

Three-Dimensional Facial Parameters and Principal Component Scores: Association with Respirator Fit

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ABSTRACT

Human facial dimensions play a significant role in the determination of respirator fit. Fit test “panels” intended to represent a range of wearer facial characteristics have been defined on the basis of specific facial dimensions such as face width and face length. The goal of this investigation was to identify facially-related variables that are worthy of further investigation. Specifically this investigation explored the extent to which facial parameters (such as angles and areas) or principal component analysis (PCA) scores derived from facial measurements of test subjects might be associated with the fit of four half-mask respirators. Thirty subjects were each evaluated for several facial parameters and PCA scores for facial size and facial shape. The facial parameter data were obtained by means of three-dimensional (3D) laser scanning technology and commercial computer software developed for the evaluation of the 3D scanned images. The same thirty subjects were each fit tested using the ambient aerosol quantitative technique while he or she wore each of four different models of half-mask respirators in small, medium, and large sizes. The fit test results and the derived facial parameters and PCA scores were analyzed by forward selection stepwise linear regression, with the derived facial parameters and PCA scores used as the independent variables. The resulting regression models had R^2 values ranging between 0.08 and 0.60 for individual models/sizes of respirators. Nose area was a significant contributor for 10 of the 12 regressions. The next closest variable (alare-sellion angle) contributed to 5 of the 12 regressions. PCA1 was a significant contributor for 8 of the 12 respirator model/size regressions, while PCA2 was a significant contributor for only 4 of the 12 regressions. The authors concluded that a non-linear 3-D parameter derived in this study (nose area) was found to be frequently correlated to respirator fit and the nose area may be more significant than other 3D parameters. The PCA score associated with overall face size (PCA1) was more important than the PCA score associated with facial shape (PCA2). The findings are significant in that they can potentially influence the composition of future respirator fit test panels.

Keywords: respirator fit, facial dimensions, three-dimensional scan, principal component analysis, PCA, fit test panels

INTRODUCTION

Human facial dimensions play a significant role in the determination of respirator fit. The testing and certification program for industrial respirators, operated by the National Institute for Occupational Safety and Health (NIOSH), relies in part on "fit test panels" that consist of human subjects with varying facial features who test respirators for fit. Respirator manufacturers also use fit test panels in the design, development, and testing of prototype devices. The fit of respirators on this subject panel is assumed to be representative of the fit of respirators on the respirator user population in the US. Failure to select the optimal facial dimensions to define the panel may result in certification or development of respirators that do not fit the user population as well as intended. Thus, facial dimensions and respirator fit have been important research topics in the past four decades.

NIOSH contracted with Los Alamos National Laboratories (LANL) in the early 1970's to define the first fit test panel. McConville et al. (1972) reported that studies of military populations, including a 1967 Air Force study, provided the most useful data relevant to respirator fit, but noted that the military population studies are not necessarily representative of the civilian workforce. LANL chose to define the panel in terms of two facial dimensions: face length and lip length (Hack, et al., 1973). Those specifications, however, when proposed by NIOSH for certification regulations, drew some criticism during the public comment period (NIOSH, 1995).

Oestenstad et al. (1990) studied the location and shape of face seal leak sites for a single brand of half-mask respirator worn by 73 subjects, and compared those observations to facial measurements, subject gender, and quantitative fit factor. They determined that 89% of the leak sites were near the nose or chin; 79% of the leaks included the nose as at least a contributing or sole leak site; and 73% of the leaks were judged to be more diffuse than point-like in shape. Males were more likely to have the diffusely shaped leaks. Fit factors for chin-related leaks were significantly lower than other categories, indicating that chin leaks are generally larger in terms of amount of leakage. Significant correlations were found for three facial dimensions (menton-subnasale, biocular breadth, and nasal root breadth), none of which are used to define the traditional fit test panels described by Hack et al. Oestenstad et al. found evidence of "streamlining" of leak sites toward the nose and mouth area, and noted that Myers et al. (1986) had found that streamlining could lead to a bias in fit test measurements. Oestenstad et al. noted the importance of limiting the number of investigators making facial measurements, and the variability of the investigator's measurements.

Gross and Horstman (1990) compared facial measurements for 121 (60 female and 61 male) civilian workers to quantitative fit test data for three different brands of respirators. They found no significant correlations between the facial measurements and respirator fit; however, when the fit test data were dichotomized to passing or failing (greater or less than 10), the investigators found the men who failed the fit test generally had larger facial dimensions than those who passed the fit test. Women who failed, on the other hand, generally had smaller noses and face lengths and longer lips than those who passed the fit test.

Oestenstad and Perkins (1992) reported on another set of comparisons of facial measurements to quantitative fit test data. They found the highest correlations for menton-subnasale length, biocular breadth, nasal root breadth, and nose width. However, even those correlation coefficients were in the range of 0.26-0.37. This finding was similar to that described for Liau et al. (1982). In an attempt to determine the predictive potential of facial measurements, Oestenstad and Perkins conducted a stepwise multiple linear regression for twelve facial measurements as the independent variables and the natural log of fit factor as the dependent variable. They found that the facial measurements were predictive when the model was gender-specific (R^2 values of at least 0.85). For all subjects combined, however, the R^2 was reduced to 0.28. The menton-subnasale measurement was found to be the most consistent predictor of respirator fit.

In a more recent report attempting to relate facial dimensions to respirator fit however, Oestenstad concluded that facial dimensions were poor predictors of fit, as judged by both linear and logistic regression methods (1994). A number of findings from this work were contrary to previous work

(as described above) led by Oestenstad. Gender was a significant influence on the correlation: seven facial measurements were correlated to fit for females, whereas only one measurement was correlated for males. Neither of the dimensions used by Hack et al. (1973) to define the respirator fit test panel was found by Oestenstad to predict respirator fit. Oestenstad's abstract ends as follows: "Facial dimensions were found to be poor predictors of respirator fit, and that (*sic*) dimensions other than those currently used may be more appropriate to define test panels whose fit is intended to be representative of worker populations."

Brazile et al. (1998) reported on 14 facial dimensions and respirator fit among 3 ethnic groups: white, African-American, and Mexican-American. Significant differences were found in the facial measurements between the ethnic groups. The only facial dimension found to be somewhat correlated with fit was nose protrusion (R^2 value = 0.1596, p = 0.0296). The authors carried out a backward-elimination stepwise regression, and found that nose width and nose protrusion had significance, but they could only account for 4.45% of the variation found in the fit test data. The authors concluded that racially influenced nose width and nose protrusion are not good predictors of respirator fit.

Kim et al. (2003) investigated the association between the fit of quarter-mask respirators on Korean faces and facial dimensions. After conducting regression analyses on the fit and facial dimension, they concluded, "The regression analysis found no common prognostic variables with the three respirator brands studied." Kim et al. (2004) have proposed a Korean test panel for half-mask respirators, using three-dimensional (3D) shape analysis. Their system uses face length (menton-sellion) and four facial shapes (flat round elliptic; bendy long elliptic; round elliptic; and flat chin and long elliptic) to define the panel constituents. The authors indicate that their panel would only be applicable to Korean faces.

Zhuang et al (2005) also studied the effect of subject gender and twelve facial dimensions on respirator fit. They found no significant effect of gender for sixteen of eighteen respirator models studied. Subsets of one to six facial dimensions were significantly correlated with respirator fit for sixteen of the thirty-three respirator model/size combinations studied. Bigonial breadth, face width, face length, and nose protrusion were the dimensions most frequently included in the subsets with significant correlation. Zhuang et al. (2005) concluded that based on the findings from this and previous studies, face length and face width are recommended measurements that should be used for defining the panel for half-facepiece respirators.

Because of the concern for the applicability of military data to civilian workers, NIOSH conducted a recent anthropometric survey of U.S. workers (Zhuang and Bradtmiller, 2005). Based on the anthropometric data collected, NIOSH researchers then developed two new panels for half- and full-face respirator fit testing (Zhuang et al., 2007). One of the new panels (NIOSH bivariate panel) included the same linear measurements used for the LANL panel. The other recommended panel was based on establishing the appropriate facial features by using principal component analysis (PCA) to identify the combination of 10 facial dimensions that best represented the variation among the faces in the data set. Both of those new panels, however, still rely on straight-line distances between two points on the head.

Since the two NIOSH panels were published, two additional studies have looked at the correlation between facial dimensions and respirator fit. Oestenstad et al. (2007) reported the association of respirator fit with twelve linear facial dimensions. While none of the twelve dimensions yielded significant associations for all six respirator models included in that study, two dimensions (bigonial breadth and face length) were associated with fit for five of the six models. Those two dimensions were also identified by Hack et al. (1973) as appropriate for use in evaluating the fit of full facepiece respirators. Oestenstad and Bartolucci (2010) conducted another study to determine if gender, respirator brand, repeated fit tests, and test exercises affected the location and shape of face seal leak sites. They found that none of these factors had a significant effect on the location and shape of leaks in categorical analysis. However, significant effects for facial dimensions were found in the linear analysis. Leak site distribution differences between this and previous work by Oestenstad may have been affected by differences in facial dimensions. These findings indicate that, in addition to size, the shape of an individual's face may be an important determinant of leak sites on a half-mask respirator.

NIOSH recognized the importance of validating the quality, relevance and potential impact of the anthropometric survey results and all relevant recommendations prior to incorporating the recommended panel updates into the respirator certification program. Because of the potential implications for the respirator users, manufacturers, and respirator market, NIOSH/NPPTL commissioned the Institute of Medicine (IOM) through the National Academies to review the NIOSH anthropometric survey (Zhuang and Bradtmiller, 2005; Zhuang, et al, 2007).

The IOM completed the review study and issued a report to NPPTL titled "Assessment of the NIOSH Head-and-Face Anthropometric Survey of U.S. Respirator Users" (Bailar et al., 2007). In the IOM report, the committee made the following conclusions and recommendations:

"Conclusion 2-2: Three-dimensional scan data may offer advantages over traditional, manually collected anthropometric data; however, there is no evidence base of best practice against which 3-D scans may be compared.

Recommendation 2-2: Consider Utilizing 3-D Scan Data. NIOSH should consider collecting and utilizing data from 3-D scans, alone or in combination with traditional manually collected data, to ensure the most robust set of data are used to develop future anthropometric face panels.

Recommendation 4-5: Determine Key Features Related to Fit Using Quantitative Fit Measures. NIOSH should perform research to determine which facial features have the greatest impact on the respiratory protection of face masks in the workplace, using quantitative measures. These research findings should be utilized in the design of future anthropometric face panel studies."

Advances in 3D scanning technology and the development of more sophisticated metrics for describing facial contours (e.g., in the nose region) available today suggest that new studies could yield improved insight. Therefore, the objective of the present study was to investigate the extent to which facial parameters (angles, surface areas, and principal component analysis scores) are associated with the fit of four selected half-mask respirators. The study objective was achieved through use of the 3D scan data suggested by the IOM report. The independent variables were the 3D facial parameters, PCA scores, and traditional measurements for each subject, with the dependent variable being mean log-transformed respirator fit for each subject when wearing each of the four selected respirators.

METHODS

Investigators

The study was conducted in NIOSH NPPTL laboratories near Pittsburgh, Pennsylvania. The linear facial measurement data were collected by investigators trained in anthropometric measurements by Anthrotech, Inc., Yellow Springs, Ohio. The investigator responsible for collecting the 3D scan data was trained by the manufacturer of the scanning equipment, Cyberware, Inc., Monterey, California. The investigator responsible for collecting respirator fit test data was trained by the staff of the NIOSH NPPTL.

Subjects

Thirty subjects (17 female, 13 male) with face sizes distributed throughout the NIOSH bivariate panel were selected based on measurements made with a manual sliding caliper, which is a standard instrument for anthropometric measurements. The subjects were recruited from the vicinity of Pittsburgh, Pennsylvania. Each subject signed a consent form as required by the NIOSH Human Subjects Review Board. The bivariate panel definition and the placement of the 30 subjects within the panel definition are provided in Figure 1. Although the recruiters did identify subjects with a wide range of face lengths and

widths, no subjects were found for cell number 5. This could affect the findings, since cell number 5 represents those subjects with the shortest, widest faces (Figure 1).

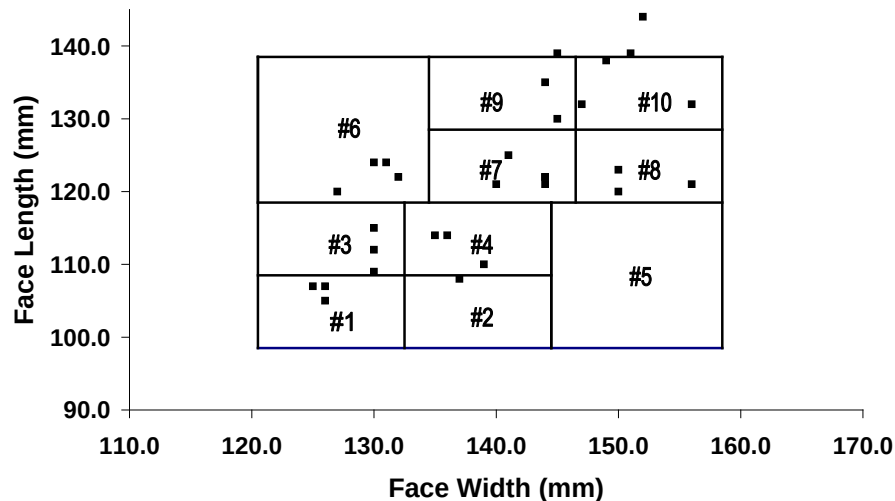


Figure 1. Placement of thirty subjects within the NIOSH bivariate fit test panel.

Facial Measurement

The facial dimensions used for subject selection were face length and face width, as measured with a sliding caliper and a spreading caliper. Face length and face width are facial dimensions used to define the NIOSH bivariate panel (Zhuang, et al., 2007). Face length is defined as the distance in the mid-sagittal plane between the menton landmark at the bottom of the chin and the sellion landmark at the deepest point of the nasal root depression at the top of the nose, as measured with a sliding caliper (see Figure 2). The subject sits looking straight ahead and with the teeth together (lightly occluded). Face width is defined as the maximum horizontal breadth of the face as measured with a spreading caliper between the zygomatic arches (see Figure 2). The points of maximum distance were located first by finger palpation of the facial tissue on each side of the face. Then the spreading caliper was placed on each of the points, and the distance was read to the nearest millimeter. Techniques for measuring the other facial dimensions using traditional tools have been described elsewhere (Zhuang et al. 2007).



Figure 2. Locations for measurement of face length (also called menton-sellion) (left) and face width (right).

Table I. Three-Dimensional Parameter Definitions and Rationale for Influence on Respirator Fit

Parameter	Definition	Rationale for influence on respirator fit
Nose area	The surface area bounded by the following points: sellion, left endocanthus, left alare, subnasale, right alare, right endocanthus, sellion (see Figure 3). This measurement was carried out using point selection and surface area function of the Cyberware software.	Nose area, as an indicator of overall nose "size", could prevent or promote sealing along much of the facepiece perimeter.
Nasal root-sellion angle	The angle formed by the left and right nasal root points, with the sellion point at the apex (see Figure 4). This and other angle measurements were carried out using the point selection and angle calculation software developed by Cyberware.	This angle near the bridge of the nose could affect the ability of the respirator to conform to a complex curvature.
Sellion-pronasale-menton angle	The angle formed by the sellion and menton points, with the pronasale point at the apex (see Figure 4).	This angle indicates an overall protrusion or depression of the nose with respect to the sellion and menton, which could affect the seal along much of the facepiece perimeter.
Gonion-pronasale angle	The angle formed by the left and right gonion points, with the pronasale point at the apex (see Figure 4).	This angle indicates an overall broadness or narrowness with respect to the position of the lower nose and could affect the seal along the sides of the facepiece perimeter.
Alare-sellion angle	The angle formed by the left and right alare points, with the sellion point at the apex (see Figure 4).	This angle indicates a combination of nose breadth and length, and could affect the facepiece seal in the vicinity of the nose.
Gonion-sellion angle	The angle formed by the left and right gonion points, with the sellion point at the apex (see Figure 4).	This angle indicates an overall face broadness or narrowness with respect to the position of the upper nose and could affect the seal along the sides of the facepiece perimeter as well as the seal near the bridge of the nose.

In addition to the manual measurements, 3D facial parameter data were obtained by means of a head- and-face laser scanner and software package (Cyberware, Inc., Monterey, CA). The scanning process requires that the subject remain seated and still on a platform for approximately 40 seconds while a scanning camera orbits about the subject's head. During the orbit, the camera maps the subject's facial features with a low-level laser with power similar to that of a supermarket checkout scanner. As the laser beam passes across the facial features, the scanner software creates a 3D digital map of the facial features. The facial maps may then be used to quantify facial features including straight-line distances, surface areas, angles, radii of curvature, and others.

For this study, six 3D parameters were investigated, including one facial surface area and five angles between defined points on the subjects' faces (see Table I and Figures 3 and 4). These 3D parameters were chosen because they are relevant (as indicated in Table I) to respirator wearers' facial regions that are either contained within a respirator facepiece or are partly transected by the facepiece seal. These 3D parameters have not been previously used for this purpose.

This study also used principal component analysis (PCA) scores based on linear facial dimensions as facial parameters. The first principal component (PCA 1) represents the overall size of the

face and the second principal component (PCA2) represents the width of the face. PCA1 and PCA2 scores were determined for each subject using 10 traditional measurements and two formulas developed by Zhuang et al (2007). The formulae for the PCA scores are as follows:

PCA1 =

$$0.343264(\text{minimum frontal breadth}) + 0.426498(\text{face width}) + \\ 0.372717(\text{bigonial breadth}) + 0.329648(\text{menton sellion length}) + \\ 0.363474(\text{interpupillary distance}) + 0.372241(\text{head breadth}) + \\ 0.113578(\text{nose protrusion}) + 0.301125(\text{nose breadth}) + \\ 0.202311(\text{nasal root breadth}) + 0.193650(\text{subnasale-sellion length})$$

PCA2 =

$$-0.152951(\text{minimum frontal breadth}) - 0.039087(\text{face width}) - \\ 0.093279(\text{bigonial breadth}) + 0.359799(\text{menton sellion length}) - \\ 0.173099(\text{interpupillary distance}) + 0.013306(\text{head breadth}) + \\ 0.551842(\text{nose protrusion}) - 0.210833(\text{nose breadth}) - \\ 0.341235(\text{nasal root breadth}) + 0.584261(\text{subnasale-sellion length})$$

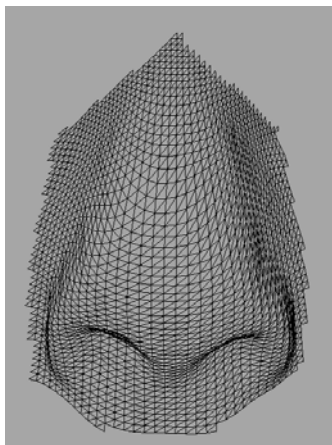


Figure 3. A typical nose area.

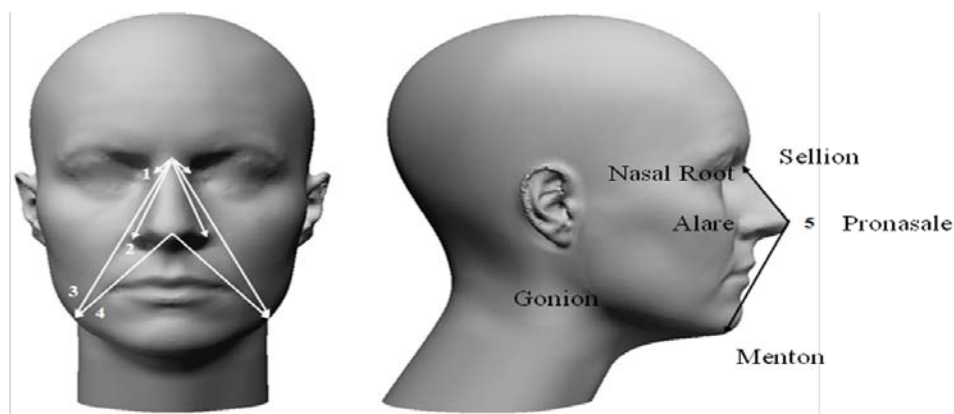


Figure 4: Five angles used as 3-D facial parameters include: 1) nasal root-sellion-nasal root 2) alare-sellion-alar 3) gonion-sellion-gonion 4) gonion-pronasale-gonion 5) sellion-pronasale-menton.

Respirators

Four models of half-mask respirators with P100 filtration in small, medium, and large sizes were selected for this study in order to measure face seal leakage only. The respirators included three elastomeric and one filtering facepiece design. The elastomeric respirators were chosen among those with P100 filtration and three sizes (small, medium, large) and to subjectively include a variety of pliability and shape. The filtering facepiece respirator was randomly selected from those available with P100 filtration and three sizes (small, medium, large).

Fit Testing

Fit testing employed the ambient aerosol quantitative technique (PORTACOUNT® Model 8020; TSI Inc., Shoreview, MN). The order of respirators tested on a given subject was randomized, so each subject experienced a different order of testing.

Three separate donnings were used for each respirator model/size combination, with a separate fit test value determined for each donning. The subjects performed three exercises for each donning: normal breathing, up-and-down head nodding, and side-to-side head movement. Each of the three exercises was sustained for one minute. After a set of the three exercises, the subjects removed the respirator being tested, and rested for three minutes. Then the subject re-donned the same respirator and repeated the same three exercises for one minute each. After the third set of exercises, the fit testing for that respirator model/size combination was completed and the subject was scheduled for fit testing on the next respirator model/size combination. For each respirator model/size, the three fit factors from independent donnings by a given subject were obtained.

The fit test exercise protocol used in this investigation is not one recognized by OSHA. The protocol was not chosen to conform to OSHA guidelines, but instead to serve as a means of gathering comparable respirator fit measurements reflecting a similar nominal range of head motions among the 30 different subjects in the present study.

Statistical Analysis

Each of the fit test values was log transformed because fit factors are usually log normally distributed. The mean log-transformed data for each respirator model/respirator size/subject combination were calculated. The mean log-transformed fit test results (as dependent variable) and the 3D facial parameters, PCA scores and traditional measurements (as independent variables) were analyzed using the SAS® (Cary, NC) PROC STEPWISE function, forward selection stepwise linear regression. The stepwise procedure was used to identify a best subset multiple regression model for each respirator model/size combination.

The facial parameter data and the PCA scores were standardized prior to entry into the regression (Kutner et al., 1996) prior to the regression analysis, using the formula:

$$X_{std} = \frac{x - \bar{x}}{s_x}$$

where,

x = observed value of variable x to be standardized (e.g., a face measurement)

X_{std} = standardized value

$\bar{x}$ = arithmetic mean of all observations of x

s_x = standard deviation of x .

RESULTS

The panel included two Asian-American females and one African-American male, with the remainder being Caucasian. The 27 Caucasian subjects consisted of 12 males and 15 females. The weight of the subjects ranged from 48.6 kg to 116.0 kg, and the stature from 1507 mm to 1900 mm.

The 3D parameters are summarized in Table II. As would be expected for the range of subject face sizes, the parameters also have large ranges.

Table II. Three-Dimensional Parameters for Each Subject

Subject ID	Angle: Alare – Sellion- Alare (Degrees)	Angle: Gonion- Pronasale- Gonion (Degrees)	Angle: Gonion- Sellion- Gonion (Degrees)	Angle: Nasal Root- Sellion- Nasal Root (Degrees)	Angle: Sellion- Pronasale- Menton (Degrees)	Nose Area (sq mm)
Range	39 – 55	43 – 70	43 – 65	85 – 134	114 – 135	2647 – 5164
Mean	45.0	53.1	51.1	99.5	124.1	3662.4

The mean log-transformed data for each respirator model/respirator size/subject combination are summarized in Table III. The range of the fit test data was high within subjects for the different respirators, indicating the influence of different respirator designs and sizes.

The results of the stepwise regression analyses for the PCA scores are summarized in Table IV. An example of the application of stepwise linear regression data in Table IV to the PCA scores and the fit test data for Respirator 1/Small is:

$$\text{Log (Respirator Fit)} = 1.81 - 0.64 (\text{standardized PCA1}) + 0.27 (\text{standardized PCA2})$$

$$(R^2 = 0.31)$$

Regressions within respirator model/size for respirator fit versus PCA scores indicated face size (PCA1) as more frequently qualifying for entry to the respirator fit regressions with $p < 0.15$, as compared to PCA2. PCA1 was a significant contributor for 8 of the 12 respirator model/size regressions, while PCA2 was a significant contributor for only 4 of the 12 regressions.

Regressions within respirator model/size for respirator fit versus 3D parameters (also in Table IV) showed “nose area” as the most frequent contributor to the respirator fit regressions. Nose area was a significant contributor for 10 of the 12 regressions. The next closest variable (alare-sellion angle) only contributed to 5 of the 12 regressions.

While none of the R^2 values for either the 3D parameters or the PCA scores were larger than 0.60, the R^2 values for small and large respirators were generally larger than those for medium sized respirators. In the case of the 3D parameter regressions, three of the four models yielded R^2 values for large and small sizes that were larger, on average, than those for the medium sizes of the respective respirator models. In the case of the PCA parameter regressions, all four of the R^2 values for large and small regressions were larger than those for medium respirators.

Table V provides the intercepts and coefficient (with significance levels) from forward stepwise linear regression of log-transformed respirator fit for all subjects with standardized traditional measurements for all subjects for each respirator. The most frequent contributors to the regressions in these analyses were face length and nose protrusion (both appeared in 4 of the 12 regressions). The R^2 values ranged from 0.16 to 0.84. The R^2 values were generally higher than those in the regression statistics for 3D and PCA parameters, perhaps as a result of the larger number of traditional measurement variables.

Table III. Mean Log-transformed Fit Factors for Each Subject by Respirator Model and Size

Subjects	Respirator Model/Size [^]											
	1/Lrg	1/Med	1/Sml	2/Lrg	2/Med	2/Sml	3/Lrg	3/Med	3/Sml	4/Lrg	4/Med	4/Sml
1	0.301	3.408	1.692	0.943	1.569	2.030	1.025	1.933	5.077	0.360	0.418	5.071
2	3.349	1.148	0.631	3.093	2.011	1.033	4.274	3.957	1.067	4.522	4.254	0.661
3	0.700	0.837	1.006	0.551	4.110	4.866	4.535	3.208	5.487	0.301	1.768	1.376
4	3.593	1.311	0.943	0.477	4.373	0.651	2.551	1.391	4.303	0.301	4.709	2.671
5	0.492	3.898	3.460	0.460	1.664	4.831	0.699	3.748	4.740	0.693	4.086	4.981
6	2.490	0.888	0.752	4.919	2.795	0.460	3.107	2.287	0.766	0.418	5.119	0.401
7	2.126	0.842	0.301	2.595	2.911	0.301	4.128	2.900	0.820	4.264	2.358	2.354
8	1.767	2.325	0.878	0.301	1.401	2.320	2.181	0.460	1.728	3.271	1.912	2.236
9	0.842	0.994	0.460	4.790	1.382	0.477	3.519	2.970	1.000	4.625	1.255	0.739
10	4.025	3.819	3.446	0.774	3.319	2.622	3.551	4.779	1.892	2.242	4.936	1.456
11	2.320	0.867	2.420	0.418	3.211	1.560	1.627	1.844	4.425	4.350	1.505	0.707
12	2.922	1.346	1.014	2.978	3.957	0.968	4.526	4.672	4.621	4.788	3.672	0.683
13	1.185	0.661	0.898	2.672	0.634	4.251	0.641	1.117	2.779	1.575	2.686	4.152
14	3.322	3.349	1.247	1.081	1.135	0.930	4.272	3.376	0.719	3.128	2.419	1.543
15	2.095	1.119	3.524	0.774	2.261	4.269	2.392	1.130	4.728	3.029	4.364	4.259
16	3.381	1.238	0.886	3.266	4.707	3.268	3.653	2.269	3.807	2.816	3.384	0.896
17	3.525	3.603	1.304	1.698	4.295	1.696	2.241	4.400	4.537	2.025	4.943	1.932
18	*	4.266	1.111	4.644	4.691	1.954	*	0.641	1.945	2.227	1.694	*
19	3.597	3.318	2.603	4.291	2.157	1.117	4.536	4.773	4.455	2.433	4.385	4.040
20	2.469	2.477	3.470	0.602	4.265	4.228	*	3.892	*	0.774	*	3.964
21	0.360	0.820	0.651	0.301	2.791	0.816	1.950	2.041	0.800	4.049	4.501	1.507
22	2.059	2.525	2.729	0.912	3.271	1.592	0.519	1.001	2.677	1.199	2.480	3.434
23	2.304	2.152	2.784	1.048	4.595	4.413	4.745	4.353	4.470	2.781	4.546	4.399
24	2.883	3.557	2.241	2.939	4.325	3.465	2.238	5.262	4.322	2.764	4.425	3.845
25	2.985	2.746	2.663	1.670	2.067	1.749	3.762	4.139	5.012	2.017	2.802	1.890
26	1.088	1.400	0.560	0.737	4.121	4.183	1.332	1.385	3.540	0.702	2.785	4.054
27	2.961	3.859	1.912	4.539	4.543	1.251	3.325	3.371	0.908	4.710	2.586	0.683
28	3.621	2.674	3.239	1.052	4.286	4.669	1.595	3.210	2.201	2.062	4.061	3.932
29	2.522	1.977	3.238	4.439	2.571	3.414	4.564	5.158	3.819	0.619	2.916	3.492
30	3.570	2.482	2.098	3.116	4.000	0.460	3.629	2.535	0.774	0.482	4.398	0.852

[^]Respirator 1 was a filtering facepiece; others were elastomeric facepiece with cartridge.

*Two subjects withdrew from the study before completing fit tests for all respirators.

Table IV. Forward Selection Stepwise Regression Coefficients, Intercepts, and R^2 for Log-Transformed Fit Factors versus 3D Facial Parameters and PCA Scores by Respirator Model and Size[#]

	Respirator Model Number / Size											
	1/L	1/M	1/S	2/L	2/M	2/S	3/L	3/M	3/S	4/L	4/M	4/S
3D Parameters												
Intercept	2.38	2.2	1.81	2.07	3.11	2.33	2.86	2.94	3.06	2.32	3.27	2.48
Coefficient												
Nose Area	0.38 ^C		-0.43 ^B	1.24 ^A		-0.89 ^A	0.80 ^A	0.45 ^C	-0.77 ^B	0.41 ^C	0.37 ^C	-0.94 ^A
Angle: Nasal Root – Sellion – Nasal Root	- 0.35 ^C	-0.46 ^B	-0.31 ^C					-0.44 ^C	-0.49 ^C			
Angle: Sellion – Pronasale- Menton		-0.34 ^C			-0.44 ^C							
Angle: Gonion – Pronasal – Gonion										0.59 ^B		
Angle: Alare – Sellion – Alare												
Angle: Gonion – Sellion – Gonion												
R^2	0.25*	0.23*	0.20*	0.60*	0.12	0.33*	0.34*	0.22*	0.24*	0.28*	0.08	0.39*
PCA Factors												
Intercept	2.34	^	1.81	2.07	^	2.33	2.89	2.94	3.07	2.31	3.28	2.47
Coefficient												
PCA1 (face size)			-0.64 ^A	1.24 ^A		-0.95 ^A	0.71 ^A	0.72 ^A	-1.00 ^A	0.78 ^A		-0.75 ^A
PCA2 (face shape)	0.57 ^A		0.27 ^C								0.49 ^B	-0.42 ^C
R^2	0.26*	^	0.31*	0.60*	^	0.37*	0.24*	0.26*	0.33*	0.27*	0.15*	0.42*

^ No variables qualified for entry to the regression at a 0.15 significance level (0.15 is the default significance level for SAS).

*The regression model is significant, with $p < 0.05$.

^A = $p < 0.01$; ^B = $p < 0.05$; ^C = $p < 0.15$.

The regression variables were standardized before entry in the model.

PCA1 is facial size; PCA2 considers vertical dimensions (face length, nose length, and nose protrusion).

Table V. Intercepts and Coefficient (with significance levels) from Forward Stepwise Linear Regression of Log (Fit Factors) with Standardized Traditional Measurements

Dimension [#] / Intercept	Respirator Model/Size											
	1/L	1/M	1/S	2/L	2/M	2/S	3/L	3/M	3/S	4/L	4/M	4/S
Intercept	2.38	2.2	1.82	2.07	3.12	2.33	2.83	2.94	3.11	2.32	3.3	2.49
Bigonial Breadth							-1.64 ^A				-1.69 ^A	
Bitracion Chin Arc												
Bitracion Frontal Arc												
Bitracion Subnasal Arc				-1.06 ^A			1.19 ^A					
Face Width									-.54 ^C			
Interpupillary Breadth					-.84 ^A				-.75 ^B			
Lip Length									.91 ^A			
Face Length							.82 ^B	1.19 ^A			.93 ^A	-.87 ^A
Menton Subnasal Length									-.71 ^B	.88 ^A		
Nasal Root Breadth		-.45 ^C	-.70 ^A		-.53 ^B							
Nose Breadth		-.74 ^B				-.62 ^B						
Nose Protrusion	.44 ^B				.55 ^A			.38 ^C				-.38 ^C
Subnasal Sellion Length				.51 ^A								
Bitracion Coronal Arc						-1.17 ^A		-1.11 ^A				
Maximum Frontal Breadth					1.09 ^A						.45 ^C	
Minimum Frontal Breadth												
Head Breadth		.73 ^B		.80 ^A							.55 ^B	
Head Circumference				1.46 ^A		1.44 ^A						
Head Length		.40 ^C				-.85 ^B						
Neck Circumference							.54 ^C					
R ²	0.16*	0.39*	0.41*	0.84*	0.52*	0.62*	0.67*	0.40*	0.62*	0.33*	0.43*	0.47*

* The regression model is significant, with $p < 0.05$. [#] The variables were standardized before regression analysis.

^A = $p < 0.01$; ^B = $p < 0.05$; ^C = $p < 0.15$.

In comparing the three sets of regressions provided in Tables IV and V (traditional facial dimensions, 3D parameters, and PCA), the 3D parameters seem to have an advantage, i.e., more frequent contributors in regression models. However, looking at the R^2 values, there appears to be no consistent advantage. The R^2 values for the traditional dimensions ranged from 0.16 – 0.84. The regression with the highest R^2 value had four facial dimensions contributing. For the 3D parameters, the R^2 ranges from 0.20 – 0.60. The highest R^2 value, 0.60, had only one 3D parameter in the regression equation. The R^2 for PCA regressions ranged from 0.15 – 0.60. Again, the highest PCA R^2 value of 0.60 had just one PCA value in the regression.

DISCUSSION

Three-dimensional parameters related to the nose (the nose area and the alare-sellion angle) may influence respirator fit more than the other 3D angles included in this study. This may be due in part to the added curvatures of the nose as compared to other sealing surfaces of half-facepiece respirators. Additional research could examine the specific features of the nose curvatures for their influence on respirator fit.

The PCA score for the overall face size (PCA1) may be more important than the PCA2 score for shape, i.e., long/narrow and short/wide. This may be due to the nature of sizing by respirator manufacturers. Subjectively, it appears that each of the four manufacturers represented in this study based “size” on increases in both facial length and width concurrently, rather than increases in a ratio of facial length and width.

The two traditional dimensions used for assigning subjects to half-facepiece respirator fit test panels (face width and face length) were selected as contributors to the regressions for only one and four model/size combinations, respectively. The most frequent contributors among the traditional measurements were face length and nose protrusion, but they were significant in only four of the 12 regressions in Table V. Thus, the traditional measurements indicate less consistency in their relationships with respirator fit.

Both the 3D and PCA parameters provided variables that were more frequent significant contributors to relationships between respirator fit and facial parameters as compared to the traditional measurement variables. One 3D parameter – nose area – was a significant contributor in 10 of the twelve regressions. These findings suggest 3D parameters can potentially be selected for defining future respirator fit test panels.

LIMITATIONS

This study only included four half-mask respirator models; other or different models may provide different outcomes. Similarly, the findings are only applicable to the fit test protocol used in the study. A longer fit test protocol or one with more or different exercises may produce different results. Also, the automated facial measurement techniques used in this study employed a laser beam scanner. The quality of the data depended on the steadiness of the subjects during the one minute scanning. Movement of the subjects during the scanning may have affected the 3D parameters obtained. Other 3D techniques have been developed since the time of the tests that may offer enhanced means of quantifying facial measurements, thus leading to improved results. Finally, the study employed a small group of 30 subjects of limited racial diversity; a study group with more racial diversity may have yielded different results. As noted previously, the subjects did not include any representation within one of the ten intended face size categories (cell 5).

CONCLUSIONS

Of the non-traditional facial parameters studied here, overall face size and nose area were most frequently found to have significant correlations with respirator fit. The two 3D parameters that most frequently contributed to correlations with respirator fit were nose area and the angle formed by the left and right alare with the sellion at the apex. The nose area may be more significant than other 3D parameters. The PCA score for overall face size, PCA1, was more closely associated with respirator fit than the PCA2 score for shape (long/narrow and short/wide).

Of the traditional measurements evaluated, face length and nose protrusion were most frequently found to have significant correlations with respirator fit. Both the 3D and PCA parameters provided variables that were more frequent significant contributors to regressions between respirator fit and facial parameters as compared to the traditional measurement variables. These findings are significant in that they can potentially influence the composition of future respirator fit test panels.

Acknowledgement

Ms. Stephanie Lynch contributed to this research as a National Research Council Resident Research Associate at the National Institute for Occupational Safety and Health (NIOSH), National Personal Protective Technology Laboratory (NPPTL).

Disclaimer

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