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AN ASSESSMENT OF CRITICAL ANTHROPOMETRIC DIMENSIONS FOR PREDICTING THE FIT OF A HALF-MASK RESPIRATOR

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The purpose of this study was to determine if facial dimensions for a group of subjects were predictive of the fit factors measured while one brand of half-mask respirator was worn. Fit factors and 12 facial dimensions measured on 30 female and 38 male subjects were analyzed by correlation coefficients; weighted, multiple linear regression; and discriminant analysis. Data were analyzed for all subjects, gender subgroups, a race subgroup (whites only), and race/gender subgroups. Significant correlation coefficients with the log-transformed fit factors were found for four dimensions; four dimensions had significant coefficients in four or more multiple linear regression models. Only two dimensions had significant coefficients in four or more discriminant analysis models. Menton-subnasale (lower face) length was the only dimension included in all three of these groups. Gender-specific regression models had very high coefficient of determination values ($R^2 > 0.85$). Discriminant analysis of the data for all subjects and race/gender subgroups found very good predictive scores for statistical software-generated models and menton-subnasale length alone; these scores were significantly better than those for the model with the respirator test panel dimensions (face length and lip width). These analyses found that facial dimensions were good predictors of respirator fit for those subjects wearing one brand of half-mask respirator. Lower face length was consistently indicated as being correlated or associated with fit. These results would indicate that dimensions other than those currently used may be more appropriate to define a half-mask respirator test panel.

Anthropometric panels for testing respirators were developed to define a group of test subjects that were representative of a working population based on relevant facial dimensions.⁽¹⁾ Selection of dimensions used to define the panels was based on experience in developing military oxygen masks and extensive military anthropometric data.⁽¹⁻³⁾ The facial

dimensions selected for full facepiece respirators were face length and face width; for half- and quarter-mask respirators the dimensions were face length and lip width.⁽¹⁾

These test panels were subsequently used in extensive fit testing to develop assigned protection factors for respirators,⁽⁴⁾ and they have been incorporated into the National Institute for Occupational Safety and Health (NIOSH) proposed rule for testing and certifying respirators.⁽⁵⁾ This use of the panel assumes that the fit attained by the test subjects would be representative of that attained by the working population of wearers.^(4,5) For this assumption to be valid, the fit of the respirators should be associated with the facial dimensions used to define the panels.

However, several studies⁽⁶⁻⁹⁾ have indicated that there is little or no association between the fit of half-mask respirators and the dimensions used to define the half-mask test panel (face length and lip width). An early paper on respirator sizing concluded that measurement of face length alone was not adequate for selection of a facepiece and that the best fit could only be attained by trying on individual sizes.⁽⁶⁾ In a later study, an analysis of fit factors (FFs) and facial dimensions for 190 white males found a low but significant correlation coefficient of 0.22 for lip width ($p = 0.02$) and -0.04 for face length, which was not significant ($p = 0.66$).⁽⁷⁾ By using several multivariate analysis procedures, the authors of a recent study of half-mask respirator selection for a sample of 61 male and 60 female workers were unable to identify any significant associations between 10 facial measurements and respirator fit.⁽⁸⁾

Correlation of FFs and 12 facial dimensions was also determined as part of a study of the distribution of half-mask respirator face seal leak sites.⁽⁹⁾ Three dimensions, none of which were face length or lip width, were found to have significant correlation coefficients with FFs for all subjects and several subject subsets. The observed coefficients ranged from 0.23 to 0.47. These findings and the lack of significant differences between face length and lip width for leak site subsets in other aspects of the study indicated that other dimensions may be more effective in predicting respirator leakage.⁽⁹⁾

Although it has been shown that some facial dimensions may be correlated to FFs, it has not been demonstrated that facial dimensions are predictive of fit. The purpose of this study was

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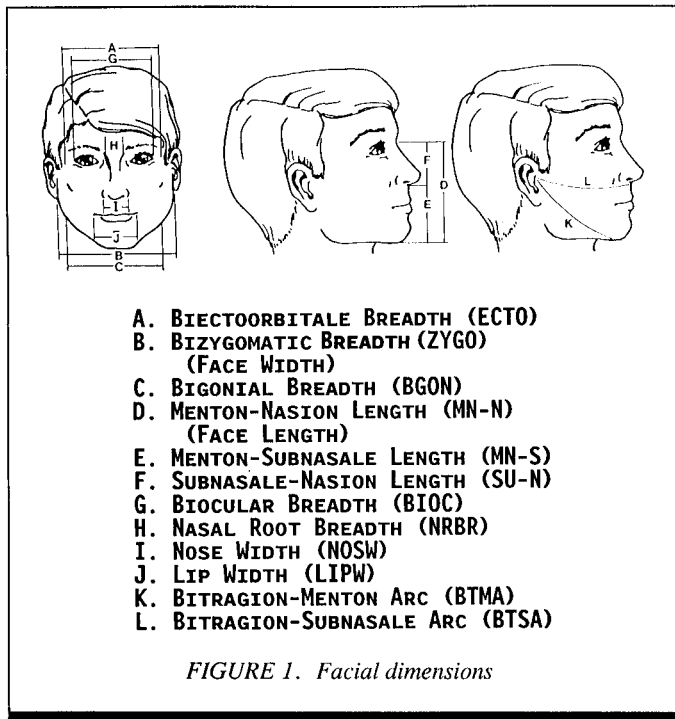


FIGURE 1. Facial dimensions

to determine if facial dimensions for a group of subjects were predictive of the FFs measured while they were wearing one brand of half-mask respirator.

EXPERIMENTAL MATERIALS AND METHODS

Data were collected by performing one fit test on subjects according to a protocol developed to identify leak sites by the deposition of a fluorescent aerosol.^(9,10) The test protocol included (1) measuring facial dimensions, (2) fitting the subjects with one size of the test respirator and performing a fit check, and (3) performing a quantitative fit test according to the method recommended in ANSI Z88.2-1980.⁽¹¹⁾ Integrated concentrations of fluorescent whitening agent within the facepiece and in the test chamber were measured with a forward light-scattering photometer.

The respirator used was one of three sizes (small, medium, or large) of the U.S. Safety Series 200 half-mask respirator (United States Safety Service Co., Kansas City, Mo.), which was carefully fitted to provide the best possible face seal. The facial dimensions illustrated in Figure 1 were measured by one investigator with sliding and spreading anthropometric calipers and a steel measuring tape. Variability of the investigator's measurements was determined by making multiple measurements on a panel of 10 subjects and was found to be within the inter-observation variation expected by Jamison and Zegura.⁽¹²⁾

Data recorded on each subject were entered into a spreadsheet

and appropriate descriptive statistics and multivariate analysis were performed by using SOLO Statistical System software.⁽¹³⁾ Two-tailed tests of hypothesis were performed by using an alpha value of 0.05 ($\alpha = 0.05$). Multivariate methods used to determine if facial dimensions were predictive of FF included correlation, multiple linear regression analysis, and discriminant analysis.⁽¹³⁾ Statistical analyses were performed on the data for all subjects, all males, all females, whites only, white males, and white females.

RESULTS AND DISCUSSION

Descriptive Statistics

Subjects included 68 university faculty, staff, and students who volunteered to participate in the study; of these, 38 were males and 30 were females: 7 were Asian, 9 were black, 3 were Hispanic, 47 were white, and 2 were Asian Indian. Their average age was 30.4 yr and ranged from 21 to 50 yr.

Results of anthropometric measurements for all subjects are summarized in Table I. As expected, the distribution for all of these facial dimensions did not significantly differ from the normal distribution.⁽²⁾ The dimensions for male and female face length, face width, nose width, and lip width were found to be in very close agreement to those measured by Gross and Horstman⁽⁸⁾ and the dimensions from 1967 and 1968 surveys of male and female U.S. Air Force personnel.^(14,15) The means for all four dimensions from the three surveys for males were within one standard deviation; the three means for all of the female dimensions except face length were also within one standard deviation.⁽¹²⁾ This indicates that the facial dimensions of the subjects used in this study were similar to those of the workers studied by Gross and Horstman⁽⁸⁾ and the military populations used to establish the respirator test panels.^(1,14,15)

Measured FFs ranged from 21 to 69 100 with an arithmetic mean of 8420, a geometric mean of 3140, and a geometric standard deviation of 5.03. A histogram of these data was right-skewed, which is consistent with the lognormal distribution, and the transformed FFs that used the natural logarithm (LNFFs) did not differ significantly from the normal distribution.⁽¹³⁾ Therefore, LNFFs were used for subsequent statistical analyses.

TABLE I. Facial Measurements of Subjects (cm)

Dimension	Mean (Standard Deviation)		
	All Subjects (n = 68)	Male (n = 38)	Female (n = 30)
Biectoorbitale breadth (ECTO)	12.3 (0.7)	12.7 (0.6)	11.9 (0.6)
Bizygomatic breadth (ZYGO) (face width)	13.5 (0.8)	13.9 (0.8)	12.9 (0.6)
Bigonial breadth (BGON)	10.9 (1.0)	11.4 (1.0)	10.3 (0.8)
Menton-nasion length (MN-N) (face length)	12.2 (0.7)	12.6 (0.7)	11.8 (0.5)
Menton-subnasale length (MN-S)	7.3 (0.6)	7.6 (0.4)	7.0 (0.5)
Subnasale-nasion length (SU-N)	5.4 (0.5)	5.4 (0.4)	5.3 (0.5)
Biocular breadth (BIOC)	8.7 (0.4)	8.9 (0.3)	8.5 (0.3)
Nasal root breadth (NRBR)	1.6 (0.2)	1.6 (0.2)	1.6 (0.2)
Nose width (NOSW)	3.5 (0.4)	3.6 (0.3)	3.3 (0.4)
Lip width (LIPW)	4.9 (0.4)	5.1 (0.4)	4.8 (0.3)
Bitragion-menton arc (BTMA)	30.9 (1.9)	32.1 (1.2)	29.5 (1.6)
Bitragion-subnasale arc (BTSA)	27.9 (1.4)	28.6 (1.1)	26.9 (1.2)

TABLE II. Correlation Coefficients of Facial Dimensions and LNFF

	ECTO	ZYGO	BGON	MN-N	MN-S ^A	SU-N	BIOC ^A	NRBR ^A	NOSW ^A	LIPW	BTMA	BTSA
ZYGO	0.92											
BGON	0.71	0.73										
MN-N	0.36	0.40	0.46									
MN-S	0.36	0.42	0.30	0.74								
SU-N	0.11	0.10	0.31	0.59	-0.02							
BIOC	0.73	0.71	0.56	0.38	0.37	0.11						
NRBR	0.48	0.47	0.37	0.11	0.25	-0.18	0.48					
NOSW	0.53	0.50	0.39	0.23	0.41	-0.10	0.52	0.50				
LIPW	0.39	0.35	0.38	0.26	0.24	0.10	0.43	0.56	0.50			
BTMA	0.65	0.66	0.70	0.61	0.44	0.33	0.56	0.37	0.54	0.49		
BTSA	0.78	0.78	0.78	0.52	0.44	0.27	0.70	0.48	0.60	0.48	0.86	
LNFF	0.18	0.18	0.18	0.18	0.37	-0.04	0.32	0.32	0.26	0.10	0.15	0.23

^ASignificant Pearson correlation coefficient between facial dimension and LNFF ($\alpha = 0.05$).

Correlation

The correlation matrix for the facial dimensions and LNFF is shown in Table II. Menton-subnasale length (lower face length), biocular breadth, nasal root breadth, and nose width had significant positive correlation coefficients with LNFF. These values are on the same order of that observed by Liau et al.⁽⁷⁾ for face width.

Biectoorbitale breadth, bizygomatic breadth, bitrignon-menton arc, and bitrignon-subnasale arc were highly correlated with many other facial dimensions. Multicollinearity between facial dimensions limits the interpretation of individual variables in the regression and discriminant analyses and could cause some of the facial dimensions not to be included in the multivariate models. Therefore, facial dimensions not included in those models should not be interpreted as being unrelated to fit.

Regression Analysis

Multiple linear regression was performed by the weighted, forward, stepwise method, which used LNFF as the dependent variable and the 12 measured facial dimensions as the independent variables.⁽¹³⁾ This method assigns weights to outlying points to reduce their effect on the estimation of regression coefficients by iterative procedures; a heuristic algorithm is then used to select the variables that result in the highest coefficient of determination (sequential R²) value for the regression model. The models developed by these procedures are summarized in Table III.

These results indicate that only the gender-specific models ac-

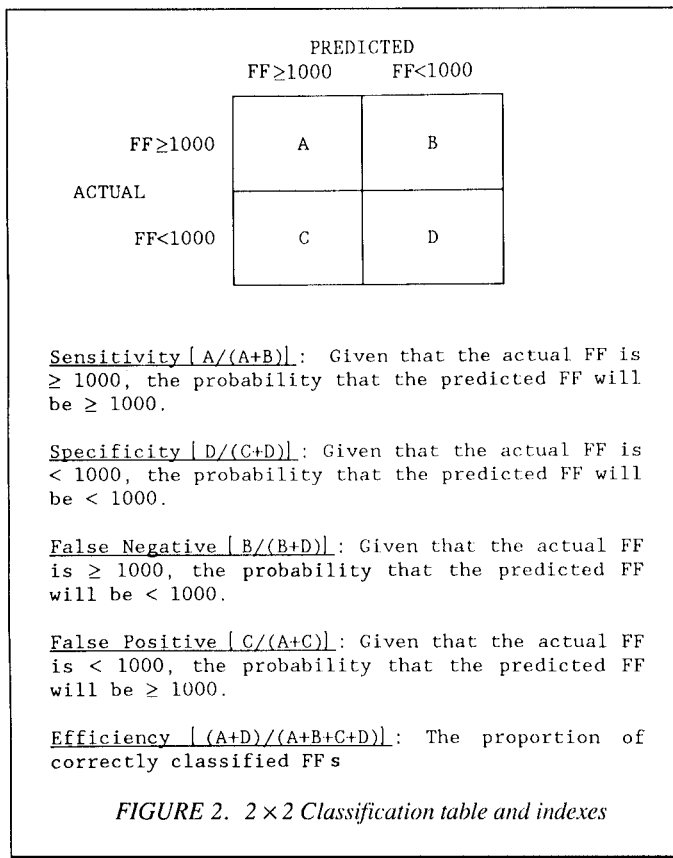
counted for a large amount of the variation in LNFF. The R² of models for all subjects and all white subjects were only 0.27 and 0.38, respectively; the gender-specific models were all greater than 0.85. As the subject subset becomes more specific, i.e., race-specific then gender-specific, the predictive ability of the model seems to become greater. This could be caused by less variability in facial dimensions for race and gender subsets⁽²⁾ or to dimensions having different relationships with LNFF between genders.

Biocular breadth and nasal root breadth, two of the facial dimensions that had significant correlation coefficients with LNFF, were included in all six models. All of the regression coefficients for nasal root breadth were significantly different from zero; five

TABLE III. Stepwise Regression Summary for Predicting LNFF

Variable	All Subjects (n = 68)	All Females (n = 30)	All Males (n = 38)	White Subjects (n = 47)	White Females (n = 22)	White Males (n = 25)
Mean Square						
Model	7.89	2.60	7.45	7.63	3.40	3.98
Error	1.89	0.08	0.25	1.00	0.11	5.63
Total	2.61	1.40	1.65	1.60	2.39	3.41
F-ratio	4.17	31.89	30.33	7.62	31.74	706.20
p-value	<0.01	<0.01	<0.01	<0.01	0.02	0.01
Adjusted R ²	0.28	0.94	0.85	0.38	0.96	1.00
<i>Coefficients for Independent Variables Included in the Regression Model</i>						
ECTO		-0.68		-0.98 ^A	-0.98	-0.91 ^A
ZYGO	-0.78	-1.06		0.73	-1.61 ^A	-0.16
BGON	0.38	0.66 ^A			0.80 ^A	0.32 ^A
MN-N	-2.23 ^A	-4.89 ^A	-4.09 ^A		-2.08 ^A	-4.96 ^A
MN-S	3.04 ^A	4.29 ^A	5.80 ^A		0.59	7.66 ^A
SU-N	2.05 ^A	4.09 ^A	3.06 ^A			3.43 ^A
BIOC	1.34 ^A	1.44 ^A	1.09 ^A	1.80 ^A	1.40	2.16 ^A
NRBR	3.10 ^A	5.04 ^A	3.30 ^A	4.46 ^A	4.77 ^A	3.28 ^A
NOSW		1.18 ^A	-1.23 ^A			-0.69 ^A
LIPW	-0.98	-2.46 ^A	-1.22 ^A		-4.01 ^A	0.46
BTMA		0.64 ^A				0.41 ^A
BTSA		-0.55 ^A			1.56 ^A	-0.43 ^A

^Ap-value for coefficients $\neq 0$ less than 0.05.



for biocular breadth were significant: all of these values had a positive sign and were very consistent among the models.

Menton-nasion length (face length) had significant regression coefficients in five models; all were numerically high and with negative signs. Lip width was included in five models; however, only three were significantly different from zero, and one had a positive sign although the other four were negative. Menton-subnasale length (lower face length) was included in five models with significant coefficients of high positive value.

Discriminant Analysis

Discriminant analysis is very similar to regression analysis, but it is used to distinguish (or discriminate) between groups or categories on the basis of several continuous, independent variables.⁽¹³⁾ In this analysis, the dependent variable was a two-level categorical variable (subjects who had measured FFs equal to or greater than 1000 and subjects who had measured FFs less than 1000); the independent variables were facial dimensions. A critical value of FF = 1000 was used to provide an adequate number of subjects with measured FFs above (n = 55) and below (n = 13) that point and yet be within the reasonable range of

FFs that can be achieved with a half-mask respirator. Given a set of facial dimensions, the models predicted the appropriate FF category for each subject. The predicted categories were then compared to the actual categories by 2 × 2 classification tables. The table format and indexes are shown in Figure 2. A model that was highly predictive of respirator fit would have high sensitivity, specificity, and efficiency values and low false positive and false negative values. The indexes of greatest interest in predicting respirator fit were false positive and efficiency.

Discriminant analyses were performed by using the individual facial dimensions for all subjects and the race/gender subgroups to determine if there was a single dimension that was a good predictor of respirator fit. Menton-subnasale length (lower face length) was found to have the highest efficiency and the lowest value false positive rates in four of the six data sets; it did not have the best values for all females and white females.

Analyses were also performed on the six data sets to determine the predictability of the two dimensions used to define the respirator test panel (face length and lip width) and for the most efficient model determined by the statistical software.⁽¹³⁾ For the most efficient model, the program selected independent variables in a forward stepwise fashion until a model was defined that maximized efficiency and included the smallest number of variables. Coefficients for the variables included in the most efficient models for each set are listed in Table IV, and the outcomes of the classification tables for the three models are shown in Table V.

Menton-subnasale length (lower face length) was included in five of the six models, and the coefficients were significantly different from zero in four of those models. Menton-nasion length (face length), one of the dimensions used to define the respirator test panel, was included in four of the models: three having coefficients significantly different from zero. The other test panel dimension, lip width, was not included in any of the models. Of the two dimensions that were included in all of the regression models, biocular breadth and nasal root breadth, only nasal root breadth had significant coefficients in two of the discriminant analysis models with coefficients significantly different from zero. The signs of the discriminant analysis coefficients were consistent among models and with their respective regression coefficients.

TABLE IV. Coefficients for Dimensions Included in the Most Efficient Discriminant Analysis Models

Dimension	All Subjects (n = 68)	All Females (n = 30)	All Males (n = 38)	White Subjects (n = 47)	White Females (n = 22)	White Males (n = 25)
ECTO	-0.51			-0.81		
ZYGO		-4.44 ^A			-10.05 ^A	
BGON					3.33	
MN-N	-3.23 ^A	-2.19	-3.27 ^A			-4.90 ^A
MN-S	5.13 ^A	1.37	10.36 ^A	1.44 ^A		13.91 ^A
SU-N	2.77				6.12 ^A	
NRBR		8.82 ^A			20.44 ^A	
BTMA					-3.18 ^A	
BTSA		1.47				

^Ap-value for coefficients $\neq 0$ less than 0.05.

TABLE V. Classification Table Summary

Model	Number Classified in 2 × 2 Table Cell				Sens.	Spec.	False Neg.	False Pos.	Efficiency
	A	B	C	D					
<i>All Subjects (n = 68)</i>									
MN-S	42	13	3	10	0.76	0.77	0.56	0.07	0.76
MN-N & LIPW	31	24	4	9	0.56	0.69	0.73	0.11	0.59
Most efficient ^A	45	10	2	11	0.82	0.85	0.48	0.04	0.82
<i>All Females (n = 30)</i>									
MN-S	14	9	4	3	0.61	0.43	0.75	0.22	0.57
MN-N & LIPW	12	11	4	3	0.52	0.43	0.79	0.25	0.50
Most efficient ^A	19	4	1	6	0.83	0.86	0.40	0.05	0.83
<i>All Males (n = 38)</i>									
MN-S	28	4	1	5	0.88	0.83	0.44	0.03	0.87
MN-N & LIPW	21	11	1	5	0.66	0.83	0.69	0.04	0.68
Most efficient ^A	31	1	0	6	0.97	1.00	0.14	0.00	0.97
<i>White Subjects (n = 47)</i>									
MN-S	25	11	3	8	0.69	0.73	0.58	0.11	0.70
MN-N & LIPW	18	18	5	6	0.50	0.54	0.75	0.22	0.51
Most efficient ^A	29	7	3	8	0.81	0.73	0.47	0.09	0.79
<i>White Females (n = 22)</i>									
MN-S	6	10	2	4	0.38	0.67	0.71	0.25	0.45
MN-N & LIPW	9	7	2	4	0.56	0.67	0.64	0.18	0.59
Most efficient ^A	13	3	0	6	0.81	1.00	0.33	0.00	0.86
<i>White Males (n = 25)</i>									
MN-S	18	2	1	4	0.90	0.80	0.33	0.05	0.88
MN-N & LIPW	13	7	2	3	0.65	0.60	0.70	0.13	0.64
Most efficient ^A	20	0	0	5	1.00	1.00	0.00	0.00	1.00

^AMost efficient model determined by forward, stepwise discriminant analysis. See Table IV for coefficients of facial dimensions included in the models.

Data in Table V indicate that the most efficient model consistently produced very good scores for all indexes: false positive rates never exceeded 0.09 and efficiencies were never less than 0.78. These models also produced very good scores for sensitivity and specificity with false negative scores that did not exceed 0.48. The most efficient model (menton-nasion length and menton-subnasale length) for white males resulted in completely concordant classification.

Classification index values for menton-subnasale length (lower face length) alone were of the same order as the most efficient model but were slightly higher for false positive values. Lower face length alone also resulted in better scores than the two test panel dimensions (face length and lip width). A two-way analysis of variance found that all indexes for the most efficient model and lower face length alone were significantly better than those for the two test panel dimensions.⁽¹³⁾

CONCLUSIONS

This study indicated that the fit of a half-mask respirator could be reasonably predicted by selected wearers' facial dimensions. However, interpretation of individual regression and discrimi-

nant coefficients is limited because of the possible effects of multicollinearity. Although there may be other dimensions that are related to fit, the regression analysis models for gender subsets accounted for a very high proportion of the variability in LNFFs for those subsets. However, these models included more facial dimensions than currently used, which may limit their application outside of a research setting.

If one were to consider a pass/fail criterion, this study implies that a single facial dimension, menton-subnasale length (lower face length), would reasonably predict if a wearer would achieve an FF above or below 1000. In addition, the most efficient models determined by discriminant analyses were highly predictive of FFs above or below 1000 with very high values for sensitivity, specificity, and efficiency; very low values for false positive; and reasonable values for false negative. However, these results need to be replicated in studies on other groups of respirator wearers.

The discriminant analysis model that used the Los Alamos half-mask respirator test panel dimensions⁽¹⁾ produced significantly lower sensitivities, specificities, and efficiencies and significantly higher false negatives and false positives than did the most efficient model or the single dimension, menton-subnasale length.

Facial dimensions that were found to have significant correlation coefficients with LNFF were biocular breadth, menton-subnasale length, nasal root breadth, and nose width. Dimensions with significant regression coefficients in four or more models were menton-nasion length, menton-subnasale length, subnasale-nasion length, biocular breadth, and nasal root breadth; significant coefficients in three or more discriminant analysis models were menton-nasion length and menton-subnasale length. Of these, only menton-nasion length is included in the Los Alamos test panel.⁽¹⁾ The facial dimension included in all three of these groups was menton-subnasale length; this dimension also produced good classification table index scores.

This analysis found that facial dimensions were good predictors of respirator fit for this group of wearers and the half-mask respirator tested in this study; however, only one of the facial dimensions used to define the half-mask respirator panel⁽¹⁾ was repeatedly included in efficient predictive models. A single dimension, menton-subnasale length, was found to be a good predictor of FF above or below a critical value of 1000. Although this topic needs more extensive research, this study indicates that dimensions other than those currently used may be more appropriate to define test groups whose fit is intended to be representative of worker populations.

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