakage of a tight-fitting half-face respirator

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ABSTRACT

Background: OSHA regulations state that an employer shall not permit tight-fitting respirators to be worn by employees who have facial hair that comes between the skin and facepiece seal. Studies have shown that facial hair in the face seal zone can increase penetration and decrease the fit factor (FF), although the relationship between the amount and characteristics of facial hair and the increase in penetration is not well quantified. This article examines the influence of facial hair length, areal density, and coarseness on FF for one model of half-face elastomeric negative-pressure air purifying respirator.

Approach: Quantitative fit tests (QNFT) were performed on 19 subjects with beards initially 0.500-in long and subsequently trimmed to 0.250, 0.125, and 0.063 in, then after a razor shave. Three fit tests were performed at each of the 5 lengths, for 285 total tests. The average diameter and areal density of cheek and chin hair were measured. Penetration was modeled as a function of hair length category, beard areal density, and hair coarseness.

Results: FF decreased with beard length, especially beyond 0.125 in. However, passing FF scores were achieved on all tests by all subjects at the smooth shave and 0.063 in conditions, and 98% of tests were passed at 0.125 in; seven subjects passed all tests at all conditions. Chin and cheek areal densities were significantly different and were only weakly correlated. Beard hair diameters were normally distributed across subjects (mean 76 μm, standard deviation 7.4 μm). Beard length and areal density, but not coarseness, were statistically significant predictors of fit using an arcsine transformed penetration model. FF decreased with increasing beard length, especially beyond 0.125 in, although FF with a "stubble" beard did not differ significantly from a smooth shave. FF also decreased with increasing areal beard hair density.

Conclusion: Beard length and areal density negatively influence FF. However, tight-fitting half-face negative-pressure respirator fit tests can achieve adequate fit factor scores even with substantial facial hair in the face seal area.

KEYWORDS
Beard; elastomeric; facial hair; leakage; penetration; respirator

Introduction

An estimated 5 million workers wear a respirator at the workplace.[1] Most will be of the air purifying type, which may consist of an elastomeric half- or full-face mask with replaceable purifying cartridges or a disposable mask composed mostly of an air-purifying matrix ("filtering facepiece"). Non-powered air purifying respirator models that rely on lung power to pull air through the respirator are negative-pressure devices in that the interior of the mask is under negative pressure relative to the contaminated atmosphere during inhalation. Half-face negative-pressure air purifying respirators are the most commonly used type.

The OSHA respiratory protection standard in Title 29 of the Code of Federal Regulations (29 CFR) Part 1910.134 for General Industry and 1926.103 for Construction requires that negative-pressure respirator wearers be fit tested. Either qualitative or quantitative fit tests (QLFT and QNFT, respectively) may be employed. A challenge agent QNFT for an air-purifying respirator is used to measure leakage as the fractional penetration of the test agent past the facepiece seal (not through the purifying medium). While penetration is measured as the fraction of outside-the-mask concentration detected inside the mask, the result is usually expressed as its inverse, the "fit factor" (FF). FF is more readily interpreted

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than penetration, in that a higher FF indicates better protection (i.e., less penetration) and regulatory requirements are written in terms of the FF, rather than penetration. QLFT is restricted to respirators that must achieve a fit factor of 100 or less. A passing score for a QNFT is 100 or greater for half-face respirators and 500 or more for full-face respirators. Further, 29 CFR 1910.134(g)(1)(i)A states that the employer shall not permit tight-fitting respirators to be worn by employees who have facial hair that comes between the skin and facepiece seal. Unacceptable facial hair has been interpreted by OSHA to include beard lengths "more than a day's growth".[2] Studies have shown that facial hair in the face seal zone can increase penetration, though the relationship between the amount and characteristics of facial hair and the increase in penetration is not well quantified. This work was concerned specifically with examining facial hair characteristics and their influence on seal leakage for 1 model of half-face elastomeric negative-pressure air purifying respirator.

Review of literature

The effect of facial hair on face seal penetration has been a subject of research since at least 1964, when Hounam et al.[3] used salt aerosol to assess full-face respirator penetration with 7 subjects over a 2-week period of beard growth. They observed mean penetrations ranging from 0.001% (100,000 FF) on Day 0 (smooth shaven) to 10.0% (10 FF) on Day 9. A number of other studies followed over the next 22 years, as reviewed by Stobbe et al. in 1988.[4] Of the 13 studies they reviewed (including Hounam et al.[5]), 5 were for air-supplied respirators only and 1 was for an aviator's oxygen mask, and not of interest in the present discussion. Two studies were cross-sectional designs that compared fit factors for half- and full-face respirators for different groups of clean-shaven vs. bearded subjects. Skretvedt and Loschiavo found median fit factors of 2,950 vs. 12 for half-face and >10,000 vs. 30 for full-face,[5] while Fergin examined workplace protection factors of 3 models of disposable half-face respirators and found geometric mean protection factors were nearly identical for clean-shaven and bearded subjects.[6]

Of the remaining 5 studies reviewed by Stobbe et al., 4 included repeated measures designs in which subjects were fit tested clean shaven and after varying periods of beard growth. One of these employed a single subject and will not be discussed further; the 3 remaining repeated measures studies of negative pressure air-purifying respirators were by Hounam et al.[3] as previously discussed, Hyatt et al.,[7] and Jonsson.[8] Hyatt et al. measured mean penetrations for a selection of half-face and full-face respirators for 4 subjects over 8 days, but only reported the full-face values. Penetrations increased over the 8-day period from 0.05% (2,000 FF) to 0.5% (200 FF) for 1 full-face respirator and 0.09% (1,111 FF) to 0.9% (111 FF) for another, with over half of the change occurring from Day 0 to Day 1 for both models. Differences in full-face respirator models were apparent in that the maximum penetration of 0.2% (500 FF) allowed for full-face respirators under current OSHA standards was not exceeded until after Day 5 for 1 model but was exceeded beginning on Day 1 for the other model, for the same test subjects. Hyatt et al. concluded that persons with excessive facial hair, including facial stubble, "cannot expect to obtain as high a degree of respiratory performance as clean shaven individuals". Finally, Jonsson assessed 8 respirators that included both half-face and full-face models, with considerable variation in penetration results ranging from 0.01–0.1% (10,000–1,000 FF) at Day 0 to 10% (10 FF) at Day 4 for 31 subjects.

In addition to beard length, beard areal density (number of follicles per unit area) and texture have been suggested as possibly influencing face seal penetration. In their study, Hyatt et al.[7] categorized areal density for 12 subjects as sparse, average, and dense, and categorized texture as fine, average, coarse, and wiry. Replicate (2 or 3) single-point-in-time penetration measures on these subjects showed a very slight and weak negative correlation between beard length and mean penetration ($r = -0.01$ for half-face and $r = -0.26$ for full-face), with 1.2 to 165-fold within-subject differences in maximum and minimum scores for replicate trials. Interestingly, among subjects with facial hair >0.5 in long (1.27 cm), 6 out of 12 subjects had at least 1 penetration of <5% (20 FF) with a half-face respirator and 4 out of 12 subjects had at least 1 penetration <1% (100 FF) with a full-face respirator (3 subjects were in both categories). Hyatt et al. concluded that hair texture and density were some of the many determinants of face seal penetration, though they did not describe the effects quantitatively.

Balkhyour and Crutchfield[9] measured half-face respirator leakage for 10 subjects over a 14-day beard growth period using a controlled negative pressure QNFT. Half of the subjects were Anglo-Saxon and half were Middle Eastern, and the aim of the study was to assess the effect of beard characteristics on respirator leakage for the 2 ethnic groups. Replicate (5) fit tests were conducted on each subject each day. Day 4 signified the largest change in respirator leak rate. After the 12-day period, a beard hair sample was collected for hair length and diameter measurement. Neither beard length nor diameter were independently correlated to leakage rate but their interaction diameter/length (inverse of aspect ratio) was positively correlated with leakage rate ($r = 0.64$, $p = 0.048$). This is a somewhat difficult measure to interpret, but indicates that shorter, thicker hairs are correlated with greater respirator leakage.

Research studies on facial hair and face seal leakage of negative-pressure air purifying respirators were mostly conducted more than 20 years ago, with results demonstrating that facial hair can negatively impact the face seal to varying degrees. While the studies did not model the impact of facial hair on leakage, they did identify beard density, texture, and length as potential influences, with considerable variation within and between individual subjects and also across respirator models. Interestingly, multiple studies showed that satisfactory FF could be achieved for some subjects with various degrees of facial hair growth but was largely ignored or under-explored in those studies.

The purpose of this pilot study was to quantitatively examine the influence of facial hair length, density, and coarseness on face seal leakage for a single model of tight-fitting, elastomeric half mask respirator. Repeated measures of FF were conducted on 20 volunteers at 5 levels of beard length from ½ in to smooth shaven.

Methods

The study protocol was approved by the University of Oklahoma Health Science Center (OUHSC) Institutional Review Board (IRB). A single-model elastomeric half-face air purifying respirator (3M Model 7586, small, medium, and large sizes, 3M Inc., St. Paul, MN) with P100 particulate filters (3M Model 2091) used in all trials. A QNFT sampling port was added to one of the filters to sample aerosol from between the nose and upper lip (Figure 1). The QNFT procedure utilized the condensation nuclei counter technique (Portacount Model 7586, TSI Inc., Shoreview, MN) as outlined in Appendix A of the OSHA respiratory protection standard 29 CFR 1910.134. The usual QNFT procedure specified in Appendix A of 29 CFR 1910.134 was slightly modified to shorten the time required, and was the same as that used by McGee et al. in a previous study with SCBAs.[10] Specifically, the grimace and bending over exercises were eliminated. Prior to beginning the testing the subject was oriented to the respirator, including how to don and doff the device, check for leaks, and assess preliminary fit.

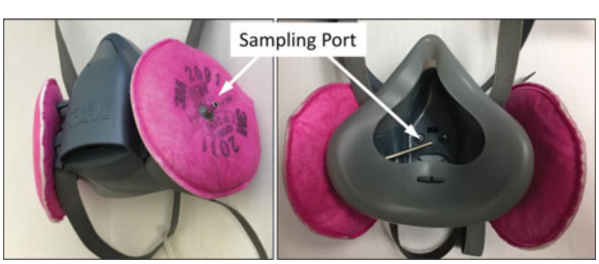

Figure 1. 3M 3500 series respirator probed for fit test with stainless steel sampling port extending to center of mask.

Twenty male subjects aged approximately 18–65 years with facial hair growth of at least 0.5 in in the face seal area were recruited. Each subject was asked to trim all of their facial hair to 0.5 in using an electric beard trimmer. Various guards for the trimmer head regulated beard length at 0.500, 0.250, and 0.125 in. Removing the guard resulted in a "no guard" or "stubble" length of approximately 0.063 in. Shaving with a razor resulted in the "smooth skin" condition. Each subject was sequentially fit tested 3 times at each beard length from 0.063–0.500 in, and finally after shaving with the razor, for a total of 15 tests per subject over 5 levels of beard length. The study was thus a repeated measures design blocked on subject but not randomized within block (which would have required regrowing the beard between some trials). The subjects had varying degrees of respirator experience, and several indicated they had never worn a respirator before. Each subject received respirator use training, including dummy fit test trials, before data collection began in order to minimize any experience effect on FF scores.

Hair growth areal density was determined when the subject was at the "stubble" hair length. A 1 cm × 1 cm square template was placed against the subject's face and a close-up photograph taken that allowed for counting the number of hairs within the square. Areal density was measured for two 1-cm^2 areas within the face seal zone at each of two locations: underneath the chin and on either cheek roughly even with the corners of the mouth. The average of the four measures was taken to represent the facial hair areal density for the subject.

Hair clippings were collected while the subject was trimming to the stubble length. Samples were mounted on light microscope slides for diameter measurement using image analysis software. Ten hairs for each subject were measured 3 times for a total of 30 diameter estimates per subject. The average was taken to represent facial hair coarseness for the subject.

Each test was conducted in a controlled office environment using a NaCl challenge aerosol with concentration $>10,000$ particles/cm^3 and maintained within 10% across fit tests. The aerosol was supplied using a TSI Model 8026 aerosol generator. The FF scores for the 6 exercises in each test were harmonically averaged to provide an overall FF for the test. Three replicate tests were conducted at each beard length for each subject, with respirator doffing, loosening of straps, and re-donning between tests.

Results

Results for subject 2 were excluded from the analysis when it was discovered that there had been an air leak at the mask sampling port during those trials. A total of 285 fit

Table 1. Median FF scores by subject for each beard length.

Subject	Median (GSD) FF at beard length				
	Smooth	0.063″	0.125″	0.250″	0.500″
1	8570 (1.17)	7830 (1.34)	4220 (1.37)	5285 (2.15)	631 (1.51)
3	8080 (1.15)	6700 (1.27)	3160 (3.21)	257 (1.38)	72 (2.61)
4	429 (2.51)	1177 (3.19)	503 (3.13)	38 (1.18)	22 (1.22)
5	26086 (1.73)	12163 (1.53)	2348 (2.51)	75 (2.44)	43 (1.13)
6	575 (1.21)	431 (1.16)	378 (1.21)	77 (4.68)	47 (1.68)
7	15143 (1.18)	17801 (1.03)	8563 (1.31)	541 (1.14)	173 (1.83)
8	16424 (1.36)	15728 (1.42)	9520 (1.22)	775 (1.56)	68 (1.45)
9	4537 (1.37)	7642 (1.53)	8177 (1.51)	560 (3.10)	102 (1.54)
10	8077 (1.20)	1786 (6.61)	579 (2.05)	198 (1.16)	155 (1.31)
11	9154 (2.80)	9062 (1.29)	9128 (1.28)	2764 (1.31)	740 (2.04)
12	7019 (1.68)	6537 (1.32)	2776 (2.51)	240 (1.45)	37 (1.58)
13	22319 (1.21)	17782 (1.34)	10252 (1.47)	418 (1.84)	147 (1.24)
14	22533 (1.23)	21245 (1.13)	503 (1.43)	72 (1.42)	67 (1.28)
15	15576 (1.07)	9012 (1.70)	10768 (1.06)	631 (1.29)	115 (1.19)
16	7351 (1.65)	6194 (2.14)	9174 (1.83)	331 (2.69)	705 (2.84)
17	15464 (15.6)	1085 (4.62)	1089 (1.53)	169 (1.27)	75 (1.60)
18	9250 (1.07)	12462 (1.12)	5482 (1.62)	302 (3.10)	106 (1.94)
19	10896 (4.23)	13578 (1.69)	10152 (1.08)	863 (1.41)	130 (2.29)
20	11748 (1.09)	10310 (1.07)	9673 (1.08)	4333 (1.83)	196 (1.25)
Minimum	**429**	**431**	**378**	**38**	**22**
Maximum	**26086**	**21245**	**10768**	**5285**	**740**

test trials were available for the analysis from the remaining subjects: 19 subjects, 5 conditions, and 3 replicates.

There was no apparent trend of improving FF scores from replicate 1–3 at each facial hair length. For a number of subjects, there was considerable variation in the range of replicate FF scores for a particular beard length due to 1 measure being much different from (usually lower than) the other 2. Therefore, the median FF score for each subject was used rather than the mean. This resulted in a total of 95 FF measures for the 19 subjects at 5 conditions. Median FF scores at each beard length for each of the remaining 19 subjects were as shown in Table 1. There was considerable variability in median FF across subjects, as shown by the 1 to 2 orders of magnitude difference between minimum and maximum values at each beard length in Table 1. Geometric standard deviations (GSD) of the replicate FF scores, another indicator of variability, are shown in parentheses. As an overall pattern, median FF for each subject declined with increasing beard length, especially for lengths greater than 0.125 in.

In order to compare the change in FF across subjects, a "relative fit", F_R, was calculated for each subject and beard length using the subject's median smooth skin FF as the reference. A subject's F_R was calculated by dividing their median FF score at each length by the smooth skin median FF. F_R decreased with increasing beard length, with average values over all subjects of $F_R = 0.97$ for 0.063 in, $F_R = 0.63$ for 0.125 in, $F_R = 0.11$ for 0.250 in, and $F_R = 0.03$ for 0.500 in.

FF score for a tight fitting half-mask respirator QNFT must be over 100 to be considered passing. Scores above 100 were achieved in approximately 98% of the 57 fit tests at 0.125 in beard length and in 100% of tests at shorter lengths. At the 2 greatest lengths, the proportion of FF scores >100 dropped off substantially, to 81% at 0.250 in and 58% at 0.500 in.

Subjects often had a mix of scores above and below 100 FF at the longer beard hair lengths. The number of fit tests <100 FF at each beard condition is shown by subject in Figure 2. Of 285 total fit tests, only 36 tests (12.6%) were below 100 FF. Subjects 4 and 14 had a particularly high number of fit tests below 100 FF, accounting for 13 of the 36. Notably, 7 out of 19 (37%) subjects did not have any fit tests below 100 FF at any of the beard lengths.

Cheek and chin areal beard density, as hairs/cm^2, for each subject were measured as described above and the average number of hairs/cm^2 in the cheek and chin areas are shown in Figure 3. A paired sample t-test indicated cheek and chin areal densities to be significantly different ($p = 0.0015$), with the ratio of chin to cheek density being >1 for 16 of the 19 subjects (median 1.38, range 0.73–4.92,

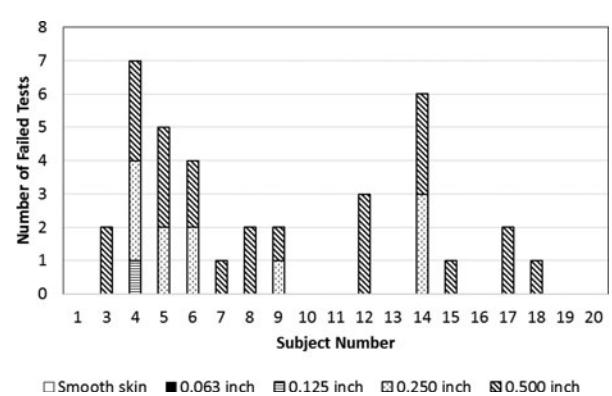

Figure 2. Failed fit tests for each subject stratified by facial hair length.

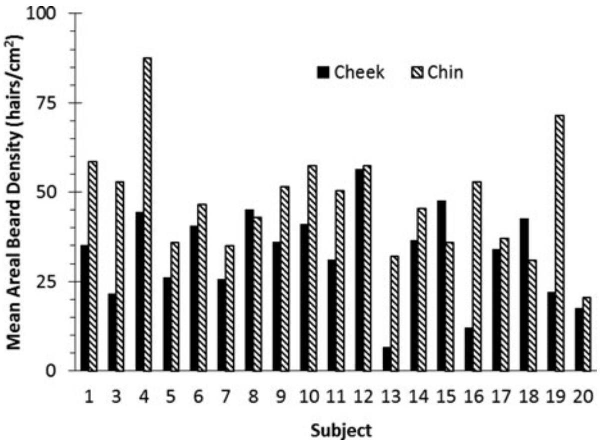

Figure 3. Average hair density for each subject at cheek and chin.

interquartile range 1.09–1.97). However, the correlation between average cheek and chin areal densities was weak (Pearson Correlation Coefficient, $r = 0.264$); therefore, cheek and chin areal densities were averaged for each subject. For the entire test group, the mean and median were quite close (40.1 vs. 41.0 hairs/cm^2, respectively) with a range of 19.0–66.0 hairs/cm^2 across subjects.

Average hair diameter (coarseness), as the average of 30 diameter measurements on each subject, are shown in Figure 4. Values ranged from 45.2 µm (subject 4) to 88.1 µm (subject 6). Average diameters for 18 of the 19 subjects were normally distributed over the range of 62.4–88.1 µm. Excluding subject 4 as an outlier to the normal distribution, the distribution mean and standard deviation were 76.0 µm and 7.4 µm. Facial hair coarseness and areal density were linearly associated but only weakly negatively correlated ($r = -0.223$).

The FF in a challenge aerosol QNFT is calculated as the ratio of the particle count concentration outside the facepiece to that inside the facepiece. The concentration inside the facepiece represents penetration, so that the fractional penetration of challenge aerosol is the inverse of

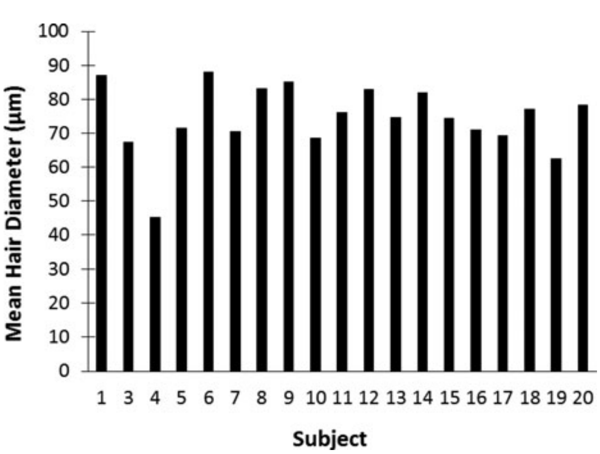

Figure 4. Mean hair diameter for each subject.

the FF, i.e., $P = 1/FF$. Concentration measured within the mask was not corrected for respiratory tract deposition and therefore underestimates penetration, as does most compliance fit testing using the ambient aerosol technique. To determine the relative influence of beard hair length, areal density, and coarseness on penetration, the data were analyzed in SAS 9.3 (SAS Institute, Cary, NC) using a mixed modeling approach. Beard length was taken as a categorical fixed effect, and areal density and coarseness as continuous random effects. Penetration into the breathing zone, $P = 1/FF$, was used as the outcome measure rather than fit factor. The experiment was a non-randomized repeated measures design blocked on subject, with three replicate measures of penetration taken at each beard length from 0.500 in to smooth skin, and the median of the three measures was taken to represent the penetration at that condition. These designs often have correlated errors, so an arcsine transformation of the penetrations was performed: $[P' = \frac{2}{\pi}\sin^{-1}[\sqrt{P}]]$. A number of regressions were conducted, starting with the three main effects of length (L), density (D), and coarseness (C) and their two-way interactions ($L \times D$, $L \times C$, and $D \times C$). After eliminating all variables with parameter estimate p-values > 0.10 via sequential regressions on reduced models, the only variables remaining were Length ($p < 0.0001$) and Density ($p = 0.0171$). The final regression model was a mixed model of arcsine-transformed median penetration measures, with an unstructured correlations covariance structure (type UNR in SAS):

$$P' = \mu + \alpha_i + \beta(density)$$

or, reversing the arcsine transformation,

$$P = \left[\sin\left(\frac{\pi}{2}[\mu + \alpha_i + \beta(density)]\right)\right]^2,$$

where P is the penetration fraction, μ is the baseline for the smooth skin beard condition, α_i are the $i = 1$–4 fixed effects corresponding to the other beard lengths 0.063, 0.125, 0.25, and 0.5 in, respectively, and β is the coefficient for the continuous variable of median areal density. The final model with coefficient estimates was:

$$P = \left[\sin\left(\frac{\pi}{2}[-0.00660 + \alpha_i + 0.000429(density)]\right)\right]^2$$

with $\alpha = 0.000631$, 0.004387, 0.003624, and 0.05762 for beard lengths 0.063, 0.125, 0.250, and 0.500 in, respectively. All coefficient p-values were <0.05 except μ for the smooth-skin condition and α_1 for the 0.063 in (stubble) length, showing no significant difference in the 0.063 in (stubble) and smooth skin lengths.

Discussion

Penetration increased, i.e., FF decreased, with beard length, especially at the longer beard lengths. Beard hair coarseness had no significant effect on penetration, but beard areal density was positively correlated with increased penetration. Nevertheless, FF scores >100 were achieved in 98–100% of tests at short beard lengths (≤0.125 in) and a number of subjects remained >100 FF throughout all tests, even at the 0.500 in length. An even larger proportion of fit tests >100 FF might have been observed if a wider selection of respirator models had been used. Clearly, for this study cohort, respirator model, and truncated QNFT method used, the simple presence of facial hair in the face seal area did not preclude achieving a FF score >100, although it did lower the FF score. The differences between this study and previous studies may be due to advances in the quality of fit of elastomeric respirators over the past 20 years, which further supports the need to re-evaluate this topic.

Perhaps the results of most practical importance were that (a) there was no significant difference in penetration values (fit factors) between the freshly shaved "smooth-skin" condition and the 0.063 in "stubble" condition, and (b) essentially all of the fit tests were >100 FF at beard lengths up to 0.125 in (a length that might be typical of beard growths of 4 to 5 days for most men). OSHA's current respiratory protection inspection guidelines define unacceptable facial hair to be "more than a day's growth".[2] Individuals with heavy beard growth develop substantial stubble over an extended shift 10–12 hr, and more-so during back-to-back 8-hr shifts. Furthermore, respirator wearers often toe the line of the OSHA inspection guideline and start a shift with stubble, perhaps to avoid shaving immediately before a shift to minimize skin irritation from respirator use. Thus, a heavy stubble growth of 0.063 in or more by shift end should perhaps be expected for many wearers. One other area that warrants further investigation is military personnel that are given a waiver from daily shaving due to skin irritation or for special assignment such as Special Forces units seeking cultural assimilation. These troops may encounter situations in which use of a respirator is necessary, but little is known about the risk of exposure with facial hair. A quantitative basis for assessing respirator fit and therefore exposure risk to these troops would be beneficial to the military as well as the soldier.

While a larger study with more subjects and a variety of respirator models is needed, the results of this study suggest that the policy of "no facial hair" might be reasonably relaxed to allow acceptable facial hair defined as "less than 1/8 in, provided a quantitative fit test has been passed".

As a pilot study, this work necessarily had some limitations. The study produced respirator fit test data on only 19 subjects from a convenience sample having an age range representative of the working adult population but little ethnic diversity. No effort was made to correlate FF with facial structure or ethnicity, both of which have been shown to influence FF. Further, only a single elastomeric half-face respirator model was used, and facepiece configuration is also a known influence on respirator fit. Our truncated fit test omitted the grimace and bend over exercises which are required exercises in the OSHA ambient aerosol QNFT due to the potential to dislodge the respirator face seal, therefore these results may not extend to a compliance fit testing. Finally, the particle-based QNFT used, might underestimate penetration (leakage) due to 2 factors: (1) scrubbing of the penetrated particles by the respiratory tract of the test subject and (2) beard hair acting as a physical filtering agent.

Conclusions

Beard length and areal density negatively influence FF. However, half-face respirator fit tests can achieve fit factor scores >100 even with some facial hair in the face seal area as was demonstrated in this study and many in the extant literature. Therefore, a relaxation of the current policy of "no facial hair" to a definition of "acceptable facial hair" might be in order, if supported by additional research.

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